leti
cea tech

TECHNOLOGY
RESEARCH
INSTITUTE

SYSTEMS

2019

SCIENTIFIC
REPORT

TECHNOLOGY
RESEARCH
INSTITUTE

COMMITTED TO INNOVATION, CEA-Leti CREATES DIFFERENTIATING SOLUTIONS WITH ITS PARTNERS.

CEA-Leti is a research institute of CEA Tech and a recognized global leader in miniaturization technologies.

CEA-Leti's teams are focused on developing secure solutions that will enable future information and communication technologies, health and wellness approaches, clean and safe energy production and recovery, sustainable transport, space exploration and cybersecurity.

For 50 years, the institute has built long term relationships with its industrial partners, tailoring innovative and differentiating solutions to their needs. Its entrepreneurship programs have sparked the creation of 65 start-ups.

CEA-Leti and its industrial partners work together through bilateral projects, joint laboratories and collaborative research programs, as illustrated in this report.

CEA-Leti maintains an excellent scientific level by working with the best research teams worldwide, establishing partnerships with major research technology organizations and academic institutions. CEA-Leti is also a member of the French Carnot Institutes network*.

*Carnot Institutes network: French network of 39 institutes serving innovation in industry.

DE LA RECHERCHE À L'INDUSTRIE

CEA Tech is the technology research branch of the French Alternative Energies and Atomic Energy Commission (CEA), a key player in research, development and innovation in defense & security, nuclear energy, technological research for industry and fundamental physical and life sciences.

www.cea.fr/english

CEA-Leti at a glance

800
publications per year

ISO 9001
certified since 2000

114
European projects

Founded in
1967

Based in
France (Grenoble)
with offices in the
US (San Francisco) and
Japan (Tokyo)

300
industrial partners

1,850
researchers

3,100
patents in portfolio

10,000
sq. meters cleanroom
100-200-300 mm wafers

65
startups created

SYSTEMS

Located on the Minatec Campus, the System Division (DSYS) gathers over 200 high level researchers and engineers. This division is at the strategic core of CEA-Leti's technological innovation and aims to provide a global and valuable "system perspective" on technological trends.

DSYS's expertise is based on four major pillars which are (i) wireless communications, (ii) innovative sensor-system design, (iii) power management and electronics for energy and (iv) security solutions for electronic systems and components. Its teams are using tools and know-hows inherited from the physics, electromagnetism and electronic areas but also from the signal and data processing domain; additionally, they have access to state-of-the-art facilities for the simulation, characterization and prototyping of complex electronic systems.

Thanks to its capability to work on specific application barriers, DSYS Division is particularly attractive for industrial partners who are facing the challenges of IoT associated with artificial intelligence (AI), 5G and beyond-5G, as well as cybersecurity. Its partners range from SMEs to major international companies, which are looking for a high level of technical expertise and strong project management experience in a business-compatible environment.

DSYS's research and innovation activities span a wide panel of applications such as factory of the future, automotive, space and aeronautics, multimedia, smart energy, smart transport, e-health, sports and leisure.

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SYSTEMS

FOREWORD

Sébastien Dauvé
HEAD OF SYSTEM DIVISION

All the teams from DSYS Division are pleased to present you a selection of the best scientific achievements of 2019. This scientific report is divided into 7 chapters presenting about 70 papers focusing on our main areas of innovation for sensors, power conversion, communication and cybersecurity.

Among the significant results and trends, the growing use of learning algorithms applied to hardware developments with a link to upcoming edge-AI applications for both communications and sensors applications (see chapters 1 and 4) is remarkable.

Concerning power management (chapter 2), whereas the use of GaN is becoming a reality for power conversion for automotive or even consumer applications, we see emerging studies on completely new approaches for power conversion (see the paper *inductorless piezoelectric converter*).

In the field of communications, DSYS has consolidated its contributions to the design, development and evaluation of innovative solutions for the forecoming generation of 5G and beyond-5G wireless communication systems exploiting high mm waves until Thz. This work includes dedicated front-end radio Innovation using RF SOI (see chapters 3, 4, 5 and 6).

Finally, 2019 sees the on-going progress of DSYS in the investigations on hardware enabled cyber security and on the identification of countermeasures to threats for the applications related to massive IoT, which have a critical impact on vertical industry needs. Significant achievements in this domain are covered in the last chapter.

I would like to thank our industrial partners, institutional fellows and academic collaborators, who have worked closely with us in 2019. Without these collaborations, the present report would not have been so relevant.

To conclude this report, we proudly acknowledge the contributions of the young researchers and students that join us each year to carry out some of the world's most advanced research projects and to become the next generation of innovators.

I hope you will find in DSYS 2019 Scientific Report inspiration for your future developments and research.

KEY FIGURES

185 researchers

38 PhD students and post-docs

35 Temporary employees and interims

33.7 M€ budget

92% external funding

3 startups created

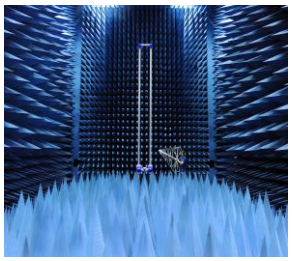
52 patents granted in 2019

483 patents portfolio

35 book chapters and journals

137 communications in conferences and workshops

6 Keynotes and invited talks



Research facilities:

3 Anechoic chambers

1 Connectivity platform

1 IT Security Evaluation Facility (ITSEF)

1 Electronic Test and Design platform

54 Industrial partners with whom we have a bilateral contract

SCIENTIFIC ACTIVITY

Publications

147 publications in 2019 including 35 book chapters and top journals and over 100 international conference communications. These include: Nano Energy IEEE Transactions on Wireless Communications, IEEE Transactions on Power Electronics, IEEE Vehicular Technology Magazine, Physical Review Applied, IEEE Transactions on Antennas and Propagation, APL Materials, IEEE Access, IEEE Antennas and Wireless Propagation Letters, Nanotechnology, IEEE Wireless Communications Letters, Smart Materials and Structures, IEEE Transactions on Circuits and Systems, Journal of Magnetic Resonance, Journal of Intelligent Material System and Structures, IEEE Transactions on Magnetics, Journal of Cryptographic Engineering, EuCAP, EuMC, ECTC, TRANSDUCERS, EUROSENSORS, RFIC, VTC Spring, DATE, IEDM, PowerMEMS, etc.

Prizes and awards

- Emilio Calvanese Strinati, Antonio Clemente, *et al.*, "5GCHAMPION – Disruptive 5G Technologies for Roll-Out in 2018", Best ETRI Journal Award, 2019.
- F. Wolf, M. Sana, S. de Rivaz, F. Dehmas, *et al.*, “Comparison of Multi-Channel Ranging Algorithms for Narrowband LPWA Network Localization“, International Symposium on Ubiquitous Networking (UNet), Best Paper Award, 2019.
- A. Pereira Da Silva, I. Brahmi, S. Leirens, B. Denis, “System-level Simulation of Cooperative Sensor Data Fusion Strategies for Improved Vulnerable Road Users Safety”, WPNC ‘19 Best Paper Runner-Up Award, 2019.
- A. Clemente, L. Di Palma, F. Diaby, L. Dussopt, K. Pham, R. Sauleau, "Electronically steerable transmitarray antennas for Ka-band", European Conference on Antennas and Propagation (EuCAP 2019), Best Antenna Design and Applications Paper, 2019.
- "PYCSEL H2020 - Thin Thermal Fingerprint Sensor", LOPEC 2019, Best Publicly-Funded Project Demonstrator Award, 2019.
- O. Savry, T. Hiscock, M. El Majihi, "Sécurité matérielle des systèmes - Vulnérabilité des processeurs et techniques d'exploitation" (Ed. Dunod), European Cyberweek 2019, Literary Award, Category: Engineering Science.
- S. Boisseau, *Smart Materials and Structures* 2019 Outstanding Reviewer Award.

Experts

1 International Expert, 2 Research Directors, 20 Senior Experts, 17 Experts, 8 of them holding an HDR.

Scientific committees

- Editors and Guest Editors of: IEEE transactions on cognitive communications and networking, ELSEVIER Comptes Rendus de l’Académie des Sciences (CRAS) Physique, Special Issue on Geolocation and Navigation, Hindawi wireless communications and mobile computing.
- Elected members and experts for: SCS and SAFE clusters, ECSO, H2020-SU-ICT-2019
- Reading and Technical Program Committees of: ICT, IEEE GLOBECOM, EuCNC 2019, IEEE VTC, IPIN, IEE ICC, IEEE PIMRC, WPNC,EuCAP, WPMC, IEEE 5G World Forum, WCNC, IEEE INFOCOM workshop, CIAP, DSD, CS2, IRT NanoElec, AMUSEC, C&sar, Casper, FIPS, RISC-V, CHES, JCEN.

Conferences and Workshops organizations

- GDR ISIS « Sub-THz Communications »
- WPNC 2019 (Special Session Chair)
- European School of Antennas (ESoA) « Antennas and Rectennas for IoT Applications »

International Collaborations

National Inter-university Consortium for Telecommunication CNIT (Italy), University La Sapienza (Rome, Italy), University of Padova (Italy), University of Bologna (Italy), Chalmers University of Technology (Sweden), IT Portugal, SuperLab (Stanford, USA), University of Ottawa (Canada), ETRI (South Korea), Tokyo Teck University (Japan), University of Florida (USA).

01
AI
AI

01 HIGH PERFORMANCE SENSORS & SYSTEMS AND SENSOR DATA FUSION

- ^{4}He Magnetometers
- MEMS sensors
- Wearables
- Shape capture
- Signal processing
- Deep learning
- Affective Computing
- Artificial Intelligence (AI)

Surface Capture for Structural Health Monitoring

RESEARCH TOPIC:
Shape capture, MEMS applications, Structural Health Monitoring, curves and surfaces

AUTHORS:
CARMONA Mikael (Morphosense), GRAU Loic (Morphosense), SAGUIN-SPRYNSKI Nathalie

Shape capture has been developed for 15 years, allowing to reconstruct any shape, defined as curves and surfaces, using MEMS sensors directly laid on shapes. Many demonstrators have been realised, like linear networks, squared-meshed networks, and a single MEMS rolling device. This technology has already been transfered into industry for curves like applications, and we have just deployed it in a surface like application with the start-up Morphosense for the lock gates monitoring.

SCIENTIFIC COLLABORATIONS: Université Grenoble Alpes, CNRS (Laboratoire Jean Kuntzmann), INRIA

Context and Challenges

A MEMS sensor network combined with specific mathematical algorithms can allow the shape reconstruction in real time and for years. In the Structural Health Monitoring context, shape capture can have several issues like being a tracker of structural variation in time or a detection alarm signaling unusual changes to the structure, or a system for measuring geometrical parameters for comparison with simulations or numerical models.This solution has been adapted for several applications, mainly for curve like shapes (for instance flexible pipes with TechnipFMC and civil engineering structures monitoring with the start-up Morphosense). This year, this technology has been deployed for surface like applications, via a project joining CEA, CNR and Morphosense, with the monitoring of a lock gate. The Company CNR has to report on the state of health of all its structures along the Rhône, and lock gates are some of them. These structures are close to their end of life, and risk failures. Nowadays, traffic is stopped one week a year, in order to realise a detailed inspection. However, it is time and money consuming. Then CNR asked us to adapt and test our solution for this specific purpose of lock gate monitoring, thinking it could be an interesting alternative. Thus we had the opportunity to monitor the door of a lock gate during some months (see Fig. 1).

Figure 1 : Lock Gate near Avignon, and Morphosense Sensor

Main Results

The start-up Morphosense has developed a measurement node, robust to harsh environments, and a hardware and software solution to provide real time measures. As the maximum deflection is a fondamental indicator of the static behavior of the structure, we thus defined the best sensors location to follow the surface shape, and then compute the global deflection. Morphosense has installed 17 sensors, in 3 vertical lines. We adapted our algorithms to reconstruct a surface via these sensors location and measures : combining sensors not regularly placed, adding boundery constraints, and determining the solution by energy minimisation. We also compared the deflection given by all the sensors, and the deflection given the central line. (see Fig. 2)

In first place, we have seen that deflection was correlated with environmental phenomena: temperature, top and bottom level of water, global rotations, in particular. Thus we have developed a methodology to compute a relative deflection, uncorrelated with these phenomena.

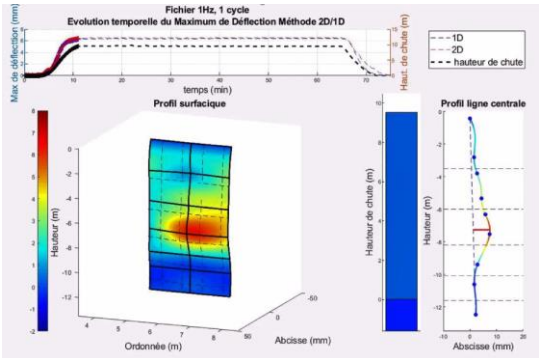


Figure 2 : Surface deformation (left), central line deformation (right), water height (middle), deflection maximum with time (top)

Perspectives

The instrumentation linked to dedicated algorithms allowed to understand some global structure behaviour, and connecting the data with numerical models allow to anticipate failures.

In other contexts, we proved the interest of surface monitoring via MEMS and can apply on solid structures (SHM) or surfaces with smooth materials (as in healthcare, sport, and consumer devices).

RELATED PUBLICATIONS:

[1] Carmona, Grau, Saguin-Sprynski, Solution innovante pour la surveillance de porte d'écluses, Smart Rivers 2019 Conference, Lyon, France.

Deep learning applied to Transportion mode recognition from GPS signals

RESEARCH TOPIC:
Machine Learning, Deep Learning, Sensors, Context Capture, Transportation Mode Recognition, Road Surface Monitoring

AUTHORS:
Andrea VASSILEV

The diffusion of an increasing number of portable devices (smartphones, connected watches, ...), embedding a multitude of sensors (accelerometer, magnetometer, gyrometer, GPS, ...) leads to a new interest for context capture applications, such as the automatic recognition of the mode of transportation used by a person. This problem has already been the subject of many researches based on 'traditional' classification approaches, i.e. hand-crafted features. Following the recent development of deep learning, we developed a deep network on the Geolife public database, a GPS collection of mobile trajectories.

SCIENTIFIC COLLABORATIONS: Institut Carnot IFPEN Transports Energie and Laboratoire d'Informatique en Image et Systèmes d'information (LIRIS)

Context and Challenges

Unlike traditional approaches, deep learning is an approach, in which the raw data is directly input to the model and the relevant features are in principle learned by the model. Deep Convolutional Neural Networks (CNN) are one example that has recently achieved impressive results in image recognition. The aim of this work is to assess the contribution of deep learning to the Geolife public database [1].

Main Results

After cleaning the base (removal of points with identical time stamp or with non-physical speed or acceleration, removal of trips that are too short), various preprocessing were applied: calculation of point features, such as speed, acceleration, jerk, orientation; resampling at constant frequency (0.5 Hz), normalization and segmentation of the trips into segments of constant size.

The performance evaluation is carried out by partitioning the base into three subsets: training, validation and test. As these subsets must be independent, we first perform the partition on the trips, then the segmentation.

Each training is carried out three times, each time modifying the different random seeds (controlling the partition and the initialization of the weights). The performance criterion used is the F1 score averaged over the six modes and calculated on the test subset. The results are presented in the form of an average ± standard deviation, calculated on the three trainings.

The performances of a classical approach using features inspired by [2] and a one hidden layer perceptron with 256 neurons leads to a performance of F1 = 75.4 ± 0.5%. For the deep learning approach [3], the architecture selected is a CNN presented in Fig.1 and the best result obtained, F1 = 78.6 ± 1.0%, is 3.2% higher than the traditional approach. Table 1 presents the confusion matrix for one of the three trainings.

We note that three modes are well estimated ('walking', 'train' and 'bike with an F1> 79%) and that the main confusion concerns the classes 'car' and 'bus', as when we applied traditional approach.

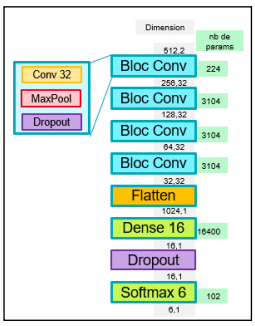


Figure 1: Deep Network Architecture

		Confusion Matrix						
		bike	bus	car	subway	train	walk	f1-score
Truth	bike	482	39	13	18	0	65	0.79
	bus	48	675	172	43	4	54	0.74
	car	51	104	463	28	37	43	0.66
	subway	10	16	10	167	3	27	0.67
	train	1	2	9	8	351	5	0.91
	walk	5	0	0	1	0	1540	0.94
		Prediction						

Table 1: Classification results

Perspectives

Concerning the Geolife database, the perspectives are to test more complex architectures than a simple CNN, for example a RESNET as well as to take into account the numerous non-labeled data of the database.

Regarding the same classification problem, it is also planned to work on another public database, SHL [4], which includes signals from other sensors such as accelerometer, gyrometer and magnetometer.

Other classification issues related to human mobility will be assessed in the near future, such as automatic estimation of the road roughness and detection of potholes.

RELATED PUBLICATIONS:

[1] Zheng, Yu, « Geolife GPS trajectory dataset – User Guide », version 1.3, août 2012.

[2] Y. Zheng et al., « Understanding Transportation Modes Based on GPS Data for Web Applications », ACM Trans Web, vol. 4, no 1, p. 1:1–1:36, janv. 2010.

[3] Vassilev, A., 2019. Reconnaissance des modes de transport par apprentissage profond à partir de signaux GPS. Presented at the GRETSI, Lille.

[4] Gjoreski, H. et al., 2018. The University of Sussex-Huawei Locomotion and Transportation Dataset for Multimodal Analytics With Mobile Devices. IEEE Access 6, 42592–42604. https://doi.org/10.1109/ACCESS.2018.2858933

Anomaly detection in rolling stock using multi-resolution analysis of micro-deformations

RESEARCH TOPIC:
Anomaly detection, wavelet transform, railway

AUTHORS:
Sylvain LEIRENS, Jérôme BOUTET

Instrumented railway sleepers with fiber Bragg grating allow to record time-domain signals of micro-deformation during train crossing. A multi-resolution analysis of micro-deformation measurements is carried out to detect rolling stock anomalies, such as axle overload and flat wheel, and provides robust axle peak detection.

Context and Challenges

Railway sleepers support the rails in railroad tracks and transfer loads to the track ballast. The charge distribution and train speed are the main sources of railway ageing. Actually, train speed has a strong impact on the mechanical behavior of track-bed materials.

Measurements from accelerometers and gauges are commonly used to study mechanical properties of the track bed. The Smart Sleeper® is a concrete sleeper instrumented with fiber Bragg gratings allowing to measure micro-deformations during train crossing. Fiber Bragg gratings offer an interesting alternative to strain or pressure gauges based sensors.

Anomaly detection of rolling stock focuses on identifying anomalies in measurement signals during train crossing on railway tracks. The main issue was to achieve the detection of the most serious rolling stock anomalies in axle peak signals using micro-deformation measurements: type 1 (axle overload) and type 2 (flat wheel), as illustrated below (figure 1).

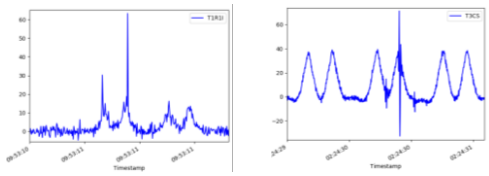


Figure 1: Type 1 (left) and type 2 (right) anomalies

Main Results

We developed a new method based on discrete-time wavelet transform able to estimate the type of anomaly, location and severity (magnitude). A wavelet based analysis fits well to this problem as the occurrence of a rolling stock anomaly results in an intense and very short transient phenomenon. By choosing the appropriate decomposition level, the signal of normal axle peaks can be separated from measurement noise and rolling stock anomaly.

The signal S decomposes at level J as the sum of an approximation A_J and residuals (sum of details): $S = A_J + \sum_{j \leq J} D_j$.

The details D_j at level j are given by $D_j = \sum_{k \in \mathbb{Z}} cD(j,k)\psi_{j,k}$, where cD are the detail coefficients and $\psi_{j,k}$ is the wavelet at level j and shifted of k samples.

Figure 2 shows detection results using the Symlet 5 wavelet and a decomposition level equal to 3. Symlet family offers good properties and a certain similarity with the transients associated to the anomalies we want to detect.

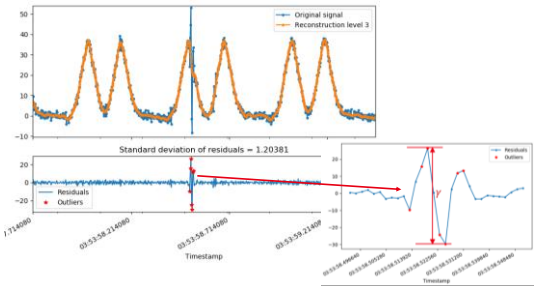


Figure 2: Detection of a type 2 anomaly in micro-deformation measurements

The reconstructed approximation signal A_J provides a signal clean of measurement noise and detected anomalies. A more robust and accurate axle peak detection allows for automatic identification of rolling stock based on micro-deformation measurements. Actually, locomotive and wagons have known physical characteristics, such as wagon dimensions and bogie location, and distances between axles can be evaluated. With at least two Smart Sleepers® separated by a known distance, the train speed can be easily estimated using the time shift between train crossings.

Perspectives

Future work will focus on machine learning techniques with signal classification using wavelet-based features. Additionally, rolling stock recognition makes possible to distinguish passenger from freight transport, as well as locomotives from wagons in order to improve anomaly detection.

RELATED PUBLICATIONS:

[1] S. Leirens, J. Boutet, "Détection d'anomalie de matériel roulant par décomposition en ondelettes de signaux de micro-déformations", XXVIIeme Colloque GRETSI, 2019.

Methodological issues in the creation of a diagnosis tool for dysgraphia

RESEARCH TOPIC:
Machine learning, dysgraphia

AUTHORS:
Louis DESCHAMPS, Clement GAFFET, Saifeddine ALOUI, Jerome BOUTET, Vincent BRAULT, Etienne LABYT

Asselborn et al. have created a diagnosis tool for dysgraphia, based on dynamic data acquired with common graphic tablets. The results they obtained seem very satisfactory. According to the authors, their work “can be deployed directly as a diagnostics tool”. We think that this conclusion should be qualified, as we have detected some methodological issues that we perceive to be important. In this comment, we outline three main arguments and several concerns that motivate our opinion.

SCIENTIFIC COLLABORATIONS: Univ. Grenoble Alpes, CNRS, Grenoble INP+, LJK, 38000 Grenoble, France

Context and Challenges

Dysgraphia is a trouble of handwriting, affecting around 8% of the scholar children. Since 2 years, CEA LETI is working in collaboration with the Laboratoire de Psychologie et Neuroscognition (CNRS, LPNC) and the Laboratoire Jean Kuntzman (CNRS, Grenoble INP) for developing a tool based on machine learning approaches to help in dysgraphia diagnosis. In 2018, Asselborn et al have reported in their paper [1] a first diagnosis tool for dysgraphia, based on dynamic data acquired with common graphic tablets. The results they obtained seem very satisfactory and authors claimed that their work ”can be deployed directly as a diagnostics tool”. However, this work suffered from methodological issues that we aimed at outlining and discussing in our paper [2].

Main Results

A first methofological issue concerned the use of two different graphic tablets for the data acquisition of typically developement children and dysphaphic children respectively. Assselborn study didn't report any calibration method applied to ensure the independence of the results with respect to the acquisition tablet. This should lead to a bias in their model which should discriminate the graphic tablet effect rather than dysgraphia.

A second methodological concern was the definition of their typically development children group (TD). Indeed, according to the literature, we could indeed expect to find at least 5% of dysgraphic children in this dataset [3]. Noteworthy, in their article, the authors wrote themselves that "None of the BHK tests from the TD dataset were rated for dysgraphia, which means that some of these children might be dysgraphic, as well.” The rating of our set of BHK tests that we recently acquired in children in primary schools confirmed the presence of 8.3% of dysgraphic children in this cohort (only considering children from 2nd to 5th grade), according to the BHK criteria. However, when training and testing their Random Forest models, the authors considered all children in the TD dataset as non-dysgraphic, neglecting the ratio of dysgraphic children in their typically development children group. As a consequence, the false negative ratio of less than 1% reported in Asselborn's study has to be carefully considered when taking into account the dysgraphic children inside the TD dataset. Moreover the excellent true positive ratio of 96% claimed by the authors can also be questioned as almost none of the dysgraphic children from the TD dataset were detected by their algorithm.

Third, in their data processing approach, the authors did not take into consideration the evolution of the features with the age of the subject. Handwriting evolves as the child grows, and some features do not apply the same for young children and their older counterparts. In our study, we have developed an approach to take into account the age effect on handwriting parameters (see figure below). Consequently, their dysgraphia diagnosis algorithm should not be robust against children age as the time evolution of handwriting parameters is not taken into consideration.

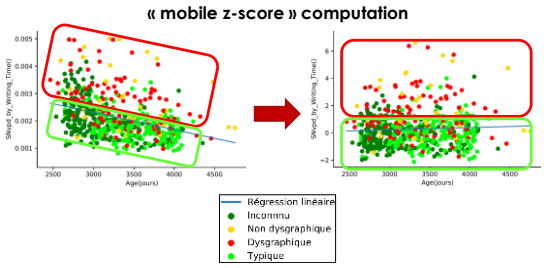


Fig. 1: Methodological approach for age effect correction of handwriting parameter

Perspectives

Asselborn et al's.approach is an interesting novel way of pre-diagnosing dysgraphia, but the tool they created should be tested at a larger scale and some biases should be dealt with before it can be deployed as a diagnosis tool.

CEA LETI is working with his partners on developing a tool based on Support Vector Machine algorithm for helping in dysgraphia diagnosis. A special care is taken for designing a robust algorithm taking into account a unprecedented large database, considering the age related changes in handwriting. We do not aim at achieving impressive performances in terms of machine learning but rather we aim at providing a reliable detection of dysgraphic children. A manuscript Is in preparation about these results.

RELATED PUBLICATIONS:

[1] Asselborn, T. T Gargot, Ł Kidziński, W Johal, D Cohen et al. Automated human-level diagnosis of dysgraphia using a consumer tablet. npj Digital Medicine 1 (2018). URL http://www.nature.com/articles/ s41746-018-0049-x

[2] Deschamps, L., Gaffet, C., Aloui, S. *et al.* Methodological issues in the creation of a diagnosis tool for dysgraphia. *npj Digit. Med.* **2,** 36 (2019). https://doi.org/10.1038/s41746-019-0114-0

[3] Charles, M., Soppelsa, R. & Albaret, J. *BHK: ´echelle d´´evaluation rapide de l´´ecriture* (les Ed. du Centre de psychologie appliqu´ee, 2004). URL https://books.google.fr/books?id=

Physiological response to acute stress against confounding factors

RESEARCH TOPIC:
Machine learning, stress monitoring, physiological signals

AUTHORS:
Gaël VILA, Christelle GODIN, Sylvie CHARBONNIER+, Oumayma SAKRI, Etienne LABYT, Aurélie CAMPAGNE+

Physiological sensors appear a promising tool to monitor psychological stress in the daily life. Yet, despite the increasing know-how developed in affective computing, physiology-driven stress detection algorithms still yield unsatisfactory results on the field. This study intends to highlight physiological patterns that are both stress-sensitive and stress-specific, at the multi-subject scale, in several contexts.

SCIENTIFIC COLLABORATIONS: Univ. Grenoble Alpes, CNRS, Grenoble INP+, 38000 Grenoble, France

Context and Challenges

'Stress' is an umbrella term to define some psychological, physiological and behavioural response to environmental factors one perceives as a potential threat. While its early manifestations (acute stress) represent a natural defence mechanism, their recurrence over an extended period ends up inducing a pathological condition (chronic stress). For the general public, an objective and timely stress evaluation would represent a true asset for self-knowledge and ability to cope with the challenges of everyday life. For highly exposed populations like the caregiving staff or firefighters, an acute stress detector could stand for a preventive tool from burnout or depressive disorders. Such a purpose may be achieved through the various unobtrusive, non-invasive wearable sensors that have gained the high-tech market in the last few years, which provide diverse physiological parameters of the user. However, there is still no standard model to detect high levels of psychological stress from its peripheral manifestations. In real-life settings, major confounding factors are to be found in mental and physical activity. While the latter can be automatically classified or discarded on the grounds of accelerometer data, this is not the case for mental activity. Peripheral physiological manifestations of stress-related autonomic adjustments have provided perspectives for the design of physiology driven stress detection models. However, there is still a need to identify a reliable physiological pattern that would be simultaneously responsive to diverse stressful situations, and independent from the context in which stress is being encountered. In that regard, this study addresses the search for both sensitive and specific physiological features, by discriminating stress-induced peripheral responses from background- and activity-related autonomic activations. It aims to present a white-box research method to highlight valid physiological responses, at the between-subject level.

Main Results

The non-specificity of physiological responses suggests to carefully consider their different sources of variation through experimental conditions. For that, we defined a notional framework which aims to express the stress sensitivity for any physiological feature. We consider that each measured variation is an indirect manifestation of the phenomena under scrutiny (e.g. emotional load or confounding factors). For that reason, we define a set of estimators for stress related or confounder-related variations and identify potential noises in this estimation. A feature selection procedure is then proposed, to exemplify our approach for determining the most stress-sensitive physiological features.

Most standard physiological features used in stress detection failed to distinguish between our most stressful experimental conditions, and the simple recruitment of cognitive and physiological skills necessary to perform similar activities in a low demanding environment. Hence, our results strongly support the need for introducing control conditions in any experimental research willing to recognize stress in real life. Context may trigger physiological responses equivalent to those of a stressful encounter, even in the absence of sustained physical activity. Nonetheless, heart activity provides the most suitable features (hrMean, hrStd and hrRmssd) for distinguishing between acute stress and a simple non stressful activity. The Pressure effects of these three features roughly follow the same variations as Stress Scores through the different conditions of the experimental protocol. A custom respiratory feature, which reflects respiration signal periodicity, was also brought forward since it showed consistent variations between the Control and Stressful subtasks at the multi-subject level.

Perspectives

Still, further research is needed to evidence more, whether unexplored or forgotten, physiological features as context-independent stress manifestations. The white-box research method proposed in this study might provide another milestone towards such ambition.

RELATED PUBLICATIONS:

[1] Gaël Vila, Christelle Godin, Sylvie Charbonnier, Oumayma Sakri, Etienne Labyt and Aurélie Campagne. Physiological response to acute stress against confounding factors:a white-box research method Biomedical Physics & Engineering Express, Volume 5, Number 5.

[2] Vila G, Godin C, Charbonnier S, Labyt E and Sakri O 2018 Pressure-Specific feature selection for acute stress detection from physiological recordings IEEE Int. Conf. on Systems, Man, and Cybernetics (SMC), 2018 (Miyazaki, Japan) (https://doi.org/10.1109/SMC.2018.00402)

Intensity calibration of a MCT-APD sensor for a Flash LiDAR System

RESEARCH TOPIC:
Flash LiDAR, intensity calibration, Time of Flight measurement

AUTHORS:
Victor PARAHYBA, Régis PERRIER

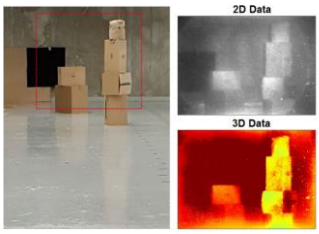
Flash LiDARs will be key components for future space missions including rover operations and the descent and landing of spacecraft. This kind of system records full 3D-images along with 2D intensity images with a single laser pulse, thus eliminating the need for a scanning device. There are well-established techniques concerning radiometric calibration (2D information). However, the illumination of the target is usually considered uniform, which is not the case for increasingly larger focal plane arrays (FPA). We propose an intensity calibration scheme for CEA-LETIs LiDAR prototype in order to compensate the nonuniform illumination of the target and present the first enhanced results based on data acquired under laboratory conditions.

SCIENTIFIC COLLABORATIONS: CEA LETI DOPT, ESA ESTEC, GIPSA lab

Context and Challenges

A flash LiDAR is like a 3D camera that enables the perception of depth. It comprises an infrared imaging sensor, a LASER to illuminate the observed scene, some optics to resolve the incoming light to the imager and an electronic acquisition board. As a single LASER pulse lights up the scene, each individual pixel of the imager evaluate the travel time of photons since their emission. Thus, knowing the speed of light, each pixel records a **depth measurement** of elements in the scene. In addition, as each pixel integrates light, flash LiDARs are able to produce **infrared intensity** images along with the depth ones. This extra intensity information could be used to improve the 3D measurement as explained in [1].

Flash LiDAR camera

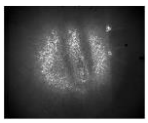


Depth (3d) and intensity (2d) images acquisition

As the LASER field of view needs to cover the entire target scene, its spatial non-uniformity becomes a nuisance to the measurements. This can be seen on the borders of the acquisition images above. The goal of our calibration procedure is to provide a **Normalization Factor image** that, when applied to the 2D intensity data, would mitigate the effect of the nonuniform illumination.

Main Results

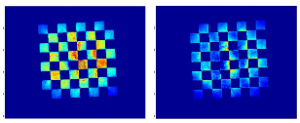
In the literature, output of most LASERs are modeled as Gaussian beams, which is too simplistic to account for all possible sources of imperfections in the pulse generation. Our calibration procedure uses a large checkerboard panel as depicted below.



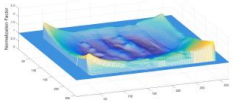
Non uniformity of LASER beam

Calibration target

The target is placed in several positions, to cover as much of the field-of-view area as possible and to mitigate local incongruities. The reflectivity difference between the white and black squares of the checkerboard improves the overall accuracy, the estimation being spit between two masks:

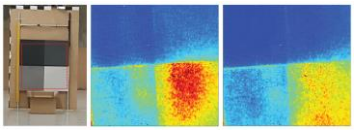


Masks for black/white squares



Estimated normalisation image

We used four targets with known reflectivity of 5%, 10%, 18% and 50% at the laser wavelength to evaluate the overall performance of the proposed calibration method:



left: targets; middle: raw intensity image of targets; right: calibrated image

The overall change on the uniformity is perceivable; the table below of pixels standard deviation per target confirms this:

Target Reflectivity	5%	10%	18%	50%
Before Calibration	0.5	0.7	1.4	2.4
After Calibration	0.3	0.6	1.0	1.5

Perspectives

The prospects for future work include the evaluation of the method robustness with experiments closer to space conditions using ESA ESTEC facilities.

RELATED PUBLICATIONS:

[1] V. ES Parahyba, E. de Borniol, R. Perrier, Y.-R. Nowicki-Bringuier, A. Ciapponi, J. Chanussot, Time-of-flight calibration of an MCT-APD sensor for a flash imaging LiDAR system - International Conference on Space Optics—ICSO 2018

Novel ultrasonic mems based on Carbon nano-membrane for frequency agility and high density arrays

RESEARCH TOPIC:
MEMS, micro-C-MUTS, carbon, membranes, mechanical properties, resonances, large bandwidth acoustic transducers

AUTHORS:
Anne GHIS, Lucie LE VAN-JODIN, Matthieu MATRINGE, François FRASSATI, François BLARD

Ultrathin Carbon is an innovative material providing new opportunities namely as moving part of MEMS. 10nm thick carbon membrane have been implemented in dense arrays of ultrasonic transducers. The mechanical specificities of thinness relieve the operation of the constraint of resonance frequency. Pioneer devices have been realized and tested : both emission and detection of ultrasonic waves have been demonstrated and worked properly at any frequency ranging between 20kHz and 1Mhz. More, the high density of arrays combined with matrix facilities open to unprecedented acoustic wave engineering facilities. Now feasibility has been demonstrated, device designs and processes can be optimized. Ultrathin carbon membrane transducers bring out new and fundamental benefits for ultrasound imaging in biology, robotics and HMI.

Context and Challenges

Ultrasound techniques are widely used as a probing tool in various fields, from medical imaging to robotics. The resolution and the depth of field of the resulting information particularly depend on the ultrasonic frequency and the size of the transducers. Most MUT (Micromachined Ultrasonic Transducers) devices are only operable around a unique frequency, set by geometrical design.

The advent of versatile frequency operability of ultrasonic transducer arrays will allow images to be collected at multiple frequencies using a single stationary device. This singular operation can be effectively implemented in MEMS if ultra-thin vibrating membranes are used. Amorphous carbon offers all the appropriate mechanical properties, toughness and flexibility, even in layers 10 nm thick, combined with the chemical inertness of diamond type carbons. This new concept was the subject of a feasibility study: dense networks of 2,500,000 micro-transducers of 10µm in diameter, equipped with carbon membranes of 10nm thick, were produced and used to experimentally explore the ultrasonic transduction features for both transmission and detection.

Main Results

The base part of the device is processed using standard microfabrication techniques. Bottom electrodes are a set of 10 parallel lines, 750µm wide and 800µm pitch. Each of the lines addresses 25000 elementary transducers. The scheme of the unitary transducer is presented in Fig. 1.

Amorphous carbon layer is grown in the LETI facilities onto a secondary substrate, and then reported over the base part, in a single stamping transfer for whole array of micro-transducers.

First, ultrasound emission is recorded using a microphone operating in the range 6Hz-140kHz. In this frequency range, ultrasound emission level increases linearly with frequency and with the square of the excitation voltage. The measure of the emitted pressure at 140kHz is 90dB SPL at a distance of 5cm.

Second, the frequency exploration experiment is conducted using two devices facing each other, one used as an emitter and the other used a detector. This set up allows for recording the combined transfer function depending on ultrasound frequency. The observed operating frequencies appears to range from 20 kHz to 1 MHz as a first try.

This confirms the non-resonant mechanical behavior of the ultrathin vibrating membranes and the feasibility of ultrasonic transducers operable over a large frequency range.

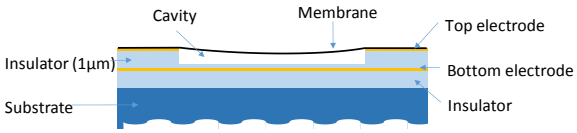


Fig. 1 scheme of the unitary capacitive transducer

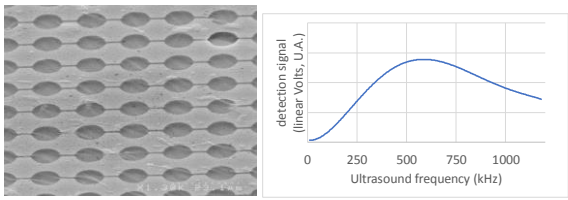


Fig. 2 Left : SEM image of the transducer array. Right : Emission+ detection function transfer between two devices. The decrease at high frequencies is due to low pass filtration in driving electrodes.

Perspectives

These results establish the proof of the original concept of pressure transduction at wide frequency range through the use of ultra-thin vibrating membranes. They were obtained using pioneering devices. Optimization of device design and manufacturing processes must be carried out before actual quantification of transduction performance. The large frequency range allows to operate very short acoustic pulses and exploit the selective properties of acoustic modulation laws.

Applicative field not only covers ultrasonic and medical imaging, but also telemetry, acoustic communications, and short range non-contact HMI.

RELATED PUBLICATIONS:

[1] A. Ghis, M. Matringe, O. Ndjoye-Kogou, F. Blard, F. Frassati, et L. Le Van-Jodin, « High Density Arrays of Carbon Nanomembrane Ultrasonic MEMS », in 2019 IEEE International Ultrasonics Symposium (IUS), 2019, p. 2148–2152

[2] A. Ghis, L. Le Van-Jodin, F. Frassati, M. Matringe, O. Ndjoye-Kogou, F. Blard, "Ultrathin and flexible carbon membranes for high density ultrasound MEMS arrays", Workshop MUT2019 - Grenoble , France, Tuesday June 11th, 2019

Wire-based piezoelectric sensors: sensitive surfaces

RESEARCH TOPIC:

Sensitive surfaces, mechanical sensor, strain mapping, flexible sensor, ZnO wire, GaN wire, piezoelectricity, piezotronics, finite element modelling

AUTHORS:

Elise SAOUTIEFF, Emmanuelle PAULIAC-VAUJOUR, Joël.EYMERY (CEA-IRIG)

CEA-Leti activities in novel and complex integrated sensor solutions for instrumented surfaces started over 10 years ago. We develop sensitive surfaces functionalized with self-powered sensor arrays, for the mechanical mapping of strain or 3D shape reconstruction with possible applications in sectors such as automotive, predictive maintenance, wearables, health, sports and wellness, etc. Our research focused on the development of piezoelectric devices that are thin, sensitive, mechanically robust and resilient, and in some cases flexible, conformable or even stretchable. We investigated several technological solutions based on either ZnO or GaN piezoelectric nanowires, depending on integration constraints (CMOS compatibility, large area, flexibility, etc.)

SCIENTIFIC COLLABORATIONS: CEA-LITEN, CEA-IRIG, G-INP IMEP-LaHC

Context and Challenges

The development of robust, highly sensitive and highly resolved force sensors in wearable or implantable systems and in electronic micro-devices has been of growing interest for many years. Such enabling technologies may affect all sectors of society: from people's safety and wellness to environment, structural health of large infrastructures monitoring and to industrial manufacture.

The challenge is to developed smart, autonomous and self-communicating sensors to equip all types of surfaces, with widening system capabilities in terms of sensing (high performances, surface distribution, etc.). These developments must be scalable and robust in front of harsh usage conditions.

We investigate new architectures of flexible systems based on the flexible piezoelectric materials with evolutionary multi-scale, multi-modality, energy efficient system configurations, which feature and combine some of the latest technologies in terms of sensing, energy harvesting, communication, etc. Based on multiphysics models, dedicated electronic interfaces and proprietary reconstruction algorithms, we aim to establish design rules for future fully-integrated wearable systems, whichh we call 'sensitive surfaces'.

Main Results

We present two demonstrators of 'sensitive surfaces' that were developed in our laboratories. The first one uses a matrix of individually contacted ZnO nanowires, integrated on a CMOS-processed Si chip (fig. 1). Each nanowire is a pixel of the matrix where a local deformation is measured when a mechanical deformation is induced, for example, by a gas flow (fig. 1b). 3D mapping of the overall deformation is deduced from integration over the different pixels of the matrix. The second one integrates a continuous composite film of piezoelectric GaN wires into a capacitive flexible device (fig. 2) which demonstrates very high sensitivity and robustness through series of compression / release cycles. Multiphysics and electrical models were developed for each configuration for current and future design optimizations.

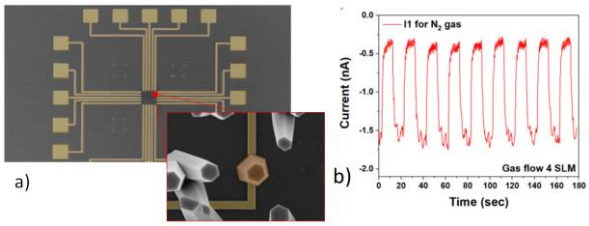


Fig. 1 a) top view SEM of the device (5 x 5 matrix of single-vertical ZnO nanowires with 2 contacts, see insert); b) electrical response of a single ZnO NW as a function of gas flow rate.

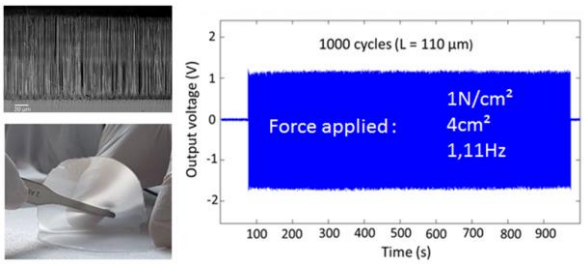


Fig. 2 (left) SEM image of GaN wires and flexible film with as grown vertical wires, which will be the active layer in the device; (right) generated piezo-potential under compression-release cycles applied to the device.

Perspectives

Electronic interfaces and reading circuits for such "sensitive surfaces" are still at a rather low maturity level, however 3D reconstruction algorithms have already been developed and tested in our laboratory. The sensitivity and stable, intrinsic piezoelectric response of these systems make them a promising solution for ultra-low-power and fully flexible systems for force and deformation mapping in a variety of applications. For this purpose, all preliminary developments were carried out so as to ensure future compatibility with additive fabrication technics and printed electronics, and hence to favour scalability, which remains a key characteristics of CEA-Leti's technological developments.

RELATED PUBLICATIONS:

[1] Parmar M., Leon Perez E., Ardila G., Saoutieff E., Pauliac-Vaujour E., Mouis M., A demonstration of the mechanical sensing capability of individually contacted vertical piezoelectric nanowires arranged in matrices, Nano Energy 56 (2019) 859–867

[2] A. El Kacimi, E. Pauliac-Vaujour, J. Eymery, "Flexible capacitive piezoelectric sensor with vertically aligned ultralong GaN wires", *ACS Applied Materials & Interfaces* **10** *(5)*, pp 4794-4800 (2018).

Multifunctional wearable platforms for health and environmental monitoring: the Convergence project

RESEARCH TOPIC:
Activity, Bio & Environmental sensors, Energy Harvesting, integration, flexible, Flexible electronics, Internet of Things, Low power, Wearable

AUTHORS:
Elise SAOUTIEFF, Laurent JOUANET, Adrien FAUCON, Audrey VIDAL, Sébastien BOISSEAU, Jean-Charles SOURIAU, Thomas ERNST, Alexandre PEREIRA (LITEN)

The CONVERGENCE FLAG-ERA H2020 project focuses on the development of energy-efficient sensor networks exploiting the convergence of multi-parameter sensors, serving data fusion for preventive life-style and healthcare. In this perspective, we aimed at creating a wireless and multifunctional wearable system, able to monitor not only the individual physical condition (physical activity, core body temperature, electrolytes and biomarkers) but also the chemical composition of the ambient air (NOx, COx, particles). CEA research has been focused on the development of flexible wearable platforms embedding health and environment sensors.

SCIENTIFIC COLLABORATIONS: EPFL, ETHZ, ENEA, UCL, HCC, TTU, G-INP, STM, IUNET, UCBM, UNICA, TAGLIAFERRI, EDI, IMT, UTBV, METU

Context and Challenges

The development of wearable platforms embedding bio and environment sensors is of high importance to enable personalized advice and assistance for health and interactions with the environment.

The work carried out over the Convergence project, was aimed at developing and demonstrating energy-efficient sensor networks for future wearables exploiting the convergence of multi-parameter such as bio, activity and environmental sensors on an autonomous system technology platform, serving data fusion for preventive life-style and healthcare.

Main Results

CEA-LETI has developed low power, wireless demonstration platform for wearable IoT flexible systems compatible with various kinds of sensors developed by consortium partners.

The wearable platform (fig.1) is a modular multi-sensors platform with : (i) data acquisition and visualization in real-time with specific App developed by CEA, (ii) Bluetooth Low Energy 2.4 GHz communication, (iii) antenna circuit designed by G-INP and (iv) low-power system

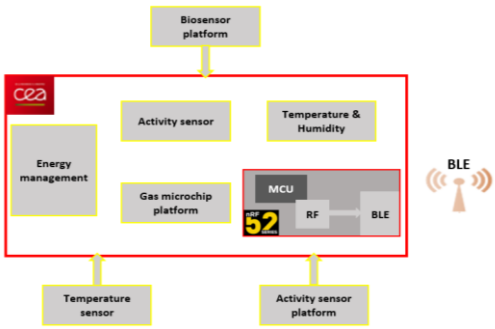


Fig. 1 Schematic of the sensor platform

The generic system platform (fig.2) is compatible with different types of sensors: Gas (NO_2, NH_3, CO), pH, Temperature, Humidity and Activity sensors.

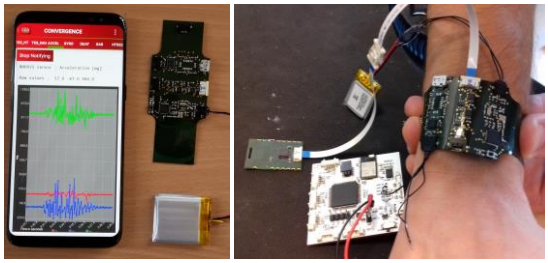


Fig. 2 (left) Flexible sensor platform tested with embedded sensors – (right) Flexible sensor platform tested with partners sensors

Advanced assembly techniques for highly flexible sensor nodes have also been demonstrated (fig.3). A new process which offers flip-chip silicon dies interconnected within a flexible film and collective thinning was developed. First tests were performed under 85°C and 85% relative humidity. No failure occurred after 500 hours in climatic chamber.

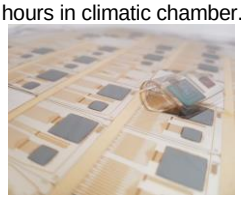


Fig. 3 Collectively thinned flip chip silicon

Perspectives

The next steps will be focused on the integration of the flexible platform on a wrist devices. Over the longer term, such devices will offer unique solutions for new generations of non-invasive quasi-continuous healthcare applications.

RELATED PUBLICATIONS:

[1] T. Polichetti, M.L. Miglietta, B. Alfano, E. Massera, S. De Vito, G. Di Francia, A. Faucon , E. Saoutieff, S. Boisseau, T. Walewyns, N. Marchand, L. A. Francis, " A Networked Wearable Device for Chemical Multisensing", Lecture Notes in Electrical Engineering - Volume 539, Pages 17-24, 2019

[2] A. Ancans, J. Ormanis, R. Cacurs, M. Greitans, E. Saoutieff, A. Faucon, "Bluetooth Low Energy throughput in densely deployed radio environment", Elektronika IR Elektrotechnika, June 2019

[3] J-C. Souriau, A. Itawi, L. Castagné, "Wafer Level Integration of Thin Silicon Bare Dies Within Flexible Label," 2019 IEEE 69th Electronic Components and Technology Conference (ECTC)

Helium-4 optically pumped magnetometers for medical imaging

RESEARCH TOPIC:
Atomic physics, medical imaging, magnetometry, optically pumped magnetometers

AUTHORS:
William FOURCAULT, Tobias MILLET, Vincent JOSSELIN, François BEATO, Gwenaël LE GAL, Matthieu LE PRADO, Etienne LABYT, Agustin PALACIOS-LALOY

Optically pumped magnetometers constitute a valuable tool for imaging biological magnetic signals without cryogenic cooling. Unlike alkali-based magnetometers, which require heating to >100°C, metastable helium-4 based magnetometers work at any temperature, which allows a direct contact with the scalp, yielding larger signals and a better patient comfort. We describe here an improved magnetometer reaching a sensitivity better than 50 fT/Hz$^{1/2}$, near the photon noise limit, with a bandwidth of 2 kHz. These magnetometers can be operated in a closed-loop architecture reaching a dynamic range of several hundredths nT. A small array of four magnetometers operating in closed-loop has been tested with a successful correction of the cross-talks.

SCIENTIFIC COLLABORATIONS: IHU Liryc, INSL, CRNL, CHU Marseille, ULB, CHU Amiens, CHU Lille

Context and Challenges

Our team develops optically pumped magnetometers (OPM) based on metastable helium-4 atoms. This sensitive species works at any temperature, needing neither cooling nor heating, unlike SQUID or alkali OPM based on th SERF effect. This allows setting the sensors in contact with the surface of the body, as close as possible to signals to be observed in medical imaging. These last years we have made proof-of-concept recordings of both magneto-cardiography (MCG) [1] and magneto-encephalography (MEG) [2] with 4He magnetometers based on parametric resonance which, however, displayed large noises of >200 fT/Hz$^{1/2}$ with 300 Hz bandwidth.

Main Results

A full rework of the sensors has allowed us to obtain sensors with more compact footprints of 2 cm x 2 cm. In contrast with other OPM we pump the atoms with linearly polarized light, yielding atomic alignment. This configuration allows measuring the component of the field radial to the head using light that propagates radially [3], which allows closer packing and a simpler optical setup. Our sensors currently have 2 kHz bandwidth, tri-axial magnetic field measurement, a dynamic range of several hundredths of nanotesla and an intrinsic noise better than 50 fT/Hz$^{1/2}$. We have also demonstrated closed-loop operation of a small array of four sensors placed side-by-side. The cross-talks of the sensors were probed and are in close agreement with the theoretical predictions, which opens the way to an automatic correction.

Perspectives

Clinical trials of the first arrays of helium-4 OPMs are scheduled with several hospitals and research centers, and will demonstrate their practical advantages for neurology and cardiology. There are also ongoing efforts to improve the robustness and performance of the sensors. We are also exploring how the coupling of our OPMs with appropriate optical structures could allow reaching the Standard Quantum Limit (SQL) of intrinsic noise.

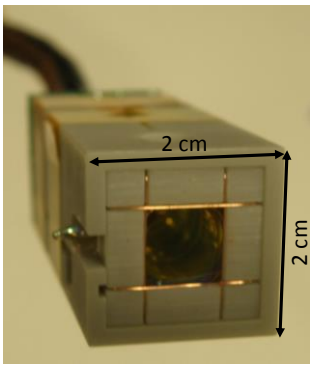


Fig. 1: Bottom of the helium-4 OPM, with its dimensions

Fig. 2: First array of four helium-4 OPM

RELATED PUBLICATIONS:

[1] S. Morales, M. C. Corsi, W. Fourcault, F. Bertrand, G. Cauffet, C. Gobbo, F. Alcouffe, F. Lenouvel, M. L. Prado, F. Berger, G. Vanzetto, and E. Labyt, Phys. Med. Biol. 62, 7267 (2017).

[2] E. Labyt, M. Corsi, W. Fourcault, A. Palacios Laloy, F. Bertrand, F. Lenouvel, G. Cauffet, M. L. Prado, F. Berger, and S. Morales, IEEE Transactions on Medical Imaging 38, 90 (2019).

[3] F. Beato, E. Belorizky, E. Labyt, M. Le Prado, and A. Palacios-Laloy, Phys. Rev. A 98, 053431 (2018).

All-optical isotropic scalar ^{4}He magnetometer

RESEARCH TOPIC:
Atomic physics, magnetometry, optically pumped magnetometers

AUTHORS:
Gaëtan LIEB, Thomas JAGER, Agustin PALACIOS-LALOY

We have proposed and tested a helium scalar magnetometer based on a triple resonance setup, showing no dead angles, and which can be implemented in an all-optical way. This triple-resonance scheme involves optical pumping with amplitude-modulated light, complemented by a modulated light-shift. Both light beams propagate parallel so that a single optical access to the atomic cell is needed. Experimental results are in good agreement with our theoretical model. The main error sources affecting the magnetometer accuracy have been studied.

SCIENTIFIC COLLABORATIONS: CIMAP, France (H. Gilles)

Context and Challenges

Accurate measurements of the local magnetic field are crucial for geomagnetic mapping, field measurements in space and Magnetic Anomaly Detection (MAD). Magnetic resonance phenomena provide unprecedented levels of accuracy for these measurements. Developed in the 1960s, optical pumping of diluted atomic gasses opened the way to a new generation of magnetic resonance magnetometers. This "double resonance magnetometers" are based on preparing the atomic states by optical pumping with appropriate light and on exciting the magnetic resonance with a radiofrequency field (RF). However, due to the symmetry breaking by the polarization of the pumping light, all optically pumped magnetometers show dead zones, where they are unable to measure the field because the resonance signal vanishes. The suppression of these dead zones is very desirable, especially for applications where the sensor is mobile, such as Earth navigation or space exploration. In parallel, aiming for simpler and lighter magnetometers, efforts are made for replacing the coil-generated RF field by a modulation of the pumping light.

Main Results

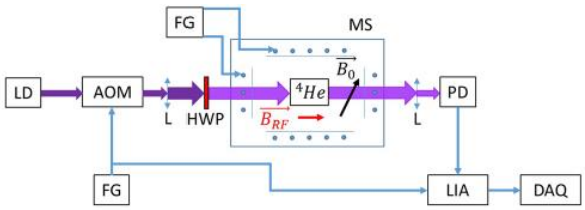
In the 1990s, the CEA-Leti pioneered an isotropic architecture based on locking the linear polarization of the pump light orthogonal to the measured magnetic field with a servo loop. Since November 2013, magnetometers based on this principle are successfully operated on board the satellites of the European Space Agency (ESA) Swarm mission.

We found that combining double resonance and pump modulation could lead to a new triple-resonance magnetometer whose architecture presents an isotropic operation point very similar to the former CEA-Leti architecture. This scheme can be implemented in an all-optical configuration combining a resonant amplitude modulated (AM) pump with an AM circularly polarized beam, which creates a light-shift RF field. Both beams propagate parallel which allows using a single optical access to the gas cell. We have experimentally tested this configuration and found good agreement with theoretical predictions.

Perspectives

Further work on a complete implementation of this configuration, including all the light modulations and the control loops, will allow to probe experimentally the frequency anisotropy and its accuracy and to compare it with other isotropic scalar magnetometry schemes.

The flexibility of addressing the measurement cell solely by optical means opens interesting possibilities of remotely addressing the sensor in Space magnetometry and oil exploration for instance.



RELATED PUBLICATIONS:
[1] G. Lieb, T. Jager, A. Palacios-Laloy, and H. Gilles, Review of Scientific Instruments 90, 075104 (2019).

Dual-axis Hanle magnetometer based on atomic alignment with a single optical access

RESEARCH TOPIC:
Atomic physics, magnetometry, optically pumped magnetometers

AUTHORS:
Gwenaël LE GAL, Gaëtan LIEB, François BEATO, Thomas JAGER, Agustin PALACIOS-LALOY

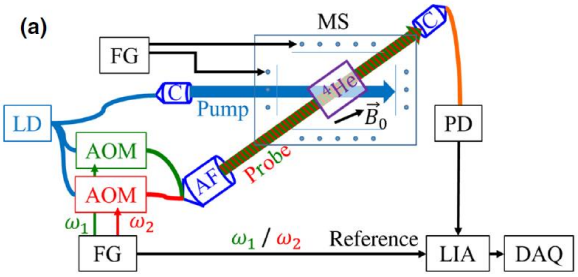
The usual Hanle-effect magnetometers allow the measurement of two components of a very-low magnetic field using three orthogonal light beams. We designed a scheme based on atomic alignment that requires only a single optical access for both a pump beam and a probe beam with a small angle between them. The results of experimental tests of this configuration are in close agreement with the theoretical predictions. We show that measurements of the third component should be possible by instrumentation of a partial depolarization of the pump beam.

SCIENTIFIC COLLABORATIONS: CIMAP, France (H. Gilles)

Context and Challenges
Measuring several components of the magnetic field is crucial for many applications such as studies of fundamental symmetries and magnetic imaging of biological currents in magnetoencephalography or magnetocardiography. Most of the vector optically-pumped magnetometer (OPM) architectures are based on parametric resonances leading to compact architectures which allow to build a dense array of sensors, required for imaging. However, the parametric resonances require radio-frequency (RF) fields, which may bring cross-talks in a dense array of sensors. To avoid such imperfections, all-optical OPMs based on the Hanle effect are interesting. Hanle-effect-based OPMs based on atomic orientation have already been studied, but lead to cumbersome OPM architectures to measure at most two components of the magnetic field and thus make the implementation in a sensor array difficult.

Main Results
In the past few years, theoretical studies of the Hanle effect on aligned atoms showed that some atomic variables depend linearly on two components of the magnetic field. However, these atomic variables do not contribute to the light absorption when using the same laser beam to pump and probe the atoms. We theoretically found that two probe beams with polarizations forming a 60° angle are required to measure two components of the magnetic field. Unlike the orientation-based Hanle-effect OPMs that require the two probe beams to propagate orthogonally one to each other and to the pump beam, but in our configuration the two probe beams can propagate along the same direction. However, this direction cannot be the pumping beam's one, but the angle between them can be as small as 35.3°in the architecture we proposed. This rather small angle allows one to send the two co-propagating probe beams and the pump beam through the same optical access to the cell, hence opening the way for realizing compact all-optical vector Hanle-effect OPMs, which can be integrated in dense sensors arrays. The experiment we carried out led to results in close agreement with the theoretical predictions.

Perspectives
We further theoretically investigated how to probe the third component of the magnetic field in this architecture by using partially polarized pumping light. The results show that it could be feasible using a third probe beam propagating orthogonally to the pump beam and thus breaking the insight of a compact three-axis all-optical Hanle-effect magnetometer. However, measuring the third component of the magnetic field would allow one to operate the sensor in a three-axe closed loop mode, which is highly desirable to avoid the artefacts brought by inter-axis sensitivities in vector OPMs.



RELATED PUBLICATIONS:
[1] G. Le Gal, G. Lieb, F. Beato, T. Jager, H. Gilles and A. Palacios-Laloy, Physical Review Applied 12,064010 (2019)
[2] Talk at the 2019 WOPM conference in Mainz available at: https://www.youtube.com/watch?v=IYK5OJn2yII&list=PLK4Df1ZL5xv2OHzXlP_aZu36egwtdgwxs&index=16

Next generation of absolute scalar ASM-V magnetometers

RESEARCH TOPIC:
Optically pumped ^{4}He magnetometers; Swarm; ASM-V instrument; Nanosatellite

AUTHORS:
Thomas JAGER, Jean-Michel LÉGER, François BERTRAND, Axel BONESS, William FOURCAULT,

We have characterized an improved and miniaturized version of the scalar/vector absolute ^{4}He magnetometers (ASM-V) operated on-board the ESA Swarm satellites. A new sensor head architecture made of alumina was operated in a monolithic configuration with a sensor volume reduction factor of 6 with respect to the ASM instruments. It has demonstrated metrological performances compatible with the scientific needs of geomagnetic missions based on nanosatellite platforms: a 0.7 pT/√Hz scalar resolution over a [DC-100 Hz] bandwidth, a measurement accuracy of 50 pT (1 σ) and a thermal sensitivity of the vector scale factors of 4 ppm/K.

SCIENTIFIC COLLABORATIONS: G. Hulot (IPGP, Paris, France), B. Faure (CNES, Toulouse, France)

Context and Challenges

To target future scientific geomagnetic missions based on nanosatellite platforms, the ASM-V instrument previously developed for the ESA Swarm mission requested miniaturization. Supported by CNES, several sensor head upgrades have been successfully performed showing that the next generation of miniaturized ASM-V instruments will meet the constraints and the performance specifications of such missions [1-3].

Main Results

Following specific activities conducted on the ASM-V DPU to significantly reduce the volume of the instrument (validation of new DFB fiber laser diodes at 1083 nm), similar activities have been performed with the sensor head. A major part of the sensor head activities have been focused in replacing the complex {stator+rotor} isotropic structure of the ASM-V instruments by a monolithic one made of alumina. With this design shown on Fig. 1, a significant size reduction of the sensor head is achieved (the sensor head volume is now of 70 cm^3).

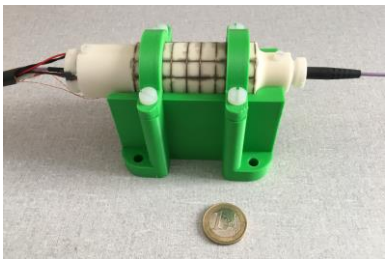


Fig. 3 : ASM-V alumina sensor head

As shown on Fig. 2.a, we were able to demonstrate a 0.7 pT/√Hz scalar resolution in the static Earth ambient magnetic field, along with an accuracy of about 50 pT (1 σ) similar to the one obtained with the Swarm ASM-V instruments.

A significant improvement of the sensor thermal behavior was demonstrated through the reduction of the thermal expansion factor of the vector scale factors (from 47 ppm/K for the PEEK on Swarm down to 4 ppm/K here with the alumina). This result is illustrated on Fig. 2.b through the evolution of the scalar residual between the instrument scalar measurement and the reconstructed vector field modulus over temperature.

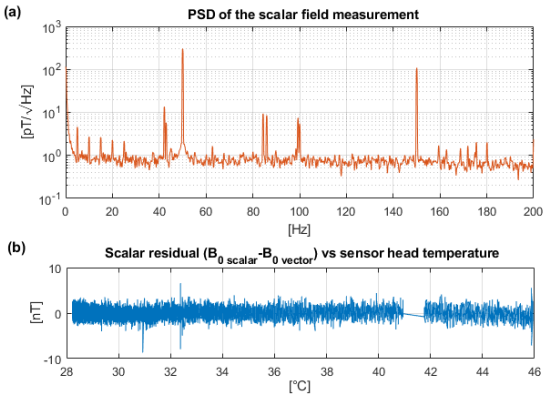


Fig. 4 : (a) demonstrated scalar resolution and (b) thermal stability of the vector field reconstruction

Perspectives

These results have already enabled a selection of the NanoMagSat project [1,3] submitted to the 2019 ESA ITT Scout call for developing future scientific missions based nanosat platforms. A six-month consolidation phase is on-going before a possible 3 years mission development program.

All these developments also benefit to other types of mobile applications, such as airbone MAD or aeromagnetic survey where project activities have also started.

RELATED PUBLICATIONS:
[1] G. Hulot et al, Towards a LEO nanosatellite constellation for permanent monitoring of the Earth's magnetic field and ionosphere: The NanoMagSat nanosatellite constellation high-precision magnetic project, AGU 2019, San Francisco, USA, 9-13/12/2019
[2] G. Hulot et al, Monitoring the Earth's magnetic field with nanosatellites, IUGG 2019, Montreal, Canada, 8-18/07/2019
[3] G. Hulot et al, The NanoMagSat (Swarm Delta) nanosatellite high-precision magnetic project, EGU 2019, Vienna, Austria,7-12/04/2019

02 ELECTRONICS FOR ENERGY

- Energy harvesting
- Power conversion
- Power management
- Wireless power transfer

DC/DC Converter Based on a very high frequency switching

RESEARCH TOPIC:
DC/DC converter, GaN Power converter, VHF Power Electronics, Self oscillating

AUTHORS:
Xavier MAYNARD, Rawad MAKHOUL

Electronic equipment tends more and more towards miniaturization. The power supply of these electronic devices must therefore follow the same trend. One way to make the switching power supplies smaller is to increase the operating frequency. Increasing the switching frequency up to tens of Megahertz also makes it possible to produce inductors without iron or even to reduce the mass of the converter by printing the inductors on the printed circuit (PCB). However, when these switching power supplies operate at more than 10 MHz, the structures commonly used, even the resonant structures, are no longer suitable. We demonstrate that a new topology of DC / DC converter, with no gate control chip and with a low voltage stress on the GaN device, can work in VHF.

SCIENTIFIC COLLABORATIONS: Stanford (USA)

Introduction
Reducing the size of switch mode power supplies (SMPS) could be made possible by increasing the switching frequency up to the VHF range (30MHz- 300MHz). However, different challenges arise in the VHF range: the switching losses, the gate driver chip often struggles with providing the correct transistor switching signal. When designed to be self-oscillating, the class Φ2 can also overcome the gate driver limitation in VHF. This work is focused on the development a DC/DC converter topology based on a VHF selfoscillating class Φ 2 inverter which we term tuned class Φ2 power oscillator and a class DE Rectifier.

Inverter Design
The class Φ 2 inverter is a single transistor, resonant ZVS topology, with fast transient response and low transistor voltage stress. The class Φ 2 circuit is designed for a single load value. If the load value changes, the zero voltage switching is lost and the efficiency drops.In order to maintain the proper behavior when the load value changes, a matching network is added. The matching network is designed for a single load value. In order to obtain a tuned power oscillator, the output voltage of the class Φ 2 inverter is extracted and reinjected into the gate of the GaN device. The feedback circuit is made of an oscillator, a gate bias circuit and harmonic LC filters.

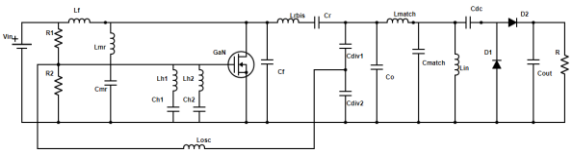


Fig. 1: DC/DC converter based on a class _2

Rectifier Design
For the rectifier part of the converter, a class DE resonant rectifier is chosen. The class DE rectifier is a low diode voltage stress, zero voltage switching (ZVS) rectifier topology suitable for VHF operation. The input current Iin resonates with shunt inductor Lin and the diodes (D1,D2) junction capacitances at the switching frequency (40 MHz). Current flows from the ground to node X when D1 is on and from node X to the output when D2 is on. Cdc is a DC block capacitor and Cout is a filter capacitor, their value is large enough so that their impedance is negligible at 40 MHz. At 40 MHz, diodes D1 and D2 are selected to be schottky diodes in order to avoid reverse recovery losses.

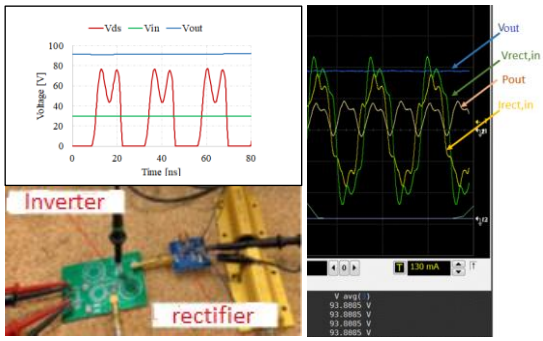


Fig. 2: DC/DC converter voltage waveforms (sim vs exp)

Experimental Results
This topology does not require any gate driver chip and yields low voltage stress on the GaN device and the rectifier diodes. A prototype was built and tested; it showed good matching between the simulation and the experimental results fig 2.

Perspectives
The inverter of class_2 is a single transistor, of ZVS resonant topology, with a fast transient response and a low transistor voltage combined with a rectifier with very low losses, could represent a relevant solution for increasing the frequency of switching of DC / DC converters and therefore an increase in power density.

RELATED PUBLICATIONS:
[1] "DC/DC Converter Based on a Very High Frequency Tuned Power Oscillator", Rawad Makhoul, Charley Lanneluc, Xavier Maynard, Pierre Perichon, Pierre-Olivier Jeannin, David Frey, Yves Lembeye, PCIM Europe 2019.

Inverter for automotive application based on Gallium Nitride semiconductor technology: The MODULED Project

RESEARCH TOPIC:
GaN technology, high power inverter, integration, control & communication, DC link sizing, user safety

AUTHORS:
Charley LANNELUC

Power density, efficiency and low cost are the main drivers of power electronics. The emergence of new wide bandgap (WBG) technologies, such as Silicon carbide (SiC) and Gallium Nitride (GaN) keep on pushing the limits. On one hand, smaller power die design can be obtained by increasing the amount of die per wafer, implying a better yield with respect to the raw materials consumed. On the other hand, power die using WBG materials enable frequency raise. Passive components size reduction results in a better power density. WBG semiconductors are also more efficient thanks to fast switching and low on-state resistance. Better heat dissipation implies cooling size reduction, which, added to innovative modulation methods, enables high power density and high efficiency systems. We present a system optimization approach of an inverter for 100kW automotive application using GaN technology. The powertrain was designed alongside industrial recommendations, in order to provide a compact, efficient and modular system.

SCIENTIFIC COLLABORATIONS : PUNCH POWERTRAIN (BELGIUM), TU/E (THE NETHERLANDS), IKA (BELGIUM)

Context and Challenges
Electrification of passenger cars and light-duty vehicles will have a knock-on effect on reducing the greenhouse gas emission from the transportation sector. However, the maturity of electrical drives and electrical engines needs a push for better performance, better comfort and cost reduction in order to generate a massive adoption worldwide. ModulED aims at developing a new generation of modular electric engine based on buried-permanent magnet motor with reduced rare earth use, and electric drivetrain for various configurations of Full and Hybrid Electric Vehicles (including cost, environmental impact, efficiency, and mass manufacturing readiness). The multiphase e-motor will integrate the latest GaN inverter for power electronics, advanced control with higher fault tolerance, advanced cooling features, with reduced sizing and higher efficiency. It will be linked with a performant electrical drive and transmission, adapting new regenerative braking strategies.

Main Results
The integration of a 100 kW inverter using 300A/650V in a motor housing was demonstrated, encompassing power conversion, DC-link, cooling, local control and communication. It powers a multiphase motor with buried permanent magnets with full bridge and reconfigurable phase topology. With low on-state resistance and fast switching, the global inverter efficiency is beyond 96% for most critical operating points.

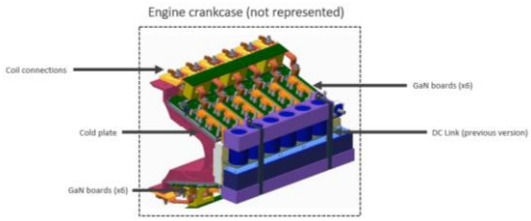


Figure1: GaN inverter integrated in the motor housing (global view).

Efficient, reliable and compact power conversion is the primary focus. Firstly regarding topology, standard inverters are composed of power legs (red rectangle, figure 2). The new topology powers motor phases with full bridges and serial switches, passing from a 6 to a 3-phase system by putting coils in series. Moreover, in case of failure, the system is able to isolate the failure and run the drivetrain by adapting the modulation, even with a decreased number of phases.

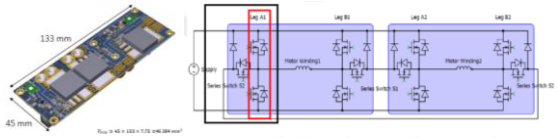


Figure 2: GaN power circuit (left) and equivalent topology (right, black rectangle).

Then, the switching cell was optimized to enable stable and reliable fast switching (20 ns - 40 ns) and optimize switching losses down to 15-20% of the overall inverter losses (against 50% in Si inverters). Finally, the DC-link was fully rethought taking into account the use of the new GaN device technology. Indeed, electrical elements of a system such as capacitance and inductance become critical with GaN technology. Mechanical and electrical constraints required to minimize reactive energy exchange between capacitor stages [1].

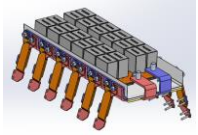


Figure 3: DC-Link design powering the 6-phase inverter.

Perspectives
Working side by side between laboratories & industrial partners enabled global system weight and volume reduction. Using an adapted and efficient semiconductor technology, we attained significant power loss and semiconductor surface reduction, , while increasing power density. Such system optimization is a promising route towards decreasing the price of each parts of the drivetrain, for cheaper future electric vehicle systems.

RELATED PUBLICATIONS:
[1] C.LANNELUC et al. "DC bus capacitor influence in a GAN motor drive inverter" PCIM Europe 2019; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management

Inductorless piezoelectric converter

RESEARCH TOPIC:
Power conversion, Piezoelectricity, Adiabatic, Inductorless, Resonator, DC/DC, AC/DC

AUTHORS:
Benjamin POLLET, Mustapha TOUHAMI, Ghislain DESPESSE

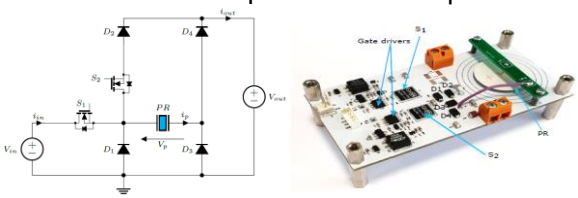
A new type of converters based on mechanical storage is investigated. A piezoelectric material is used as an energy storage element like an inductance in a classical Buck-Boost power electronic converter. The proposed topology enables to dynamically adjust the output power and ratio keeping a high efficiency for a wide range of output powers and for a wide range of conversion ratios taking advantage of piezoelectric high quality factor and achieving zero voltage switching. An efficiency higher than 98% for a 160mW power conversion was experimentally achieved, decreasing slowly to 90% at 750 mW and 78% at 1.4 W for a 10 V to 20 V step-up conversion in radial resonance mode (100 kHz). And a power of 39,2 W was experimentally achieved in a 120 V to 49 V step-down conversion in thickness resonant mode (1,04 MHz) with an efficiency of 90% and by using GaN transistors.

SCIENTIFIC COLLABORATIONS: SATIE (ENS Paris-Saclay, France) - François COSTA

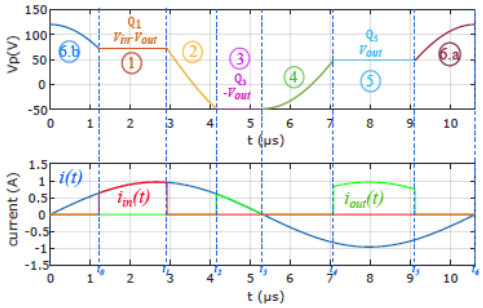
Introduction
In power electronics, piezoelectric elements enable to have a high power density, a thin and planar geometry, low EMI radiations, an excellent efficiency; moreover, they can be integrated on silicon more easily than popular wire wound magnetic components. That is why piezoelectric converters are very relevant for compact and planar low power conversions (from mW to few tens of W), and are therefore particularly well adapted in power management for energy harvesting, medical applications and autonomous devices (phone, computer, touch pad…).

Principle
The conversion principle, conceived by the CEA, is based on the energy and electrical balance during each conversion period. In one period, the input source transfers electrical energy to PR (Piezoelectric Resonator), which stores it temporarily as mechanical energy (indirect effect of piezoelectricity). Then, the PR restores this energy as electrical energy when it is connected to the output load (direct effect of piezoelectricity). Therefore, the input energy is equal to the output energy with adding losses. Assuming the energy balance in steady state, the amplitude of current i is constant, which allows getting a sustainable-oscillation.

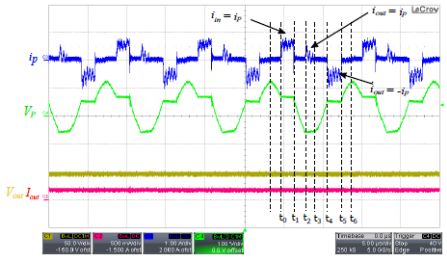
Power circuit and experimental set-up:



Conversion cycle:
The conversion cycle in steady state is presented in the following figure for a 120 - 48 V input-output voltage and 10 W output power. The period of conversion is composed of 6-steps: three steps at constant voltage (connected steps) and three steps at constant electrical charge (isolated steps). The constant voltage steps allow the PR to exchange energy with input source and output load, while the constant electrical charge allows evolving VP to achieve soft switching.



Experimental waveform:



Conclusions
- Improved power density relative to the magnetic components when the operating frequency is greater than 200 kHz
- High efficiency over a wide power range (>90%) with a pic of 98%
- Up to 39,2W with only one piezoelectric resonator with a thin form factor (750µm*ø25mm)

RELATED PUBLICATIONS:
[1] Effects of disc-shaped piezoelectric size reduction on resonant inductorless DC-DC converter, Benjamin Pollet, Mustapha Touhami, Ghislain Despesse, François Costa, IEEE 20th International Conference on Solid-State Sensors, Actuators and Microsystems & Eurosensors, 2019
[2] A New Non-Isolated Low-Power Inductorless Piezoelectric DC–DC Converter, B Pollet, G Despesse, F Costa, IEEE Transactions on Power Electronics 34 (11), 11002-11013.
[3] A new inductorless DC-DC piezoelectric flyback converter, B Pollet, F Costa, G Despesse, 2018 IEEE International Conference on Industrial Technology (ICIT), 585-590

Optimization of a magnetodynamic receiver for versatile low-frequency wireless power transfer

RESEARCH TOPIC:

Wireless power transfer, through-metal transmission, Internet of Things, wearable, bio-implant, autonomous vehicles

AUTHORS:

Nicolas GARRAUD, Pierre GASNIER, Sébastien BOISSEAU, Baptiste ALESSANDRI (DAVIDSON)

Magnetodynamic wireless power transfer (WPT) is a low-frequency WPT technology based on an electromechanical receiver comprising a permanent magnet moving in a coil. Because of the low-frequency field, this technology is safe around humans and enables transfer through conductive media as seawater and metal. In this work, we focus on the design and the optimization of the power receiver with advanced modelling methods. The fabricated 25-cm^3 receiver presents substantial improvements in terms of transferred power (4.9 W) and power density (x40) compared to previous receivers in the same conditions of fields.

SCIENTIFIC COLLABORATIONS: David Arnold from the Interdisciplinary Microsystems Group at University of Florida

Context and Challenges

Inductive coupling solutions dominate the market of wireless power transfer (WPT). However, this technology is highly susceptible to the presence of conductive media around the coils (salted water, metal…). Magnetodynamic WPT is based on the magnetic coupling between a transmitter generating a low-frequency magnetic field and a receiver comprising a magnet physically moving within a receiver coil (Fig. 1) [1-2]. The time-varying magnetic field from the transmitter creates a varying torque on the magnet that tends to rotate. The relative motion of the magnet with respect to the receiver coil changes the magnetic flux through it and generates an electromotive force at its terminals by electromagnetic induction.

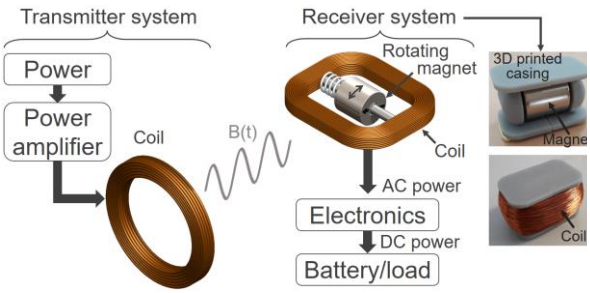


Figure 1: Magnetodynamic WPT principle.

The low frequency of operation has the advantages to be safe around humans and in presence of metallic objects, to be possible through conducting media, and to be less susceptible to creating electromagnetic interferences (EMI) (Fig. 2).

Figure 2: Magnetodynamic WPT can transfer high power safely through various media because of its low operating frequency.

Main Results

The design of the power receiver is optimized using advanced numerical modelling. The magneto-electric transduction coefficient is determined by finite element analysis (Altair Flux) and the maximum power output and optimal load are determined using Simulink for a 10-mT 50-Hz field. The 25-cm^3 optimized and fabricated receiver generates up to 4.9 W of power at the center of a 40-W 18.5-cm transmitter coil, which represents 12 % of efficiency and 0.2 W·cm^{-3} of power density, which is 40 times better than previous versions in the same conditions of field (70 Hz, 6.6 mT).

Numerical simulations (COMSOL) show the screening effect of metals on alternating magnetic fields (Fig. 3): the field in a 2.3-mm-thick aluminum box decreases by 31 % at 100 Hz, and by 99.6 % at 100 kHz. Experimental tests further prove the transmission through a metal box at low frequency: 1.2 W are transmitted at 50 Hz, which represents a 42 % decrease from the configuration without the box.

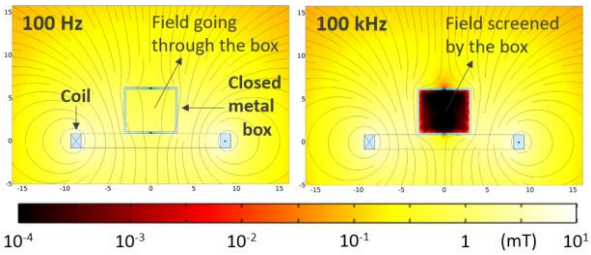


Figure 3: Simulations of alternating magnetic field through a metal box.

Perspectives

In the future, this technology will be further developed to power autonomous systems for biomedical applications (implants, wearables) and systems for industrial interests (autonomous vehicles, isolated sensor node).

RELATED PUBLICATIONS:

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[2] N. Garraud, D. Alabi, S. Chyczewski, J. D. Varela, D. P. Arnold, A. Garraud, Extending the range of wireless power transmission for bio-implants and wearables, Journal of Physics : Conference Series (PowerMEMS 2017), 1052 (2018) 012023,

[3] N. Garraud, B. Alessandri, P. Gasnier, D. Arnold, S. Boisseau, Optimization of a magnetodynamic receiver for versatile low-frequency wireless power transfer, PowerMEMS 2019, Krakov, 2019.

Acoustic power transfer and data communication through metal walls

RESEARCH TOPIC:
Acoustic Power Transfer, Isolated and inaccessible Sensor Nodes, Data communication

AUTHORS:
Olivier FREYCHET, François FRASSATI, Vincent JOSSELIN, Sébastien BOISSEAU, Ghislain DESPESSE

Acoustic Power Transfer is of great interest to supply and communicate with sensors located behind metal walls without drilling holes. The system we propose consists in using two piezoelectric discs placed on both sides of the metal wall, enabling power and data transfer thanks to ultrasonic waves. Hereafter are presented power transmission results and a fast and easy-to-implement characterization method for this technology. We demonstrate that high efficiencies and high power transfers can be obtained: up to 76% of power transfer efficiency and more than 10 W reached on a 1.2 mm-thick steel wall and 50 % of transfer efficiency reached on a 55 mm-thick steel wall. The characterization method allows to get efficiencies and power per volts capabilities over frequencies with a single frequency sweep with a Vector Network Analyzer (VNA). It moreover gives the optimum electrical loads to connect at the emitter and at the receiver sides to reach the best performances.

Introduction
Powering sensors behind metal walls without drilling holes to pass wires is of great interest as holes may result in weakened structures, loss of pressure or chemical leakage issues. Also, electromagnetic techniques are ineffective to communicate through non-thin metal walls because of Faraday shielding. The solution under study consists in transmitting power and data by using ultrasonic waves generated by piezoelectric actuators and propagating within metal walls (Fig. 1).

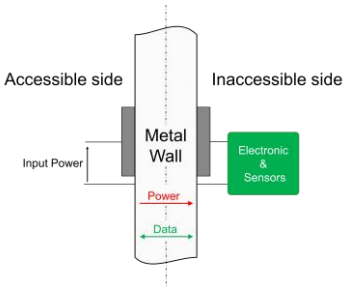


Fig. 1 - Schematic of the system

VNA-based characterization method
The Acoustic Power Transfer device presented in this paper is a linear system and can be fully-described by its impedance matrix, linking input and output currents and voltages. So as to characterize and optimize our system, we developed a novel method [1] based on the exploitation of Scattering matrices provided by a Voltage Network Analyzer to determine in real time the maximum transmitted powers, the maximum efficiencies and the optimal electrical loads to connect both at the emitter and at receiver sides.

Power Transfer Efficiencies for various walls
The effectiveness of this characterization method combined with an efficient fixation system [1] have been tested on various walls with various thicknesses, permeabilities or conductivities (Fig. 2). We have proven that: power transfer efficiencies up to 50% are reachable even with 55mm-thick steel walls. On thin walls (1-2mm), power transfer efficiencies reach 70-80%. These results have been obtained using the VNA-based characterization method at low signal excitation and have been confirmed at higher powers. In particular, we have proven that up to 10 W can be transmitted through these walls with efficiencies closed to the ones determined by the VNA-based method. Advanced models and experiments have also shown (i) the necessity of using good acoustic couplants to maximize power transfer efficiencies, (ii) the impact of misalignment and (iii) the impact of temperatures on efficiencies.

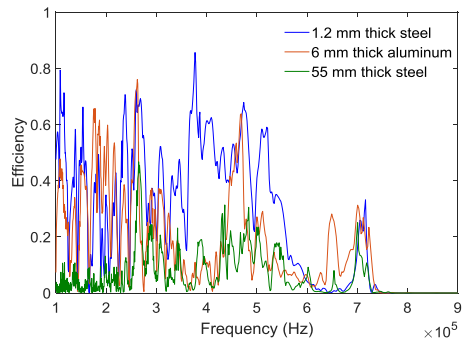


Fig. 2 - Power transmission efficiency on different metal walls with various thicknesses

Perspectives
The next steps will be focused on the improvement and the robustification of the concept, by optimizing the piezoelectric shape or by using other techniques such as MIMO (Multi-Input Multi-Output). Another perspective is to improve data communication obtained previously (2.5 kbps across the 55 mm wall) to tens of Mbps by using innovative communication schemes.

RELATED PUBLICATIONS:
[1] A Versatile Through-Metal-Wall Acoustic Power and Data Transfer Solution, O. Freychet, S. Boisseau, F. Frassati, V. Josselin, P. Gasnier, N. Garraud, R. Gohier, D. Gibus, Brulais, G. Despesse, Proc. PowerMEMS 2019.

RF Energy harvesting & Wireless power transmission

RESEARCH TOPIC:
Energy Harvesting, Wireless Power Transfer, Low-Power Electronics, Wireless Sensor Nodes

AUTHORS:
Sébastien BOISSEAU

RF Energy Harvesting and Wireless Power Transmission are promising technologies to supply Wireless Sensor Nodes. Hereafter is presented a compact rectenna array for ambient RF energy harvesting on the 2.45 GHz ISM band and its power management circuit. The rectenna arrays are based on 9 series-connected rectenna cells to increase the output voltages. Each cell is composed of a stacked fractal antenna and a RF-to-dc conversion circuit. The devices are connected to a low-power energy management circuit to supply a wireless sensor node with a Bluetooth Low Energy data transmission. We demonstrate that the sensor node can work down to an input power of -11.6dBm, where 1µW/cm² is available.

SCIENTIFIC COLLABORATIONS: ESYCOM (Marne-la-Vallée), USTHB (Alger)

Introduction

RF energy harvesting is a promising technology for powering wireless devices and especially when no other sources such as light, thermal gradients or vibrations are available. The key component of RF energy harvesting systems is the rectenna, which consists in a receiving antenna and a rectifier to convert the received AC RF power to DC power. This work is focused on the development of a compact stacked rectenna array able to harvest wireless power from low power levels. The antenna and the rectifier topologies are chosen to give the highest output voltage with the minimum size [1].

Rectenna Design & Rectenna Arrays

Fractal antennas which shows a good trade-off between size and gain have been chosen for the rectenna. More precisely, the rectennas rely on a third iteration Koch fractal geometry (Fig. 1a). The antenna has a dimension of 29x29mm² for a gain of 2.72dBi. As our goal is to obtain a high output voltage from low input power levels, in the µW range, a combination of multiplier circuits and full-wave rectification is used. It consists in cascading two stages of a Dickson voltage multiplier on each branches of a full wave (Fig. 1b). The rectenna has output voltages of 2V at -10 dBm, 0.77 V at -15 dBm and 0.25 V at -20 dBm, which is among the highest output voltages per input µW/cm² in the state of the art.

Power Management Circuit and Wireless Sensor Node Power Supply

However, a single rectenna does not deliver enough voltage/power to supply electronic functions. Nine rectennas have been connected in series to generate output voltages in the 2-4V range, and connected to a power management circuit (hysteresis comparator switch) to supply a wireless sensor node (Fig. 2). The switch is controlled by the voltage across capacitor C_s (V_s). When V_s reaches 2.5 V, the switch is closed supplying the wireless sensor node, which sends data via a Bluetooth link to a data collection station (smartphone).

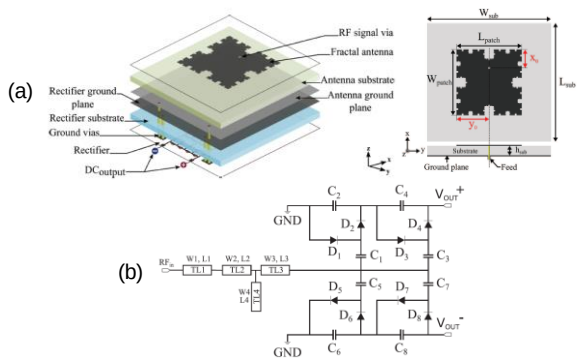


Fig. 1 - (a) Single-cell rectenna design and (b) Rectifier design

The nine-cell rectenna was tested to remotely power a wireless sensor node, which performs a measurement cycle (measure, analysis and Bluetooth Low Energy emission) every 1 min at a power density of 1.7 µW/cm² and every 5 minutes at 1 µW/cm².

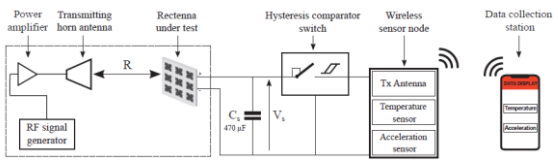


Fig. 2 - Schematic of the sensors data transmission experiment

Perspectives

The high output voltage at low power densities that the proposed rectenna array allows, combined with the hysteresis comparator switch with very low losses, could represent a relevant solution for supplying battery-free wireless sensors. The next steps will be focused on the development of active power management circuits to improve power conversion efficiencies and to decrease operating input power levels.

RELATED PUBLICATIONS:

[1] Wireless Sensor Node Remote Supply using a Compact Stacked Rectenna Array with Voltage Multipliers at 2.45 GHz, H. Mahfoudi, H. Takhedmit, M. Tellache, S. Boisseau, International Journal of Microwave and Wireless Technologies, 2019

Recent progress on broadband vibration energy harvesting for industrial applications: nonlinearities and characterization methods

RESEARCH TOPIC:
Vibration energy harvesting, Broadband, Piezoelectric, Characterization methods, Nonlinearities,

AUTHORS:
Pierre GASNIER, David GIBUS, Olivier FREYCHET, Adrien MOREL, Ghislain DESPESSE, François FRASSATI, Sébastien BOISSEAU

In the context of vibration energy harvesting to power Wireless Sensor Nodes (WSNs), we show the recent progress of our team on the broadband issues and the characterization aspects of our harvesters. We proposed a new method allowing to efficiently characterize vibration energy harvesters (VEH). It predicts the maximum harvestable power while taking into account the dielectric losses, the higher modes influences, and the variations of mechanical damping. Concerning our work on highly-coupled piezoelectric generators, we worked on the bandwidth enhancement of PMN-PT cantilevers (with strong electromechanical coupling) exhibiting softening nonlinearities. These two advancements allow us to go a step further on the understanding and optimization of broadband vibration energy harvesters for their adoption in industrial applications.

SCIENTIFIC COLLABORATIONS: SYMME / Savoie Mont Blanc University (USMB) - Prof A. Badel

Context and Challenges

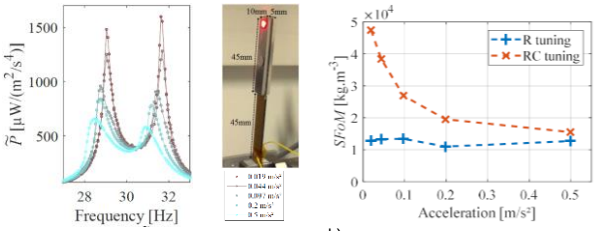
Piezoelectric systems based on mechanical resonators (typically cantilevers) are interesting for their high power density at small scale to deliver electrical energy to WSNs in environments where batteries cannot operate. However, their frequency bandwidth limits are still an important issue. In collaboration with SYMME laboratory (USMB), we have recently proposed electrical nonlinear methods to enlarge the harvesting bandwidth by tuning the resonant frequency of linear piezoelectric harvesters. In opposition to nonlinear mechanical harvesters, these techniques are not dependent on the input excitation level and are based on the influence between the mechanical resonator dynamics and the electrical circuit. For that purpose, the use of highly-coupled piezoelectric generators is mandatory to enlarge the frequency response. However, few works in prior art have proposed modeling, design and characterization methods for highly coupled harvesters in the purpose of broadband energy harvesting and even less by taking their inherent nonlinearities into account.

A new characterization method

In this context, we have recently proposed a new method [1] allowing to efficiently characterize vibration energy harvesters (VEH). It enables to determine the optimal electrical loads at any frequency or the maximum output power; and this with only two measurements: two frequency sweeps on a shaker with two well-chosen electrical loads. This technique, while being time efficient, greatly simplifies the determination of the maximum output power of VEH without requiring a measurement of the output power with many resistors. Furthermore, our method accurately predicts the maximum harvestable power while taking into account the dielectric losses, the higher modes influences, and the variations of mechanical damping, which are usually not considered. The proposed methodology has been tested and validated on a piezoelectric VEH and it is compatible with any linear vibration harvester, not only the piezoelectric ones. As a result, it opens the way towards a general simplified characterization method for linear VEH and electronic macromodels.

Nonlinearities influences on broadband VEHs

We also worked on the bandwidth enhancement of strongly coupled piezoelectric harvesters exhibiting softening nonlinearities [2]. Indeed, we studied the relative increase of bandwidth due to the piezoelectric nonlinearities of a PMN-PT cantilever according to the electrical frequency tuning technique used. We showed that the exploitation of nonlinearities highly increases the harvesting bandwidth with R-tuning techniques (3.5% to 12.3%), competing with RC-tuning ones (10.1% to 12.3%) at high-acceleration levels (Fig. 1). The bandwidth rises enough with respect to the decrease in the normalized power so the systematic figure of merit considering both bandwidth and power density is unchanged. By extending those results, we expect that these nonlinearities offer bandwidth enhancement for other "single tuning parameter electrical techniques" as the N-SECE previously proposed by the Leti and the USMB.



a) b)

Fig 1. a) Measured normalized power as a function of the frequency and b) Systematic figure of merit vs acceleration and tuning strategy

Perspectives

To go another step further on this nonlinearity aspect for broadband vibration energy harvesters, we are currently working on extensive modeling and characterization methods for predicting their behavior. This is a crucial issue since real applications such as industrial ones often show very complex and time changing environments (multi frequency content, varying input acceleration and temperature).

RELATED PUBLICATIONS:

[1] O. Freychet, S. Boisseau, F. Frassati, A. Morel, P. Gasnier, D. Gibus, A. Badel and G. Despesse, “Efficient optimal load and maximum output power determination for linear vibration energy harvesters with a two-measurement characterization method,” Smart Mater. Struct., vol. 29, no. 1, p. 015003, Nov. 2019

[2] D. Gibus, P. Gasnier, A. Morel, S. Boisseau and A. Badel., "Nonlinearities influences on performances of a strongly-coupled piezoelectric generator for broadband vibration energy harvesting," Proc. PowerMEMS, Krakow, Poland, 2019

Water Flow & Air Flow Energy Harvesters

RESEARCH TOPIC:
Energy Harvesting, Air Flow Energy Harvesters, Water Flow Harvesters, Water Distribution, Smart Buildings

AUTHORS:
Elise SAOUTIEFF, Pierre GASNIER, Baptiste ALESSANDRI (DAVIDSON), Martin GAUROY, Sébastien BOISSEAU

Fluids flow is a powerful form of energy. As a result, we also focus our research on the design, simulation and fabrication of cm-scale flow harvesters to supply sensor nodes. The peculiarity of our systems is to have minimal volume occupations (a few cm^3) and to operate in environments where fluid velocities are very low (a few m/s). To that end, we have developed two energy harvesters converting fluid flows into electricity. The first one is a water flow energy harvester which was used in energy efficient and cost effective solutions for district heating and cooling systems within the framework of a European project. The second one is an airflow harvester used to harvest power from low-speed airflows in conventional applications like inside buildings equipped with ventilation (HVAC).

SCIENTIFIC COLLABORATIONS: European INDEAL project's partners (City University, NAITEC, SERM, SNCU…) and SAFRAN

Context and Challenges

Beyond the economic impact, the IoT applications for science and technology are very advantageous: for example, more accurate weather predictions, better agriculture, and even more efficient manufacturing. Concerning agriculture, sensors and actuators distributed in crop fields associated with local weather predictions result in a more localized and real time decision making, decreasing waste of resources (e.g. water, fertilizer) and increasing crop yield. Such a massive integration of devices involves the deployment of energy sources in many locations, which inevitably increases maintenance costs. The fluid flow is a powerful form of energy which can be used to make such a device autonomous or to extend its operating conditions. It has been used for many centuries, as megawatts wind mills or hydropower plants. Indeed, the maximum power that can be extracted from the wind, independent of the design of a turbine, is proportional to the flow section and the cube of the fluid velocity. In the frame of miniaturized autonomous devices for IoT, the challenge is then to produce sufficiently high power levels in environments where wind velocities are very low in minimal volume occupation. In that context, CEA-Leti has proposed both cm-scale water and air flow energy harvesters for autonomous Smart Water Grid systems and HVAC applications respectively.

Main Results: water flow energy harvesters

Within the framework of the InDeal European project, we have proposed the design and optimization of a water flow energy harvester (Ø=40mm) based on an axial turbine (horizontal axis propeller) coupled to a customized permanent magnet converter. These optimisations, centred on the propeller and the generator mainly, have enabled to increase the electrical power by 2.7 @ 1.5 $m^3.h^{-1}$ (3.2 mW) and up to 14.1 @ 9 $m^3.h^{-1}$ (490 mW) compared to a basic air coil converter and with very low pressure drops. The figure of merit of our harvester, which takes the electrical power and the pressure drops in the pipe into account, is greater than previously reported harvesters, and corresponds to an overall conversion efficiency of 5.15%.

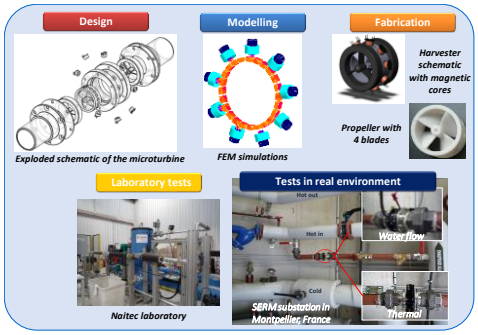


Fig. 1. Optimization of the whole energy harvesting chain for a flow energy harvester (example of the waterflow energy harvester)

Main Results: air flow energy harvesters

We have also developed a cm-scale (Ø=35mm) airflow-driven harvester thanks to a model-based design tool implemented in Matlab-Simulink, which takes both computational fluid dynamics and electromagnetic finite element simulations. Our experiments showed that the harvester has a cut-in speed of 2 m/s and that it is particularly efficient in the low airflow environments since its end-to-end efficiency ranges from 10.5% to 23.9% and its maximum output power from 200 µW to 3.7 mW at 1.5 m/s and 3 m/s respectively. In the cm-scale and low airflow velocity ranges, the proposed harvester without shroud outperforms the state of the art in terms of power density and end-to-end efficiency (23.9% at 3 m/s, 28% at 5 m/s) and it still exhibits one of the highest performances with its shroud.

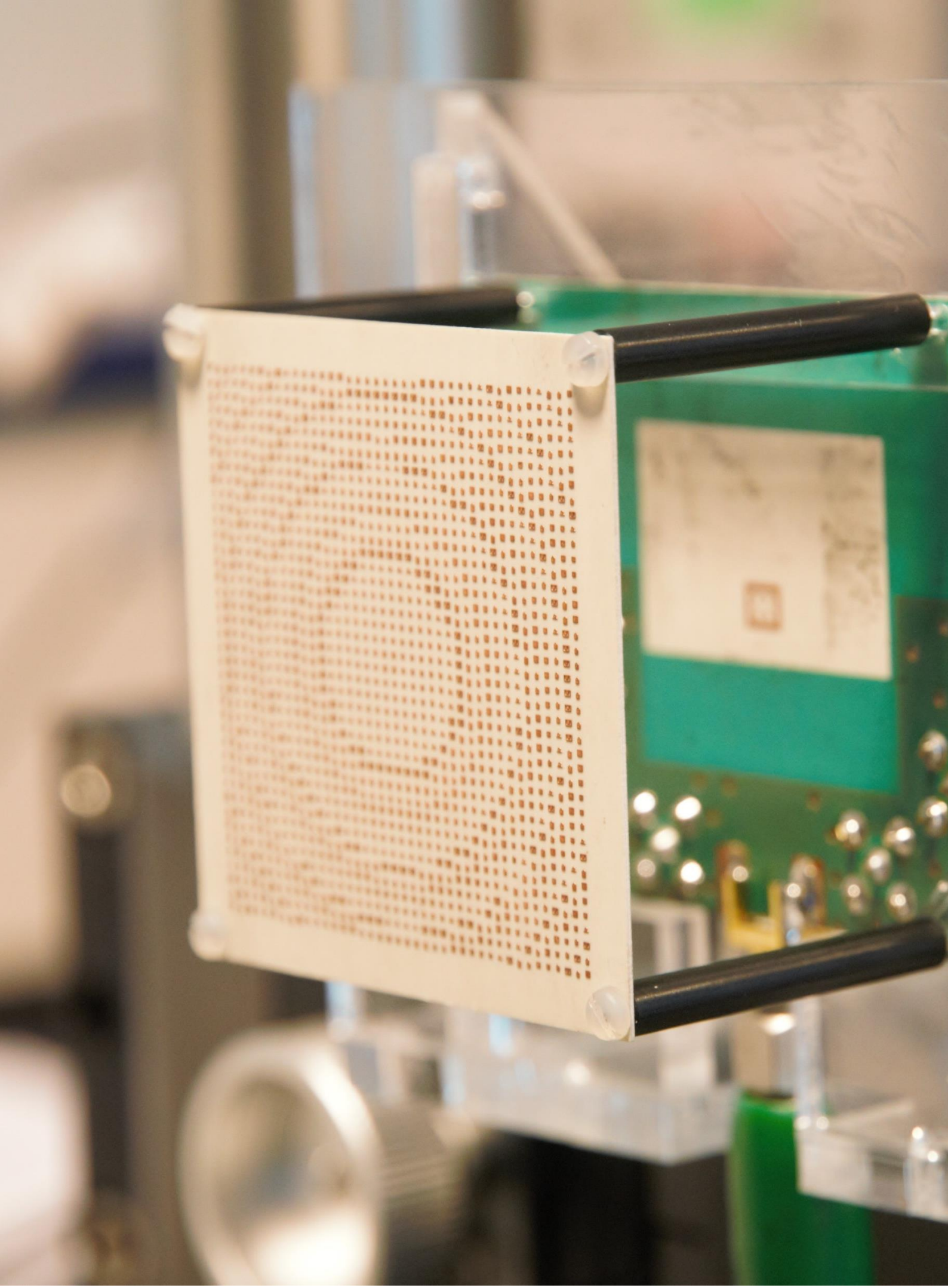
Perspectives

In future works, we will investigate the impact of the pipe form (water case) and the shroud (air case) on the power performances. Another important point is the reduction of the harvesters' cut-in speeds, in order to extend their operating range even more: for this purpose, the rotation to electrical converter has to be downsized and optimized.

RELATED PUBLICATIONS:

[1] Moustakidis, S.; Meintanis, I.; Karkanias, N.; Halikias, G.; Saoutieff, E.; Gasnier, P.; Ojer-Aranguren, J.; Anagnostis, A.; Marciniak, B.; Rodot, I.; Lezak, E.; Pluta, J.; Penev, M.; Jäppinen, H.; Petit, S.; Krajnc, M.; Kouvaris, K.; Eleftheriou, A. Innovative Technologies for District Heating and Cooling: InDeal Project. Computer Science & Mathematics, mdpi, *Proceedings* 2019, *5*, 1.

[2] Gasnier P, Alessandri B., Fayer T., Garraud N., Pauliac-Vaujour E., Boisseau S.; Modelling and Characterization of a High-Efficiency, Cm-Scale and Low Velocity Airflow-Driven Harvester for Autonomous Wireless Sensor Nodes; Proc. PowerMEMS, Kracow, Poland, 2019



03 ANTENNA DESIGN & RADIO PROPAGATION CHARACTERIZATION

- Antenna design, characterization & experimentation
- Reconfigurable transmit array
- Low profile antennas
- Channel modeling
- Environment mapping

Electronically-steerable transmitarray antennas for ka-band

RESEARCH TOPIC:
Antennas, beamforming, 5G networks, satellite communications, reconfigurable antenna systems

AUTHORS:
Antonio CLEMENTE, Luca DI PALMA, Fatimata DIABY, Kien PHAM, Ronan SAULEAU

This paper reports the design and experimental validation of electronically-steerable transmitarrays at Ka-band. Two transmitarrays with 20×20 and 14×14 elements have been prototyped and full characterized, for an operation in switchable circular or linear polarization. They are based on 1-bit and 2-bit phase quantization tunable unit-cells, respectively. To control locally the transmission phase on the transmitarray aperture, two or four p-i-n diodes have been integrated on each unit-cell for the 1- or 2-bit designs, respectively. The measured broadside gain at 29 GHz of the 1-bit prototype is equal to 20.8 dBic with a 3-dB relative bandwidth of 14.6%. For the 2-bit architecture, the measured broadside gain at 29 GHz is equal to 19.8 dBi with a 3-dB bandwidth of 16.2%.

SCIENTIFIC COLLABORATIONS: IETR, Université de Rennes 1

Context and Challenges

In the Internet of Space (IoS) paradigm, satellite and satellite-on-the-move communication systems (SATCOM and SOTM) at Ka-band (17.7 – 21.2 GHz and 27.5 – 31.0 GHz, respectively for the downlink and uplink) are a key technology in the development of the future and high performance 5G and "beyond 5G" mobile networks. Thanks to their spatial feeding architecture, relatively low-cost, and the possibility to easily control the phase-shift on the array aperture, transmitarrays are excellent antenna solutions for applications requiring high gain and efficiency, and wide field of view (> 60°) scanning capabilities.

(a) (b)

Fig. 1. Realized steerable transmitarray prototypes at Ka-band. (a) 1-bit circularly-polarized and (b) 2-bit linearly-polarized transmitarrays.

We review here the main achievements on electronically-steerable transmitarrays at Ka-band studied at CEA-Leti in collaboration with IETR [1]-[4]. This work [4] has been awarded the prize for the Best Antenna Design and Applications Paper during the 13th European Conference on Antennas and Propagation (EuCAP 2019).

Main Results

The two demonstrated prototypes, with 400 (Prototype #1) and 196 (Prototype #2) elements, are presented in Fig. 1. They operates at Ka-band and are based on a 1- and a 2-bit electronically reconfigurable unit-cell. Both unit-cells operate in linear polarization and use p-i-n diode to electronically control the phase distribution on the array aperture. Two and four p-i-n diodes are used to achieve the 1- and the 2-bit phase resolution, respectively. The achieved results at broadside are synthetized in the following table.

	Prototype #1	*Prototype #2*
N. of elements	400 (20×20)	196 (14×14)
N. of p-i-n diodes	800	784
Polarization	CP (switchable)	LP (single)
Meas. gain (dBi)	20.8	19.8
Meas. 3-dB bandwidth (%)	14.6	16.2

Both antennas demonstrate a 2D scanning capability over a 140°×140° angular window (Fig. 2). All the details and results are presented in [1]-[2].

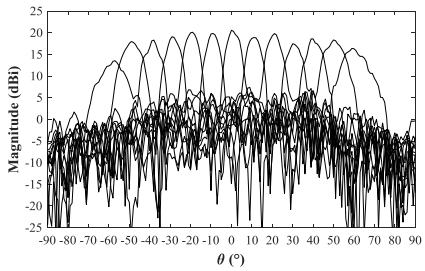


Fig. 2. Gain radiation patterns as a function of the steering angle of the 1-bit circularly-polarized transmitarray.

Perspectives

Ultra-low profile electronically steerable transmitarray with a relatively large aperture (up to 1600 unit-cells) will be studied to SOTM applications requiring circular polarization.

RELATED PUBLICATIONS:

[1] L. Di Palma, A. Clemente, L. Dussopt, R. Sauleau, P. Potier, and P. Pouliguen, "Circularly-polarized reconfigurable transmitarray in Ka-band with beam scanning and polarization switching capabilities," IEEE Trans. Antennas Propag., vol. 65, no. 2, pp. 529–540, Feb. 2017.

[2] F. Diaby, A. Clemente, R. Sauleau, K. T. Pham, and L. Dussopt, "2-bit reconfigurable unit-cell and electronically steerable transmitarray at Ka-band," IEEE Trans. Antennas Propag., in press.

[3] L. Di Palma, A. Clemente, L. Dussopt, R. Sauleau, P. Potier, and P. Pouliguen, "Experimental characterization of a circularly-polarized 1-bit unit-cell for beam steerable transmitarrays at Ka-band," *IEEE Trans. Antennas Propag.*, vol. 67, no. 2, pp. 1300-1305, Feb. 2019.

[4] A. Clemente, L. Di Palma, F. Diaby, L. Dussopt, K. Pham, and R. Sauleau, "Electronically-steerable transmitarray antennas for Ka-band," in Proc. 13th European Conf. Antennas Propag. (EuCAP 2019), Krakow, Poland, 2019.

Low-cost flat lens antenna module driven by a CMOS frequency multiplier for D-band High Data-Rate Links

RESEARCH TOPIC:

Millimeter-wave antennas, systems-in-package, beyond-5G communications, short-range wireless links.

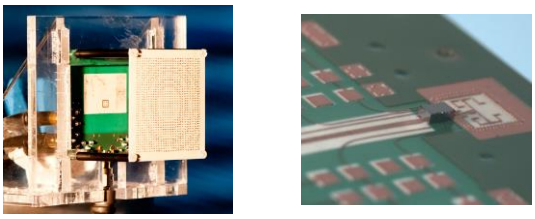
AUTHORS:

Francesco FOGLIA MANZILLO, José Luis GONZÁLEZ-JIMÉNEZ, Antonio CLEMENTE, Alexandre SILIGARIS, Benjamin BLAMPEY, Cedric DEHOS

A compact D-band antenna module for ultrafast short-range communications is presented. The system comprises a planar lens fed by an antenna-in-package embedding an integrated 28-nm bulk CMOS frequency multiplier. Both lens and primary source are fabricated using low-cost printed circuit board (PCB) technology. The module achieves a peak gain of 25 dBi and works between 114 GHz and 138 GHz with a gain drop lower than 3 dB. The proposed solution paves the way for low-loss and low-profile wireless systems entirely integrated in planar multilayer substrate modules.

Context and Challenges

Emerging applications requiring ultralow-latency and massive capacity, e.g. downloading wireless kiosks, real-time streaming and remote surgery, are boosting the development of short-range over-10-Gbit/s transceivers at D-band. Whilst integrated circuit (IC) technologies are relative mature, there is a clear need for low-cost, compact antennas and packaging techniques enabling their pervasive deployment. Dielectric lens antennas are popular solutions to achieve wideband and high-gain at D-band, even though bulky and inefficient. Except for expensive silicon-based realizations, lenses and primary sources are fabricated using different processes, e.g. PCB and additive manufacturing, requiring an additional effort for their assembly. Instead, we demonstrated in [1], [2] the feasibility of a wideband transmitarray antenna (TA) module with integrated active circuit using low-cost PCB technology. As shown in Fig. 1, the proposed architectures combines two PCB sub-systems: an antenna-in-package (AiP) source and a planar discrete lens.

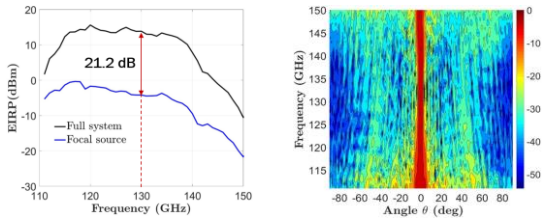


(a) (b)

Fig. 1: (a) Picture of the prototype. (b) Detail of the backside of the focal source with the flip-chipped frequency multiplier.

Main Results

The stack-ups of the primary source and the flat lens are the same, comprising two substrates and a bonding layer, so that they can be fabricated in the same 0.5mm-thick panel. The AiP features a 2×2 array of aperture-coupled patches. The array is surrounded by a via-fence cavity to mitigate the impact of surface waves. The simulated peak gain is 8.5 dBi, whilst the -3-dB gain bandwidth ranges from 110 to 145 GHz. A 28-nm CMOS IC is flip-chipped on the backside of the AiP, at the input of the array feed network. The IC up-converts the input K-band signal to D-band. It delivers to the antenna a constant output power (about -10 dBm) from 110 to 140 GHz, accounting for the impact of pads and soldering bumps. A 40 × 40 3-bit broadside TA was optimized based on the simulated radiation pattern of the AiP, for a focal distance of 32 mm. The unit cells (UCs) of the TA are either aperture-coupled or via-connected patches [3]. The combination of two types of UCs greatly enhances the bandwidth as compared to standard designs [1]. Both the stand-alone AiP and the full TA module were experimentally characterized. The multiplier on the IC also allowed us to test the module in conditions similar to those occurring in the presence of a fully functional transceiver. Fig. 2a shows that the equivalent isotropic radiated power (EIRP) of the full TA varies less than 3-dB between 114 and 138 GHz. In this band, the stable beam properties are observed (see Fig. 2b). The bandwidth is limited in part by the drop of the IC output power at 140 GHz. The EIRP increases by ~21 dB when the lens is added above the AiP. The estimated gain of the full TA is 25 dBi, accounting for the IC-to-antenna interconnect loss. These results are comparable to those reported in the literature for bulkier D-band modules combining dielectric lenses and AiP feeds realized using a costly high-density interconnect process.



(a) (b)

Fig. 2. (a) Measured EIRP (feed and full system) (b) Radiation pattern (H-plane) in dB as a function of frequency and angle.

Perspectives

Full transceivers will be assembled on the AiP and the performance of point-to-point links characterized. Folded TA architectures will be developed to further reduce the focal length and enable the integration of the system in a monolithic module.

RELATED PUBLICATIONS:

[1] F. Foglia Manzillo, A. Clemente, B. Blampey, G. Pares, A. Siligaris, and J. L González-Jiménez, "Transmitarray antenna with integrated frequency multiplier for high-speed D-band communications in low-cost PCB technology", in Proc. *13th Eur. Conf. Antennas Propag.* (EuCAP), Krakow, Poland, 2019, pp. 1-4.

[2] F. Foglia Manzillo, J. L. González-Jiménez,, A. Clemente, A. Siligaris, B. Blampey and C. Dehos, "Low-cost, high-gain antenna module integrating a CMOS frequency multiplier driver for communications at D-band", in Proc. *IEEE Radio Freq. Integr. Circuits Symp.*, Boston, MA, USA, 2019, pp. 19-22.

[3] F. Foglia Manzillo, A. Clemente and J. L. González-Jiménez, "High-gain D-Band transmitarrays in standard PCB technology for beyond-5G communications", IEEE Trans. Antennas Propag., vol. 68, no. 1, pp. 587-592, Jan. 2020.

Millimeter-Wave Gaussian-Beam Transmitarray Antennas for Quasi-Optical S-Parameter Characterization

RESEARCH TOPIC:
Quasi-optical measurement, transmitarray antennas, Gaussian-beam antennas, millimeter-wave

AUTHORS:
Laurent DUSSOPT, Kossaila MEDRAR, Loïc MARNAT

Millimeter-wave Gaussian-beam transmitarray antennas are studied and the main design trade-offs and theoretical performances investigated. Two V-band antenna prototypes are fabricated in a low cost planar technology. These prototypes are first validated through transmission measurements. Antenna efficiency of 61.2% at 61.5 GHz and Gaussian efficiency better than 90% are observed. Near-field measurements demonstrate a Gaussian field distribution with a nearly planar wavefront in the focal plane. The Gaussian-beam transmitarrays are used to implement a V-band quasi-optical vectorial S-parameter measurement set up. Transmitarray unit-cells are then fully characterized over a wide 50-70 GHz frequency range showing a very good agreement with simulated results

Context and Challenges

Quasi-optical S-parameter measurement systems are used classically to characterize dielectric materials, radomes and quasi-optical structures, e.g. frequency-selective surfaces, polarizing grids, etc. Such systems are based on Gaussian-beam antennas synthesizing a focused beam with a normal incidence and planar wavefront on the device-under-test. They are usually implemented as corrugated horns or use dielectric lenses. Quasi-optical measurement technique is attractive to characterize S parameters of transmitarray unit-cells where vectorial (magnitude/phase) measurements are necessary both in reflection and transmission. Characterizations in waveguide set-ups have been demonstrated up to 30-35 GHz in linear and circular polarization [2] but such technique can hardly be implemented at higher frequencies with a good accuracy.

Transmitarray antennas may provide significant advantages over other large-aperture antennas in terms of manufacturability and polarization control [1-2]. Hence, transmitarray antennas can be manufactured using standard printed-circuit-board (PCB) technologies up to the 300 GHz bands [3].

Main Results

In this work, Gaussian-beam transmitarray antennas (GBTA) are introduced. Within the paraxial approximation, the field distribution of a fundamental Gaussian beam propagating along the z direction is:

$$A(r,z) = A_0 \frac{w(0)}{w(z)} e^{\left(\frac{-r^2}{w(z)^2}\right)} e^{j\left(-kz+tan^{-1}\left(\frac{z}{Z_R}\right)-\frac{kr^2}{2R(z)}\right)}$$

where $w(z)$ is the half beam waist (minimum at $z = 0$).

The design and optimization criteria related to such antennas are investigated (e.g. trade-offs between the focal distance, Gaussian efficiency and beam waist). Gaussian efficiency is defined at $z = 0$ by:

$$\eta_G = \frac{|\iint A_A A_G dS|^2}{\iint |A_A|^2 dS \iint |A_G|^2 dS}$$

where A_A is the antenna radiated field and A_G is an ideal Gaussian distribution with the same waist.

Two V-band linearly-polarized GBTA are fabricated. A 2-port quasi-optical S-parameter measurements set-up is presented in (fig. 1). The transmission and reflection of seven transmitarray unit-cells fabricated in a previous work [4] are extracted over 50–70 GHz with this set-up. Very good experimental results in transmission magnitude and phase have been observed (fig. 2). In addition, experimental results have demonstrated a very good Gaussian coupling, between 94-97%, and antenna efficiency of 61.2% at 61.5 GHz.

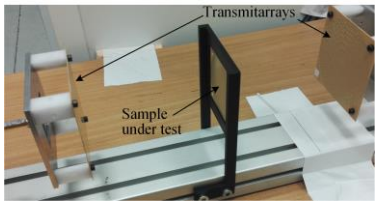


Fig. 1: Quasi-optical characterization set-up with two identical fabricated Gaussian-beam transmitarray antennas (GBTA).

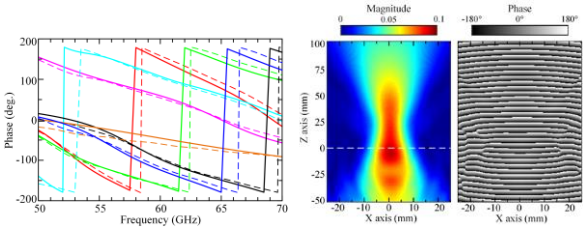


Fig. 2: a) Extracted unit-cell transmission phase (dash line: sim.; solid line: meas.) (setup in fig. 1) and b) measured amplitude and phase of GBTA near electric field at 61.5 GHz.

Perspectives

These results demonstrate for the first time the capabilities of transmitarray antennas to generate a Gaussian beam at millimeter-wave frequencies with performance suitable for quasi-optical S-parameter measurements over a significant frequency band. It can be expected that future millimeter-wave quasi-optical systems may benefit from the excellent properties of transmitarray antennas to generate circular polarization with very low axial ratio over a broad frequency band, polarization

RELATED PUBLICATIONS:

[1] L. Dussopt, "Transmitarray Antennas," in Aperture Antennas for MM and Sub-MM Wave Applications, A. Boriskin and R. Sauleau (Ed.), Springer, Sept. 2017.

[2] L. Di Palma, A. Clemente, L. Dussopt, R. Sauleau, P. Potier, P. Pouliguen, "Experimental characterization of a circularly-polarized 1-bit unit-cell for beam steerable transmitarrays at Ka-band," IEEE Transaction on Antennas Propagation, vol. 67, no. 2, pp. 1300–1305, February 2019.

[3] L. Marnat, K. Medrar, L. Dussopt, "Highly Integrable High Gain Substrate-integrated Planar Lens for Wide D-band Applications," 14th European Conference on Antennas and Propagation, 1-4, March 2020.

[4] L. Dussopt, A. Moknache, J. Säily, A. Lamminen, M. Kaunisto, J. Aurinsalo, T. Bateman, J. Francey, "A V-Band Switched-Beam Linearly-Polarized Transmitarray Antenna for Wireless Backhaul Applications," IEEE Transaction on Antennas Propagation, vol. 65, no. 12, December 2017, pp. 6788–6793.

Novel solutions enabling High-gain transmitarray antennas in standard PCB technology beyond 100 GHz

RESEARCH TOPIC:

Millimeter-wave antennas, flat lens antennas, beyond-5G communications, short-range wireless links.

AUTHORS:

Francesco FOGLIA MANZILLO, Antonio CLEMENTE, José Luis GONZÁLEZ JIMÉNEZ

The design and experimental validation of a fixed-beam transmitarray operating in the D-band (110−170 GHz) are presented. The proposed flat lens is suitable for standard PCB manufacturing and features three-layer unit cells achieving a 3-bit phase quantization. The cells leverage different coupling mechanisms among receiving and transmitting elements to cover a wide frequency band of 50 GHz (35.7% at 140 GHz) with low transmission loss and phase errors. A 40 × 40 broadside transmitarray has been optimized to attain a gain between 30 dBi and 33 dBi over a 30-GHz bandwidth when fed by a 10-dBi source. The measured -1-dB relative gain bandwidth of 11.7% outperforms state-of-the-art designs in D-band based on more complex technologies.

Context and Challenges

Short-range wireless links operating beyond 100 GHz will be key for providing ultrahigh-throughput connectivity in future mobile networks. The research on D-band antenna systems achieving the high gain values (>30 dBi) and bandwidth (>20%) necessary to reach data rates of tens of Gbit/s is still at an early stage. In this context, transmitarray antennas (TAs) [1]-[3] are attractive candidates in view of their compact profile, lightweight and low losses at millimeter-waves as compared to architectures requiring complex feed networks. However, the limited resolution of standard printed circuit board (PCB) processes makes the design of D-band TAs challenging and lead to narrow fractional bandwidths (< 6%). State-of-the-art TAs beyond 100 GHz comprise a large number of layers and resort to more complex technologies, e.g. silicon micro-machining and low-temperature co-fired ceramic (LTCC), to achieve moderate bandwidths. In contrast to these solutions, we developed and experimentally validated a design approach enabling the realization of high-gain and wideband TAs using only three metal layers and standard PCB technology.

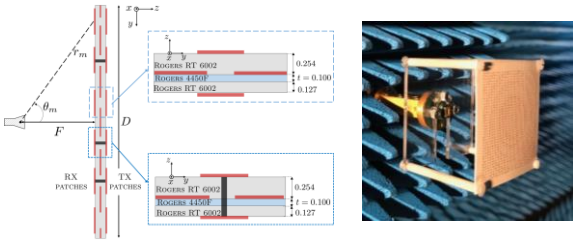
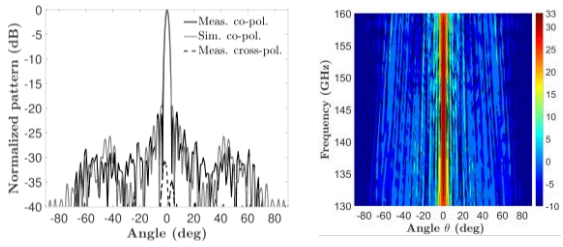


Fig. 1: Schematic view of the 3-bit transmitarray comprising two different types of cells (insets) and picture of the prototype.

Main Results

A key goal was to design eight 3-layer unit cells (UCs) providing a uniform 3-bit quantization of the 360° phase range and small directivity loss in a band wider than 30 GHz. Standard TAs comprise parametric variations of a single UC type. In this work, instead, we combine two different types of UCs [3], as shown in Fig. 1. The outer layers comprise receiving (Rx) and transmitting (Tx) patches. In the first class of UCs (3 phase states) these patches are aperture-coupled, while they are connected by a via in the second one (5 phase states). The two different coupling mechanisms increase the degrees of freedom in the design. A broadband 3-bit phase quantization is attained using only 3 layers and fulfilling the design rules of PCB technology (minimum trace width and via-diameter of 80 µm, via-diameter of 100 µm). The average insertion loss of the 8 UCs is < 1 dB in a relative bandwidth of 35.3% at 145 GHz. Based on these UCs, a 40 × 40 broadside TA (D = 42.6 mm) is optimized at 137 GHz for a 10-dBi in-focus horn and a focal length F = 32 mm. The measured peak gain is 33 dBi, corresponding to a 38% aperture efficiency. The -3-dB gain-bandwidth ranges from 130 to 160 GHz (19.8%). Radiation patterns are in tight agreement with simulations and the beam characteristics are very stable over the band (see Fig. 2). The average first sidelobe level is −18.6 dB in the H-plane. The peak cross-polarization is −30 dB. These results are comparable to those attained by similar V-band TAs [2] benefiting from less stringent design rules. The proposed TA outperforms, in terms of -1-dB gain-bandwidth, state-of-the-art D-band TAs using less metal layers, a cheaper technology and a shorter focal length.



(a) (b)

Fig. 2. (a) Radiation pattern at 145 GHz in the H-plane. (b) Gain (H-plane) in dBi as a function of frequency and elevation angle.

Perspectives

The integration of switches, e.g. custom p-i-n diodes, on the proposed UCs is currently being investigated to demonstrate low-power electronically reconfigurable TAs in D-band.

RELATED PUBLICATIONS:

[1] L. Dussopt, "Transmitarray Antennas," in *Aperture Antennas for millimeter and sub-millimeter wave applications*, 1st ed., Springer, 2018, pp. 191-220.

[2] C. Jouanlanne, A. Clemente, M. Huchard, J. Keignart, C. Barbier, T. Le Nadan, and L. Petit, "Wideband linearly polarized transmitarray antenna for 60 GHz backhauling", *IEEE Trans. Antennas Propag.*, vol. 65, no. 3,pp. 1440–1445, Mar. 2017.

[3] F. Foglia Manzillo, A. Clemente and J. L. González-Jiménez, "High-gain D-Band transmitarrays in standard PCB technology for beyond-5G communications", *IEEE Trans. Antennas Propag.*, vol. 68, no. 1, pp. 587-592, Jan. 2020.

Miniaturization strategy of compact antenna using magneto-dielectric material

RESEARCH TOPIC:
Electrically small antennas, magneto-dielectric material, VHF band

AUTHORS:
Lotfi BATEL, Christophe DELAVEAUD, Jean-François PINTOS

Antenna miniaturization for airborne systems is an important issue for reducing the weight and improving the aero dynamic shape. Nevertheless, reducing antenna size becomes critical at V/UHF bands as the wave lengths are large at those frequencies and the performances of the small antennas are reduced following the fundamental physical laws. A miniaturization strategy for an electrically small Monopolar Wire-Plate Antenna (MWPA) loaded by Magneto-Dielectric Material (MDM) is described. This approach consists in multiplying the number of antenna's short-circuit wires in order to magnify the interaction with the material. A model showing the equivalence between a single-shorted MWPA and n-shorted wires is proposed to serve this strategy of miniaturization.

SCIENTIFIC COLLABORATIONS: **DGA, LABSTICC, IETR, COBHAM**

Context and Challenges

Reducing the size of antennas in VHF frequency band is challenging since the wavelength are large at those frequencies. Recent works dealing with material fabrication at microwave frequencies has made it possible to consider using MDM ($\varepsilon_r > 1$, $\mu_r > 1$) as a promising solution for antenna miniaturization. This opportunity led us to evaluate the performances of MWPA while loading by a MDM, which represents an original work according to the current state of the art. The work proposed in [1] highlighted that loading the MWPA by a MDM around antenna's short-circuit is optimal toward miniaturization because it is more sensitive to material's properties since its fundamental radiation mode is mainly based on the strong currents located on the antenna's short-circuit. Considering this result, the work in [2] investigates the potential of miniaturization using multiple short-circuits loaded with MDM in MWPA geometry.

Main Results

A preliminary study has been performed in order to demonstrate the equivalence between a single-shorted MWPA and a MWPA with 6 short-circuits, where both antennas are unloaded with material. The two considered antennas shown in Figure 1 has been designed with the same physical dimensions (capacitive plate and ground plane) and the same resonance frequencies. The only difference is the number of short-circuits, the distance between them and their respective radii that controls antenna's resonance frequency.

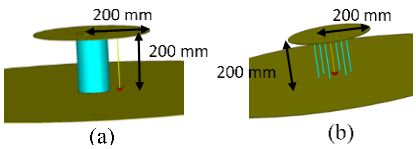


Figure 5: (a) Single shorted MWPA, (b) 6 short-circuits MWPA, both loaded with MDM (blue)

This demonstration led us to propose a generalized model showing the equivalence between n parallel short-circuits with the same radius a, spaced by a distance b, to a single wider short-circuit with the equivalent radius R_{eq} defined as follows:

$$R_{eq} = (a\, b^{n-1})^{\frac{1}{n}}$$

The two considered antennas without material are equivalent since they have the same physical and electrical dimensions. They have been loaded with a fabricated MDM($\varepsilon_r = 13, \tan\delta_e = 0.05, \mu_r = 19, \tan\delta_m = 0.03$ in the frequency band 100-200 MHz) enclosing their respective short-circuits (blue cylinders in Figure 1).The effect of miniaturization through antenna's input impedance is shown in Figure 2. The 6 shorted wires antenna exhibits a 32% lower resonance frequency (86 MHz) compared to the single shorted antenna (127 MHz) loaded with the same volume of material (2.8 10^4 mm^3). This result shows that multiplying the number of short-circuits of a MWPA magnifies the interaction between the MDM and the antenna toward miniaturization [3]. In addition, the two loaded antennas has the same radiation efficiency of 95%. In order to perform the same resonance frequency, the single shorted MWPA should be loaded with a 20 times larger volume of MDM that should increase antenna's weight and significantly decrease its radiation efficiency to 58% (contribution of MDM losses)

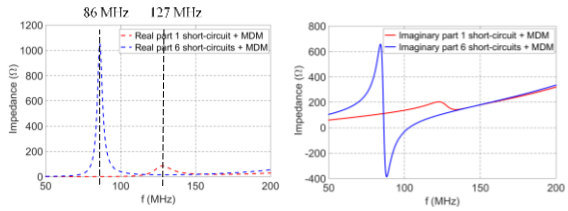


Figure 6: Resonance frequencies of MWPA loaded with MDM

Perspectives

Multiplication of MWPA short-circuits loaded with MDM shows promising perspectives for airborne application in order to obtain smaller, light and low cost antenna systems. Future works will concern a specific antenna design with 6 short-circuits and its experimental validation.

Acknowledgment: This work is partially supported by the French National Research Agency (ANR-15-CE24-0030, MISTRAL project).

RELATED PUBLICATIONS:

[1] L. Batel, J. Pintos and C. Delaveaud, "Design of a monopolar wire-plate antenna loaded with magneto-dielectric material," *12th European Conference on Antennas and Propagation (EuCAP 2018)*, London, 2018, pp. 1-5.

[2] L. Batel, C. Delaveaud and J. Pintos, "Miniaturization of a Monopolar Wire-Plate Antenna Using Magneto-Dielectric Material," 2019 International Workshop on Antenna Technology (iWAT), Miami, FL, USA, 2019, pp. 91-94.

[3] C. Delaveaud, L Batel, J.F. Pintos, "Antenne fil-plaque monopolaire", N° E.N. 1873167,18/12/2018,

Transmission Line Model For Lossy Inverted F Antenna Miniaturization

RESEARCH TOPIC:

Electrically small antenna, miniaturization, impedance, radiation efficiency, modelling

AUTHORS:

Rana BERRO, Serge BORIES, Christophe DELAVEAUD

In this work, a transmission line (TL) model is derived to allow the study and optimization of a compact Inverted F Antenna (IFA) characteristics as a function of its geometry and manufacturing materials. The model allows calculating the antenna's electrical (input impedance, quality factor) and electromagnetic (radiation efficiency) properties. The expressions of the IFA radio electrical characteristics are generalized by including all kinds of losses in the antenna, and most particularly the radiation losses which are not considered in conventional TL models. Furthermore, to ensure high accuracy of the model, the coupling effects between the antenna lines and its terminations have been identified as critical. An apparent terminal impedance has been defined to accurately model the local end-effect loading on the transmission line parameters. Tests of improved antenna model accuracy have been carried out by comparing impedance and radiation efficiency with full wave simulation results.

Context and Challenges

Electrically small antennas are the subject of numerous investigations aimed at optimizing their performance limited by the laws of physics. Mostly studied with the help of an electromagnetic simulator rigorously solving Maxwell's equations, their behavior is not always easily related to the associated physical phenomena. To better understand and exploit the behavior of a compact Inverted F Antenna (IFA) antenna, a physical model has been developed to reproduce the electrical behavior of the antenna (its impedance) but also the electromagnetic properties via the calculation of its radiation efficiency, which is an important miniature antenna parameter.

Main Results

A convenient way to describe a small IFA is by an equivalent transmission line (TL) model, where the excitation is modelled as a shunt generator, and the open and shunt driven arms are represented as two wire transmission lines sections in parallel. The conventional TL theory is used to calculate the antenna input impedance [1]. However, effects between the antenna lines and the loads at its end are not correctly taken into account (infinite line model). In order to have higher accuracy in the impedance model, the end effects between the line and its terminal impedances (the short and the open circuit impedances) have been modelled using an apparent terminal impedance which takes into account the local terminal load effect on the transmission line parameters [2]. Based on this model, the expressions of the current distribution on IFA structure is derived to calculate both the radiated and dissipated powers.

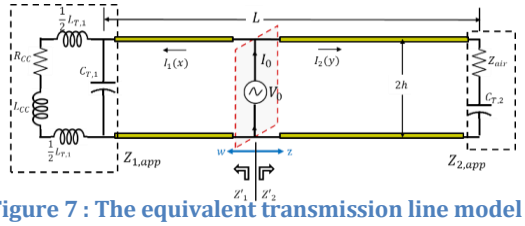
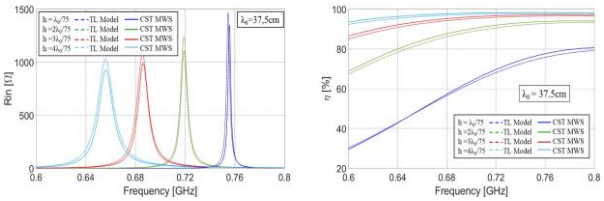


Figure 7 : The equivalent transmission line model of an IFA (including electrical image) with the terminal zone networks

These physical quantities have been used to assess the IFA radiation efficiency and particularly the correction of efficiency curve singularity has been demonstrated [1] thanks to the introduction of ohmic losses (limited conductivity of metal) in the model. The radiation efficiency of an IFA is then generalized to include all kinds of losses (finite conductivity in metallic parts, non–ideal terminations, and any kind of loading element in shunt or series configuration inside the antenna structure). Moreover, to predict the antenna input impedance, the TL model is further improved by using the accurate radiated power expression. Indeed, in the case of an antenna modelling, the radiation properties are not classically integrated in the TL electrical model considering that the wave is only guided along the line and not radiated. For this reason, the radiation loss has been added in the TL via a distributed radiation resistance derived from calculated radiated power. A major improvement in the modelling of the impedance resonant behavior (magnitude, quality factor) has been observed [1]. Illustration of accuracy of the improved antenna model are given in fig. 2 comparing the modelled input impedance and radiation efficiency to the simulated ones for different IFA heights.



(a) (b)

Figure 2 : Comparison of IFA input impedances (a) and radiation efficiencies (a) for different IFA heights

Perspectives

A TL model of an IFA has been developed showing outstanding accuracy to predict IFA antenna behavior. This model contributes to analyze the properties of small antenna (loss effect) and will be enriched by introducing lumped element models inside antenna structure to study frequency agile antenna capabilities.

RELATED PUBLICATIONS:

[1] R. Berro, S. Bories and C. Delaveaud, "Generalization of King IFA Model for Lossy Loaded Antenna Miniaturization," 2019 13th European Conference on Antennas and Propagation (EuCAP), Krakow, Poland, 2019, pp. 1-5.

[2] R. Berro, S. Bories and C. Delaveaud, "Transmission Line Model for Lossy Inverted F Antenna Miniaturization," 2019 International Conference on Electromagnetics in Advanced Applications (ICEAA), Granada, Spain, 2019, pp. 0797-0802

Limitations and optimization of supergain end-fire arrays

RESEARCH TOPIC:
Antennas, antenna limitations, antenna efficiency, end-fire arrays, superdirectivity, supergain, electrically small antennas

AUTHORS:
Alexandre DEBARD, Antonio CLEMENTE, Christophe DELAVEAUD, Patrick POTIER, Philippe POULIGUEN

In this paper, the possibility to optimize supergain end-fire arrays is numerically investigated. Firstly, the optimization problems in terms of directivity and gain are introduced. Then, infinitesimal-dipole based end-fire arrays have been optimized as a function of the number of elements and inter-element spacing. It is shown that, their radiation efficiency can be predicted and, for close inter-element spacing, even optimized to provide a higher gain than the one obtained with the classical directivity optimization methods. The numerical analysis is detailed and validated by full wave simulations in the case of three half-wavelength dipoles.

SCIENTIFIC COLLABORATIONS: Direction Générale de l'Armement (DGA)

Context and Challenges

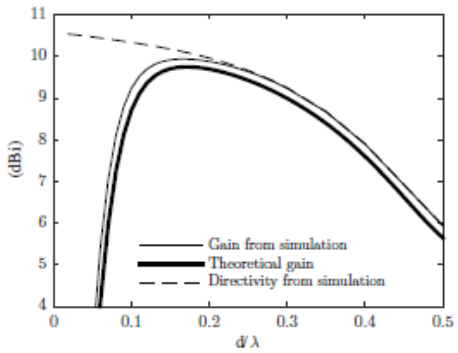
The mathematical theory, which demonstrated that end-fire arrays of P isotropic sources could reach a directivity of P^2, when the inter-element distance tends to zero, is well known at least since 1946. However, for a long time, superdirective arrays were considered impractical due to their sensitivity to excitation and their relatively poor efficiency. Recently, superdirectivity has been the object of several practical studies and demonstrations. In fact, since 2005, superdirective end-fire arrays, with an inter-element spacing < 0.2λ, have been optimized by using procedures based on array theory or spherical wave expansion [1], built, and experimentally characterized. These works demonstrated the feasibility of two-, three- or four-element compact arrays, even showing that relatively good efficiency could be reached, when the number of the elements is limited to two, or when a trade-off between the inter-element spacing and the number of elements is considered.

The directivity limits for dipole- and Huygens-source-based end-fire arrays were also clearly presented and computed as a function of the number of the elements and the inter-element distance [2]. However, at the best of our knowledge, the limits on the gain and radiation efficiency were not clearly determined yet, unless in the general case of isotropic individual radiators.

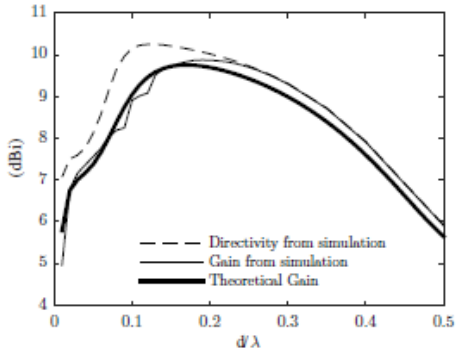
Main Results

In [3], the efficiency limits of compact infinitesimal dipole based end-fire arrays have been analytically predicted in the case of the optimization of the directivity (Fig. 1(a)) and gain (Fig. 1(b)). The proposed theory has been validated in the case of a three half wavelength dipole array considering full wave simulations. The results of Fig. 1 show that higher gain is achieved when the excitation coefficients associated to the array elements are opportunely optimized. A good agreement between numerical and simulated results has been obtained in both cases.

The complete theoretical background is detailed in [1] and [3].



(a) Directivity maximization



(b) Gain maximization

Fig. 1: Simulated and theoretical directivity and gain of an array of three half-wavelength copper dipoles. The analysis is computed as a function of the inter-element spacing *d*.

Perspectives

In the future works, the proposed analysis will be validated with experimental results obtained from prototypes.

RELATED PUBLICATIONS:

[1] A. Clemente, M. Pigeon, L. Rudant, and C. Delaveaud, "Design of a super directive four-element compact antenna array using spherical wave expansion," IEEE Trans. Antennas Propag., vol. 63, no. 11, pp. 4715–4722, Nov. 2015.

[2] A. Debard, A. Clemente, C. Delaveaud, C. Djoma, P. Potier, and P. Pouliguen, "Analysis of superdirective Huygens source based end-fire arrays," in Proc. 11th European Conf. Antennas Propaga. (EUCAP 2017), Paris, France, 2017.

[3] A. Dabard ,A. Clemente, C. Delaveaud, P. Potier, and P. Pouliguen, "Limitations and optimization of end-fire arrays," in Proc. 13th European Conf. Antennas Propag. (EuCAP 2019), Krakow, Poland, 2019.

Superdirective and Compact Electronically-Beam-Switchable Antenna for Smart Communication Objects

RESEARCH TOPIC:
Beam-forming, beam-switching, electrically small antennas, superdirectivity, parasitic arrays

AUTHORS:
Lotfi BATEL, Antonio CLEMENTE, Christophe DELAVEAUD

A directive and compact circular Electrically Steerable Passive Array Radiators (ESPAR) antenna composed of 9 symmetrical radiating elements (1 fed and 8 parasitic elements) with electronically beam-switching capabilities is proposed. Thanks to the superdirectivity principle and the use of a floating ground plane, the proposed closely spaced antenna array achieves a maximum realized gain of 4 dBi steered in 8 directions on the horizontal plane. The proposed antenna operates at 868 MHz with a maximum directivity of 8.5 dBi and achieving a 1-dB directivity bandwidth of 10 MHz. This antenna architecture offers new perspectives for the future wireless communication systems requiring spatial filtering, electromagnetic field exposure and energy consumption reduction, wireless systems cohabitation, and miniaturization.

SCIENTIFIC COLLABORATIONS: Kompai Robotics

Context and Challenges

Generalization of compact and smart connected objects in a specific context of IoT generates a need of increasingly small and performing antennas. Antenna miniaturization becomes a real challenge in UHF frequency band as the wavelength are wide at those frequencies (tens of centimeters). Antenna miniaturization to fit the compact smart objects should reduce the performances of the system following electrically small antennas fundamental laws. ESPAR antennas are classically used to achieve a directive and switchable radiation pattern on the antenna horizontal plane. Using monopolar-type radiating elements on a ground plane is useful to connect the electronic beam steering circuits but the maximum gain of the antenna is tilted from the horizontal plane due to the finite size of the ground plane. A classical technique to reduce this tilt is to add a $\frac{\lambda_0}{4}$ squirt to the ground plane at the cost of a significant increase of the antenna thickness.

Main Results

The proposed architecture is based on superdirectivity principle which consists in the use of strong coupled antennas in order to achieve a small antenna array with high directive radiation pattern [1]. Typically, the procedure detailed in [2] is used to optimize the designed compact parasitic antenna array and to calculate the complex excitation required to maximize the end-fire directivity. This method requires balanced antennas with a perfect control of their radiating modes. An electrically small symmetrical dipolar wire-plate antenna has been designed at 868 MHz as the elementary source of the array and its radiofrequency performances have been characterized.

A floating ground plane, which is decoupled at radiofrequency and does not affect the radiation pattern is also introduced to facilitate the integration of the electronic devices required to control the beam-switching. This particular floating behavior is due to the position in the center of the symmetrical compact dipole structure. Typically, the ground plane used in this configuration could be as small as possible without changing the antenna radiation properties as it has no radiofrequency interaction with the antenna. That has a real advantage for antenna miniaturization compared to the classical ESPAR antennas designed with a $\frac{\lambda_0}{2}$ finite ground plane.

The symmetrical antenna and the floating ground plane has been used to build a small-size circular 9-element array [3] for UHF RFID applications shown in Figure 1-a. Thanks to symmetrical radiating elements design, the antenna system achieves a directive radiation pattern with a maximum directivity and gain in the horizontal plane.

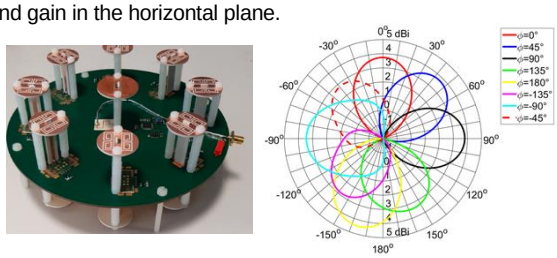


Figure 7: (a) Directive and compact 9-element antenna array (b) Antenna gain steered in the horizontal plane

The antenna located at the center of the array is the only one fed through a balun circuit to ensure the balanced feeding of the symmetrical elementary antenna. The other antennas are parasitic and strongly coupled to the driven element. They are loaded with optimized impedances computed according to superdirectivity optimization method described in [2], in order to achieve a directive beam in the direction of interest. The parasitic antennas are spaced by $\frac{\lambda_0}{5}$ from the central antenna. The array is low profile with a height of 70 mm ($\frac{\lambda_0}{5}$). This height is divided by 2 compared to classical ESPAR antenna in the state of the art. A compromise has been made between radiation performances and electronic circuit complexity and has led to implement a dedicated switching electronic circuit with 4 different states of load connected to each parasitic antenna in order to steer antenna array's radiation pattern in 8 directions of the horizontal plane. As shown in Figure 1-b, the optimized array shows a maximum realized gain of 4 dBi at 868 MHz steered every 45° in 8 directions of the horizontal plane. These performances associated to the small size of the antenna array is relevant considering the current state of the art.

RELATED PUBLICATIONS:

[1] L. Batel, A. Clemente and C. Delaveaud, "Superdirective and Compact Electronically-Beam-Switchable Antenna for Smart Communication Objects," *2019 13th European Conference on Antennas and Propagation (EuCAP)*, Krakow, Poland, 2019, pp. 1-4.

[2] A. Clemente, M. Pigeon, L. Rudant, and C. Delaveaud, "Design of a super directive four-element compact antenna array using spherical wave expansion," IEEE Trans. Antennas Propag., vol. 63, no. 11, pp. 4715–4722, Nov. 2015.

[3] L.Batel,A. Clemente, C. Delaveaud, "Dispositif antennaire compact", FR n°18/57848 ,31/08/2018,

Search of Avalanches Victims with Monopulse Antenna mounted on a small UAV

RESEARCH TOPIC:
Radio link model, monopulse antenna, antenna array, DOA estimation

AUTHORS:
Serge BORIES, Kaoutar ALLABOUCHE, Norbert DANIELE

A complete system is designed to localize the avalanche victims through their smartphone radio transmission. The innovation takes advantage from the speed and medium altitude of a small quadcopter UAV equipped with a monopulse direction finding antenna to assess the direction of arrival (DOA) of radio signals and then to converge above the victim position. A system model is developed to optimize the search strategy duration and to specify both the antenna array features (gain, beam width) and the UAV trajectory strategy. The different hardware components such as the 2 by 2 patch antenna array with circular polarization and the monopulse RF circuit are co-designed. The performance of 2D angular estimations are also analyzed in the CEA-Leti anechoic chamber.

Context and Challenges

The survival rate of an avalanche buried victim is directly related to the quick localization and extrication operations of first responders. The proposed work aims to localize from a small quadcopter UAV, the radio signal transmitted by the skier's smartphone.

Unlike WiFi and cellular standards, the Bluetooth Low Energy (BLE) mode has a low complexity, a low power, and is already in most smartphones which will foster its widespread use. However the main drawback is its limited RF budget link: weak transmitted (Tx) power level (+3 dBm) and poor snow propagation conditions in the 2.4 GHz frequency band compared to sub- GHz cellular band. To reach fine resolution localization, we propose to hybridize a maximum RSSI strategy with DOA estimation.

Main Results

The constrained BLE radio budget link is optimized thanks to a system model described in scenario Fig. 1, in order to assess the accuracy/duration of the localization and to specify hardware components (antenna array, beamforming network, BLE receiver).

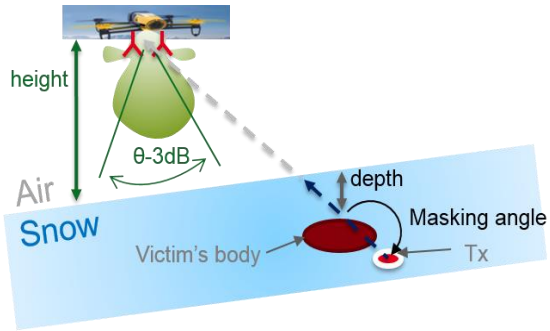
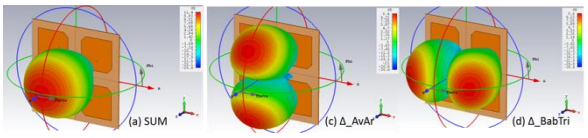


Fig. 9. Avalanche scenario BLE link (buried smartphone in Tx mode and a UAV with monopulse antenna array in Rx)

From four circular polarized patch antennas, the co-designed monopulse RF Beam Forming Network (BFN) circuit realizes three RF outputs. Each synthesizes a different radiation pattern (Sum and Deltas, Fig. 2). The 2D DOA (longitudinal and lateral angles) is estimated from this pattern diversity by the BLE receiver microprocessor through the Delta/Sum RSSIs ratio. The more the UAV trajectory converges towards the Tx nadir, the lower the DOA angular error is (up to 2°).



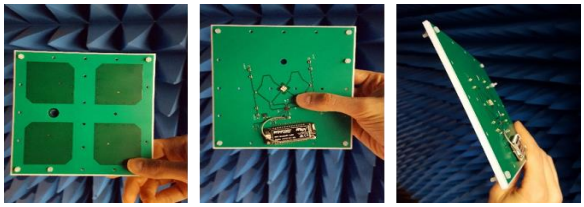


Fig. 10 Co-simulated monopulse "BFN + Antenna array" gain pattern for three modes: Sum (a), longitudinal Delta (c), and lateral Delta (d).

In conclusion, BLE budget link is weak compared to others existing technologies but its advantages in term of battery autonomy and large widespread makes it as a competitive solution. From our system model, the UAV converges at the vertical of the victim in less than 3 minutes to cover an area of 1 hectare.

Perspectives

In the future works, the field test 'winter' campaign will validate the convergence delay, maximum range and positioning accuracy with 1m depth buried BLE transmitter.

RELATED PUBLICATIONS:

[1] S. Bories, K. Allabouche, N. Daniele, "Recent Development on Searh of Avalanches Victims with Monopulse Antenna Mounted on a Small UAV," in Proc. 13th European Conf. Antennas Propag. (EuCAP 2019), Krakow, Poland, 2019.

High self-interference mitigation achieved thanks to significant antenna isolation and advanced RF frontend for In-Band Full-Duplex communications

RESEARCH TOPIC:
In-band full duplex, radar, interferences, antennas, dual polarization

AUTHORS:
Camille JOUVAUD, David DASSONVILLE, Patrick ROSSON

The ANR DUPLEX project focuses on the development of an efficient complete In-Band Full Duplex (IBFD) system comprising multistage of signal isolation. Indeed, IBFD devices require at least 100 dB of Isolation between the Rx and the Rx signal. In this perspective, we aimed at CEA-LETI at creating three stages of isolation able to generate a high level Self-Interference (SI) isolation. Stages comprise an antenna presenting an isolation of 47.5 dB between RX and Tx, and an analog and digital cancellers that bring 48.9 dB more cancellation to reach a total 103 dB Self Interference mitigation.

SCIENTIFIC COLLABORATIONS: Thales, LEAT (Cote d'Azur University), Eurecom

Context and Challenges

IBFD consists of simultaneous transmission and reception in the same frequency band. Theoretically, under certain conditions, this allows to increase the capacity of radio links. Nowadays, most communication systems are compliant with Frequency Division Duplexing (FDD) or Time Division Duplexing (TDD). Nevertheless, IBFD has the problem of SI that must be mitigated. To separate the Rx and Tx signals, a high isolation is required between the outcoming and incoming signals [1]. Then, the main challenge consists in reducing the SI. Requirement is about - 100 dB of SI cancellation in small cell scenario.

Main Results

A specific design of antenna is developed [2]. An isolation of 47.5 dB is experimentally obtained between the two cross-polarized ports of a particular patch antenna. Matching of the antenna's reflection parameters to -20 dB and broadside gains of 8 dBi are obtained. This antenna is based on a patch antenna excited by 3 wide slots etched in the ground plane. The reason for this design comes from the need to minimize SI by cancelling surface currents and near field radiations in the symmetric axis of the antenna. Thanks to the symmetry introduced in the antenna, a large part of the currents and near field radiations transmitted by Rx1 and Rx2 are cancelled on Tx (i.e. Figure 1).

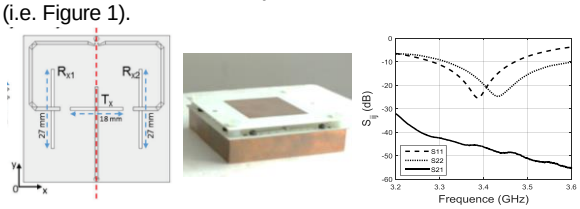


Fig. 1 Description, realized antenna and measured reflexion and isolation coefficients

Moreover, this design allows to obtain the same direction of radiation for Rx and Tx. This ensures that isolation is not partly achieved by different directions of main radiation between Rx and Tx.

Complementary, the Hybrid Self Interference Canceler (HSIC) brings the second stage of cancellation. It reduces the self-interference power and prevents the receiver saturation. After the converter, the Digital Self Interference Canceler (DSIC) improves the cancellation up to the system receiver noise. Thanks to the high isolation obtained by the dual port antenna, the analog cancellation is based only on the HSIC. DSIC will mitigate nonlinear contribution. Figure 3 gives an architecture overview of the completed set-up.

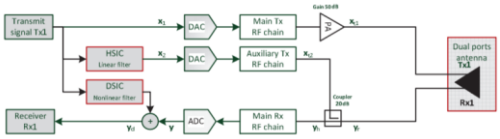


Fig. 2 Global architecture overview

Figure 2 presents the test bench. It allows to evaluate the overall cancellation from the high isolation Tx/Rx antenna, to the analog and the digital cancellers [3].

	Power (dBm)	Cancellation (dB)
Power before Tx antenna	23.0	
Power after Rx antenna	-24.5	47.5
Received Power (HSIC off)	-29.5	6
Received Power (HSIC on)	-68.5	37.4
Power after DSIC	-80	11.5
Total Cancellation		**103**

Table. 1 Transmitted power and SI power in setup

This work shows the experimental self-interference mitigation performed by a dual polarized antenna, a HSIC and a DSIC. Globally, the three techniques reduce by 103 dB the self-interferences over a 20 MHz bandwidth.

Perspectives

Interest in full duplex applications being large, developments of full duplex in high frequency bands (K band- N band) appear to be a strong scientific and technologic interest for our future developments.

RELATED PUBLICATIONS:
[1] S. Bories et al., "Duplexer-less RF Front-end for LTE Pico-Cell using a Dual Polarization Antenna," in 17th European Wireless 2011, 2011, pp. 1–3.
[2] C.Jouvaud et al, "High self-interference mitigation achieved thanks to significant antenna isolation and advanced RF frontend for In-Band Full-Duplex communications" *2019 16th European Radar Conference (EuRAD)*, PARIS, France, 2019, pp. 437-440.
[3] A. Debard et al., "Flexible In-Band Full Duplex Transceivers Based on a Modified MIMO RF Architecture" CrownCom, Grenoble (2016)

On the Non-Stationarity of Device to Device Channels with Dual Mobility in Indoor Environments

RESEARCH TOPIC:
Device-to-Device, propagation, measurement, channel modeling.

AUTHORS:
Gloria MAKHOUL, Raffaele D'ERRICO, Claude OESTGES

In this work we present recent results about the Device-to-Device dynamic channel modeling for indoor environments. Investigations are based on measurements conducted in room-to-room and in room environments at sub-6 GHz bands, resulting in a strong non-stationary behavior depending on the relative distance between terminals and the propagation environment.

SCIENTIFIC COLLABORATIONS: ICTEAM, Université catholique de Louvain, Belgique

Context and Challenges

Device-to-Device (D2D) communication networks have emerged as a powerful 5G solution to enhance the quality of data service with low energy consumption. A particular subset of the D2D networks is the wireless body area networks that typically consist of transceiver nodes placed on or near the human body and encompass a large number of applications, such as cooperative communications, e-health, and entertainment. Understanding the radio channel behavior is critical to develop efficient body-centric communications systems, especially when relay and cooperative techniques are considered to overcome the severity of on-body path-loss and/or body shadowing. In particular, the prediction and modeling of channel dynamics may strongly differ from classical wireless transmissions, especially in the case of body-to-body (B2B) transmissions.

Main Results

In this work, we considered wireless communications between different persons, who may be located in the same room or in neighboring rooms. It is likely that typical body motion and shadowing will induce non-stationary conditions. In [1], the auto-correlation functions (ACFs) of B2B fading channels for different mobility patterns are analytically modeled based on measurements carried out in indoor environment at 2.48 GHz. A general framework for ACF modeling is developed assuming a typical mobile-to-mobile propagation scenario where some local scatterers are moving at random speeds and in random directions. To validate the model, the general framework was applied to the experimental scenarios, i.e. parallel and opposite directions with two moving scatterers (humans). Fig. 1 compares the measured ACFs (|R(Δt)|) and the models showing the significant impact of the mobility patterns on the ACF.

In [2], two metrics, i.e. Kolmogorov-Smirnov test and collinearity test, were used to quantify the non-stationary aspect of the small-scale fading. Accordingly, a stationary behavior in large sense was seen for non-line-of-sight (NLoS) scenarios, probably due the large effect of the multipath components presented in such an environment and the less impact of the coherent component. For the LoS scenario, the small-scale fading distribution depends on Tx-Rx distance and the Doppler spectrum has a time variation aspect and in particular in the

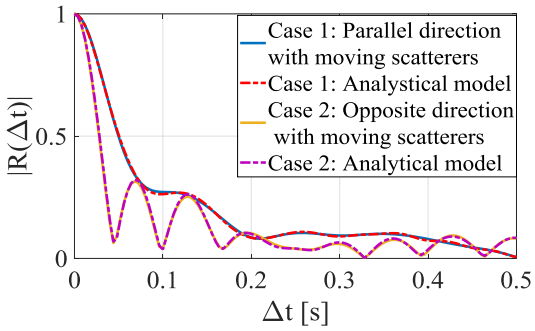


Figure 1: ACF modeling of B2B scenarios

opposite direction (cf. Fig. 2). This can simply be related to the rapid variation of the Tx-Rx distance resulting in the rapid variation of the coherent power.

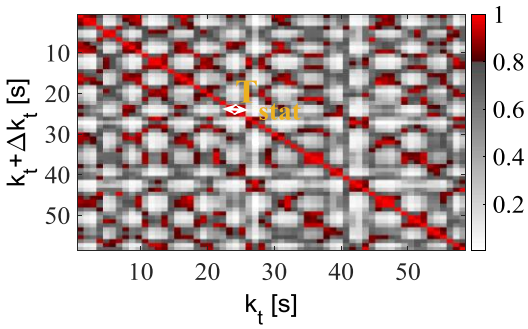


Figure 11: Example of B2B stationarity results (kt is the index in time of a measured block).

Perspectives

The non-stationnary model here proposed allow a precise description of channel characteristics for D2D communication.

This work was partially funded by ANR project MoReOVer.

RELATED PUBLICATIONS:
[1] G. Makhoul, R. D'Errico and C. Oestges, "On the Non-Stationarity of Device to Device Channels with Dual Mobility in Indoor Environment," 2019 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting, Atlanta, GA, USA, 2019, pp. 2073-2074.
[2] C. Oestges, G. Makhoul, R. D'Errico and E. Vinogradov, "Channel Dynamics in Mobile-to-Mobile Communications: Recent Results and Challenges," 2019 International Symposium on Antennas and Propagation (ISAP), Xi'an, China, 2019, pp. 1-3.

A Radio channel model for industrial scenarios

RESEARCH TOPIC:
5G networks, Propagation, Radio Channel, Industrial IOT

AUTHORS:
Raffaele D'ERRICO, Jessen NARRAINEN, Gloria MAKHOUL

This work presents the channel modeling activity for Industrial Internet of Things (IIOT) applications, in the framework of 5G networks. A MIMO measurement campaign was carried out in an industrial environment for a band covering from 2 GHz to 6 GHz. Different environment conditions were considered, i.e. line-of-sight (LOS), obstructed-line-of-sight (OLOS) and non-line-of-sight (NLOS) conditions. The measurements were exploited to propose a statistical channel model for industrial environments that was promoted to the standardization.

Context and Challenges

A novel industrial revolution, known as Industry 4.0, has developed in the recent years. It groups different technologies and concepts, e.g. Cyber-Physical Systems (CPS), the Internet of Things (IoT) and the Internet of Services (IoS). In the context of the Smart Factory, CPS communicate and cooperate with each other and with humans in real time through wireless communications. The exact knowledge of the radio channel is indispensable to determine the reliability and the performance limits of such links. Note that the industrial-like environments can be thought to be harsh/severe in the point of view of electromagnetic wave propagation. It is evident that the physical characteristics of a factory site will lead to more complex propagation phenomena that can be source of degradation for the system's reliability.

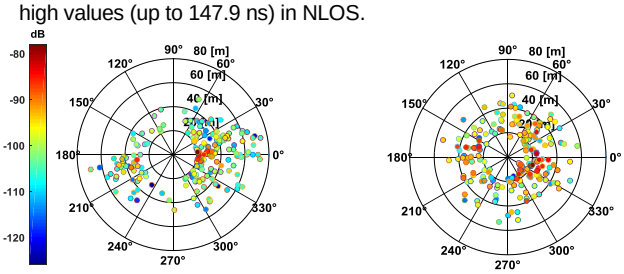
This work has been funded by the French National Agency for Research (ANR) under the project named MoReOVer.

(a) (b)

Fig. 1: Radio channel measurements in industrial scenarios

Main Results

Extensive radio channel measurements were carried out in a machinery room in CEA-Leti in order to characterize and model the radio channel in an electromagnetically dense and harsh scenarios. Three environment conditions were investigated, i.e. LOS, OLOS and NLOS. At a first step, a SAGE algorithm was employed in order to extract the parameters of the channel multi-path components (MPCs), i.e. amplitude, delay and Angle of Arrival (AoA). The characterization of the path loss, delay and angular spreads were presented in [1]. The delay spread varies between 24.1 ns and 59.4 ns in LOS, while it could reach high values (up to 147.9 ns) in NLOS.



(a) (b)

Fig. 2: Example of multipath (amplitude, angle and distance) for (a) LOS and (b) NLOS conditions

In both LOS and NLOS conditions this channel are quite rich in terms of multipath (see Fig. 2). The K-mean algorithm was then applied in order to group the MPCs into clusters. The intra- and inter-clusters characteristics, i.e. the decay constant and the inter-arrival rate, were then presented for a given environment. It was found that the arrival time of clusters and rays can be modeled using a Poisson distribution [2]. We show that overlapping of the clusters in the delay domain can be observed in industrial scenario. A first analysis of dense components was provided. A single slope model was used for the residual power delay profile, and the reverberation time was estimated in the different scenarios [3]. This work was promoted to COST IRACON action [3], and contributed to the 3GPP Special Interest Group on IIOT channel model. This activity resulted in seven official contributions to 3GPP standardization (TDoC) and the addition (adding) of a new channel model for these applications [4].

Perspectives

The model here introduced will be a unique tool for the design

RELATED PUBLICATIONS:

[1] J. Narrainen, R. D'Errico, "Large scale channel parameters in industrial environment", accepted to 13th European Conference on Antennas and Propagation (EUCAP), pp. 1-5, 2019.

[2] J. Narrainen, G. Makhoul and R. D'Errico, "Inter- and Intra-Cluster Characteristics of MIMO Industrial Channels," 2019 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting, Atlanta, GA, USA, 2019, pp. 2113-2114.

[3] R. D'Errico "Cluster Characteristics and Dense Components in Industrial Environments" CA15104 TD(19)11026 Gdansk, Poland September 4-6, 2019.

[4] 3GPPP R1-1909807 "Addition of indoor industrial channel model", Ericsson, NTT DOCOMO, Nokia, CEA-LETI, Fraunhofer HHI, Fraunhofer IIS. RAN WG1 Meeting #98.

Wideband Measurement-Based Vehicle-to-Pedestrian Channel Models

RESEARCH TOPIC:
Device-to-Device, Vehicular communication, stationarity, propagation, measurement, channel modeling.

AUTHORS:
Gloria MAKHOUL, Raffaele D'ERRICO, Claude OESTGES

Vehicle-to-pedestrian (V2P) channel model is proposed based on measurement campaign carried out at 3.8 GHz. Several propagation conditions and different mobility patterns were investigated. The model consists of two components, i.e. the first path component and the secondary multi-path components (MPCs). These components were detected via a detection and tracking algorithms. It was found that the time variant contributions of each detected path can be modeled as a combination of path loss (PL), large- and small-scale fading.

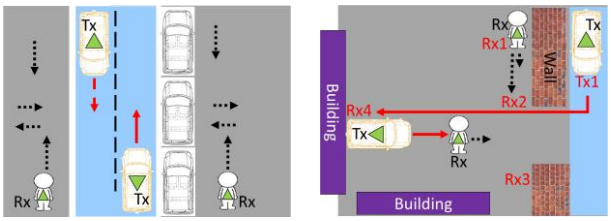
SCIENTIFIC COLLABORATIONS: ICTEAM, Université catholique de Louvain, Belgique

Context and Challenges

Vehicle-to-Everything (V2X) communication is a fast growing 5G technology that has the potential to enhance road safety. Multiple communication protocols, e.g. IEEE 802.11p, 3GPP, LTE etc., were shaped to be the basic standards of intelligent transportation systems (ITS). However, the inherent dual mobility generates non-stationarity properties of the propagation channel, implying that accurate dynamic models are required for system design and communication network simulation.

Main Results

The limited modeling of vehicle-to-pedestrian (V2P) channels motivate the realization of V2P measurements using a channel sounder. The center frequency and the bandwidth were set to 3.8 GHz and 200 MHz, respectively. The Tx dipole antenna was mounted on a car roof and the Rx dipole antenna was carried by a pedestrian. The experimental environments include a two-lane avenue and a courtyard entrance; with the pedestrian on the sidewalk or entering the yard (cf. Fig. 1). The vehicle speed was around 30 km/h and the V2P distance varied from of 2 m to 40 m depending on the scenario.



(a) (b)

Figure 12: V2P measurements: a) LoS and partial LoS scenarios b) NLoS/LoS scenarios.

The time varying channel impulse response can be divided into two major components: first path component, which mainly consists of the line-of-sight (LoS) and ground reflection paths, and the secondary multipath components (MPCs) arising from specular reflection of scatterers. A detection and tracking algorithms were implemented in order to track the first path component and the discrete scatterer MPCs over time. They are best fitted with a combination of path loss (PL), large-scale and small-scale fading. The latter was described with a Rice distribution while the large-scale fading was characterized in dB by a normal distribution. The PL of MPCs was described with log-distance model and a PL model for the first path component is given depending on the scenario. Therefore, a two rays model and a log-distance model were used to depict the PL of the first path component in LoS and partial LoS scenarios, respectively. In the NLoS/LoS scenarios, a model based on three equations was proposed in order to present the LoS, NLoS and the partial NLoS regions (cf. Fig. 2). Note that the non-stationary channel behavior is also formed considering the dynamic change of scatterers around the moving terminal.

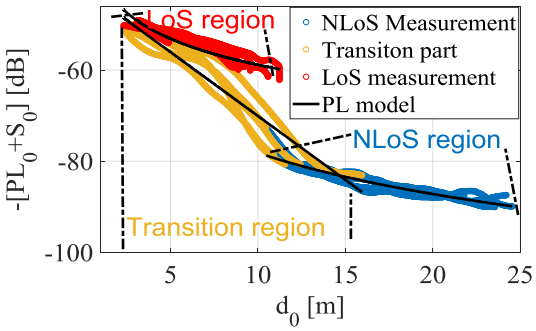


Figure 11: PL model model of NLoS/LoS scenario.

Perspectives

The V2P channel model proposed will enable 5G and beyond system design for safety road applications.

This work was partially funded by ANR project MoReOVer.

RELATED PUBLICATIONS:

[1] G. Makhoul, R. D'Errico and C. Oestges, "Wideband Measurement-Based Vehicle-to-Pedestrian Channel Models," in IEEE Transactions on Vehicular Technology, vol. 68, no. 10, pp. 9339-9347, Oct. 2019

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04 HIGH SPEED CONNECTIVITY SYSTEMS & ARCHITECTURES

- 5G, Beyond-5G, 6G
- mmWave, sub-THz
- Mobile edge computing & caching
- Machine learning
- Quantum coding

Phase Noise Models for Sub-THz Communications

RESEARCH TOPIC:
Beyond 5G networks, Millimeter-wave communications, Physical layer, Phase noise

AUTHORS:
Simon BICAÏS, Jean-Baptiste DORE

To face the exponential data traffic growth, the sub-THz spectrum (100-300 GHz) is envisioned for wireless communications. However, sub-THz systems are critically impacted by the strong phase noise of high frequency oscillators. This work discusses the appropriate choice of phase noise model for sub-THz communications. Two phase noise models are introduced and compared: one correlated, accurate but complex, and another uncorrelated, analytically simpler. The expression of the likelihood ratio allows us to propose an analytical condition to select the best of the two models for a measured oscillator spectral characteristic. Numerical simulations are performed with realistic phase noise generated according to a state-of-the-art sub-THz oscillator and show that an uncorrelated Gaussian process is appropriate to model the impact of phase noise in sub-THz systems.

Context and Challenges

With a specific demand for wireless connectivity, the current exponential data traffic growth will lead to a 100+ Gbit/s requirement within few years. To meet this demand, the large bands available in the sub-THz spectrum are studied for wireless communications. To reach 100+ Gbit/s data rates, classical coherent architectures are combined with high spectral efficiency schemes. This entails numerous constraints on the design of radio-frequency components especially at the oscillator level. Indeed, high frequency oscillators severely impair sub-THz systems with Phase Noise (PN). It is hence essential to discuss the PN model selection to design dedicated signal processing and thus performant schemes.

Main Results

A wide range of PN models have been introduced in the literature: Non-linear, Tikhonov, Wiener models to name a few. The selection of the PN model is application-dependent. For millimeter-wave systems, the PN is usually modeled by the superposition of a correlated contribution (colored PN) and an uncorrelated one (white PN floor). However, sub-THz systems exploit wider bands and thus require to reconsider the PN model. It has been shown in that performance of wide-band systems are significantly more impacted by the uncorrelated contribution of PN than the correlated one. This result prompts us to compare the efficiency of an uncorrelated Gaussian PN model to the common correlated one used for millimeter-wave, superposition of Wiener PN and Gaussian PN.

In this work, we provide analytical tools for sub-THz communication design and circuit specifications. Though the results of the paper are presented within the context of sub-THz communication, the analysis remain true for other scenarios such as next generation of millimeter-wave communications.

Two PN models are introduced and compared: one correlated, accurate but complex, and another uncorrelated, analytically simpler as depicted in Fig 1. The correlated model is based on the physical modeling of the PN generation in oscillators and is frequently used for millimeter-wave systems. It describes the superposition of a correlated contribution (colored PN) and an uncorrelated one (white PN floor). The uncorrelated model describing only the white PN floor, its mathematical expression is hence simple and commonly exploited to optimize the signal processing for PN channels.

Firstly, we assess the accuracy of the uncorrelated Gaussian PN model with a Pearson's chi-squared goodness of fit test. Simulations have been performed considering realistic PN corresponding to a state-of-the-art 200 GHz oscillator. We demonstrate that the Gaussian PN model is accurate when the oscillator corner frequency remains small compared to the system bandwidth [1].

Secondly, the closed-form expression of the likelihood-ratio of the two models are proposed. Thereupon, an analytical condition is proposed to determine whether the correlated or the uncorrelated model is the most efficient given a system bandwidth and an oscillator spectral characterization.

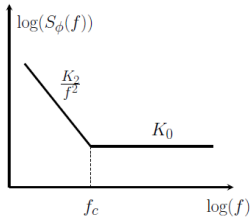

Fig. 1: PN model considered within this work.

Numerical simulations have been performed with realistic PN generated according to a state-of-the-art sub-THz oscillator. Simulation results show that an uncorrelated Gaussian process is appropriate to model the impact of PN in sub-THz systems

Nemo enim ipsam voluptatem, quia voluptas sit, aspernatur aut odit aut fgit, sed quia consequuntur magni dolores eos, qui ratione voluptatem sequi nesciunt, neque porro quisquam

Perspectives

The proposed results on model selection can be applied to link adaptation in the presence of PN. Upon the analysis of the bit error rate of phase modulated signals, we are able to choose the most robust scheme between a coherent and a differential modulation as well as the most appropriate modulation and coding scheme. It gives a new degree of freedom to consider to pave the way of broadband communication in sub-THZ bands.

RELATED PUBLICATIONS:

[1] Simon Bicaïs and Jean-Baptiste Doré. Phase Noise Model Selection for Sub-THz Communications. IEEE Global Communications Conference 2019, Dec 2019

An Algebraic Framework for Digital Envelope Modulation

RESEARCH TOPIC:
Beyond 5G networks, Millimeter-wave communications, Physical layer, Envelope detectors

AUTHORS:
Simon BICAÏS, Jean-Baptiste DORE

Sub-THz communications based on coherent receivers suffer from strong phase impairments issued by oscillators. Envelope detection, inherently robust to this impairment, is hence considered for the design of sub-THz systems. This work proposes an algebraic framework for envelope modulation. In the first place, we introduce a Hilbert space to represent waveforms with non-negative real values. Then, it is shown that the proposed framework provides powerful tools to design new envelope modulation schemes. To do so, we present the transmission of an In-phase Quadrature signal upon an envelope modulation to prevent the impact of phase noise on communication performance. We also demonstrate that constraints on embedded analog-to-digital converters can be relaxed with the use of orthogonal non-negative waveforms

Context and Challenges

Wireless communications within the sub-THz spectrum (100-300 GHz) are contemplated to face the exponential data traffic growth. The sub-THz spectrum offers unprecedentedly large bands, but it comes with severe radio-frequency impairments that must be mitigated. In particular, sub-THz communications suffer from strong phase impairments issued by oscillators like phase noise or carrier frequency offset. Research projects have either addressed compensation of phase impairments or signal processing optimization to enable the development of coherent sub-THz systems. In contrast, non-coherent schemes have long been exploited: they achieve robustness with low complexity. Indeed, envelope detection is inherently robust to phase impairments. It is hence a valuable scheme to perform frequency translation within sub-THz receivers. Subsequently, it is relevant to consider the design of sub-THz communications systems based on envelope modulation and detection.

Main Results

In this work, we propose an algebraic framework for envelope modulation that could enable the design of new envelope modulation schemes adapted to sub-THz communications as depicted in Fig 1. First, a Hilbert space is introduced to represent waveforms with non-negative real values (see Fig 2). Hilbert spaces provide an efficient framework for the development of communication systems. This enables to redefine fundamental properties and operators for non-negative signals: orthogonality, projection, etc. Nonetheless, we also desire to exploit existing schemes developed for real signals. Therefore, the introduced Hilbert space is defined by transport of structure of signal-space L^2 - the commonly used Hilbert space of square-integrable real-valued functions. Accordingly, any orthonormal sequence in L^2 can be exploited upon envelope modulation with an appropriate transport of structure. This result entails that new orthogonal code modulation or multiplexing schemes can be designed with non-negative waveforms.

Second, we show that the proposed framework provides efficient tools to design envelope modulation schemes. We hence study the transmission of an In-phase Quadrature (IQ) signal upon an envelope modulation to prevent the impact of phase noise on communication performance. The impact of phase noise on a coherent transmission has been largely investigated in the literature. It has been shown that phase noise greatly impact of the performance with an increase of the error floor. In contrast, the presented transmission of an IQ signal over envelope modulation may achieve any targeted BER though it entails some performance loss in terms of SNR [1]. Therefore, in comparison to a communication system impacted by phase noise, this scheme appears to be relevant for sub-THz applications.

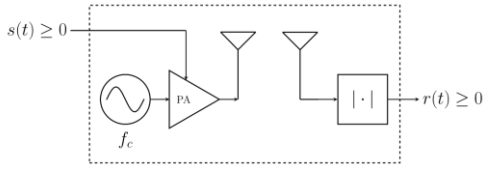

Fig. 1: Frequency translation with envelope modulation and detection.

Further, it is demonstrated that constraints on embedded Analog-to-Digital Converters (ADC) may be relaxed with the use of orthogonal non-negative waveforms.

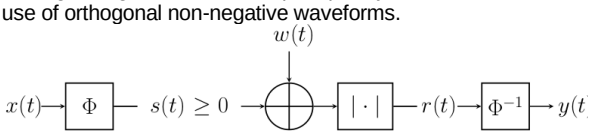

Fig. 2: Illustration of the non-negative channel.

Perspectives

One of the possible applications of sub-THz communications is the so-called "kiosk" scenario: A short-range hot-spot supplies users with downlink very high data-rates. Receivers' architectures must remain simple in order to be embedded into users' terminals. Even if low complexity schemes are implemented, e.g. OOK, it is difficult for embedded ADC to sample several GHz of band. Our objective is therefore to relax the constraints on ADC. We show that the sampling rate of ADC can be made twice slower by multiplexing symbols on two orthogonal non-negative waveforms.

RELATED PUBLICATIONS:

[1] Simon Bicaïs and Jean-Baptiste Doré. An Algebraic Framework for Digital Envelope Modulation," 27th European Signal Processing Conference (EUSIPCO), 2019.

Air Interface Challenges and Solutions for future 6G

RESEARCH TOPIC:
Next wireless technologies, beyond 5G, 6G

AUTHORS:
Jean-Baptiste DORE, Emilio CALVANESE STRINATI, Benoit MISCOPEIN, Dimitri KTENAS

5G networks are expected to be deployed in 2020 and are considered as a global game changer from a technological, economic, societal and environmental perspective. In our vision, the next generation of wireless systems will transform the 5G service-oriented networks into user and machine ad-hoc dynamic (re)configuration of network slices. This will be enabled by software-defined end-to-end solutions from the core to the radio access network, including the air interface as well as the RF and antenna systems which are envisioned as one of the keys to meet the user/service requirements. Users and machines will be indeed able to dynamically configure network slices thanks to intelligent personal edges. This work presents our perspective of the 6G air interface and raises the concept of software defined artificial intelligence and air interface (SD-AI²) as a framework of 6G air interface.

Context and Challenges
From an air-interface perspective, the 3GPP fifth Generation New Radio (5G-NR) standard proposes to adapt the air interface configuration to the provided service and carrier frequency. By doing so, the requirements for each service can be satisfied. However the air interface is usually statically configured after field trials run by operators before commercial deployments. Moreover, it has been demonstrated that the coexistence of different air interface configurations within the same spectrum chunk can be ensured only with a huge compromise in terms of spectral efficiency. On the other hand, the concept of network slicing is expected to play a critical role in 5G networks because of the very wide gamut of expected use cases and new services. Slicing is currently foreseen as a service-level; extending this concept down to the physical layer remains an open question.

Main Results
To address these challenges, we propose the concept of *software defined artificial intelligence and air interface* (SD-AI²) [1] as the framework of the beyond 5G air interface (see Fig 1). This concept provides a scalable and configurable mechanism to customize the air interface design and to support user-centric services based on the potential of latest artificial intelligence (AI) breakthroughs. The development of software-defined radio techniques offers opportunities for the implementation of smart, flexible and configurable air interface. The main evolution of the proposed concept is the possibility to dynamically adapt the waveform, the link adaption strategies, channel and bandwidth based on the context of a user (geographical position, motion, services, etc.). Many challenges have to be addressed. First, the design of an efficient waveform supporting the multiplexing of various waveform types with a limited self interference generation needs to be considered. Therefore, one can envisaged to dynamically change the structure of the waveform according to the channel conditions. Secondly, the use of the spatial filtering by configurable antenna radiation patterns is also an efficient manner to limit the mixed numerology interference by isolating numerologies in different radiation beams. At high frequency, antenna integration allows efficient multi-user beamforming schemes, but when it comes to sub 6-GHz bands, the design and integration of small and energy efficient antenna systems remains an open challenge. Current works are focusing on hybrid beamforming schemes which reduce the cost and power consumption but require complex optimization problem to solve.

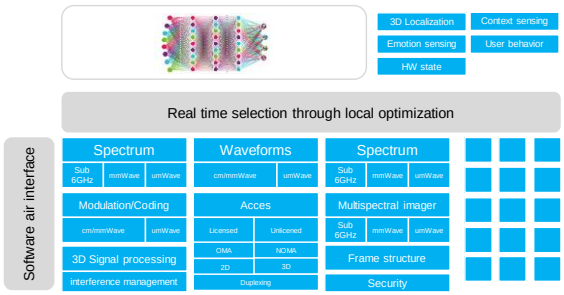

Fig. 1: Principle of the proposed SD-AI² framework.

With the growing interest of artificial intelligence (AI) technologies in image and signal processing, the introduction of AI technologies into wireless communication systems could introduce a new paradigm in the design of modern wireless system. Currently, many researches are focused on the use of neural networks for solving difficult problems, such resource allocation optimization in wireless communication systems. In the framework of our proposed SD-AI², it could be considered to collect and analyze channel state information (CSI) as well as localization context (including RSSI, GNNS signal etc.) with a learning network to classify and select the best set of parameters to exchange data, including channel, frequency and spatial resources to be used as well as numerology and modulation and coding scheme..

Perspectives
The next generation of wireless systems will transform the 5G service-oriented networks into user and machine ad-hoc dynamic configuration of network slices. This will be enabled by software-defined end-to-end solutions from the core to the radio access network, including the air interface as well as the RF and antenna systems. Our current researches are focusing on how the use of modern IA concepts could help in the design and optimization of future wireless system both at PHY and MAC layers.

RELATED PUBLICATIONS:
[1] JB Doré, E Calvanese Strinati, B Miscopein, D Kténas, Sergio Barbarossa, "*Air Interface Challenges and Solutions for future 6G Networks*", 6G wireless summit, 2019.

Study of OFDM Precoded Filter-Bank Waveforms

RESEARCH TOPIC:
5G New Radio, Beyond 5G, PHY-layer, waveform design

AUTHORS:
David DEMMER, Jean-Baptiste DORE

Forthcoming Beyond-5G wireless networks will have to cope with heterogeneous and dense traffic patterns. High demands in terms of bandwidth use efficiency and increased flexibility are therefore required for the related air-interface technology. In this context, Filter-Bank MultiCarrier (FBMC) waveforms have been recognized as an enabling technology. However, the orthogonality property of FBMC waveforms is reduced to the complex real field. FBMC waveforms are then not compatible with all the 5G known-how techniques like MIMO, which prevents them to be considered as an practical alternative to OFDM. That is why we propose a novel precoding method for FBMC waveforms so as to jointly ensure a plain complex orthogonality and a strong user isolation by benefiting from the sharp spectrum confinement of filter-banks.

SCIENTIFIC COLLABORATION: CNAM Paris, University Rennes 1

Context and Challenges

To cope with the heterogeneous quality of services in Beyond-5G networks, enhanced isolation of user traffic must be provided. In this context, FBMC waveforms are highly appealing thanks to the strong spectrum confinement they provide. However, the limitation of the orthogonality to the complex real field limits the reuse of 5G know-how techniques like MIMO. To cope with these limitations, we propose a novel OFDM precoding scheme which restores the complex orthogonality of FBMC waveforms. In this paper, the complete system model of the waveform is derived and the performance gain for several key indicators of interest is evaluated.

Two waveforms, namely Fast-Fourier-Transform FBMC (FFT-FBMC) and Block-Filtered OFDM (BF-OFDM), relying on the proposed precoding scheme are studied in depth in this paper. Albeit being very similar, the major difference between these two proposals lies on the receiver scheme. Indeed, while FFT-FBMC performs the matched processing at the receiver side (i.e. demodulation by a filter-bank and OFDM decoding), the BF-OFDM receiver is designed to only perform a transposition in frequency without any filtering stage (i.e. demodulation by FFT), hence being reduced to a simple FFT processing block like in plain Cyclic-Prefix (CP) OFDM.

Main Results

In this work, a generalized system model for the filter-banks is preferred with respect to the conventional FBMC model. The parametrization of the waveforms becomes more flexible in this framework. The resulting system model is derived and the practical configurations of each waveforms (cyclic prefix length, allocated subcarriers,…) which ensure the complex orthogonality are defined as well.

The two waveforms are then parametrized to be compliant with 5G standard (sampling frequency, symbol density, subcarrier spacing …). The best configuration is determined by considering both the quality of the orthogonality property and the complexity of the whole scheme. Resulting parametrizations are then compared to CP-OFDM and conventional FBMC.

As shown in Figure 13, the studied waveforms exhibit a more confined spectrum with respect to CP-OFDM but emit more out-of-band emissions that conventional FBMC waveform (consequences of the Balian-Low theorem). It leads to an improved user isolation in the frequency domain than 5G-NR, based on CP-OFDM. The two proposed solutions are therefore appealing for multiplexing non-orthogonal traffics such as the 5G different services. In addition to that, BF-OFDM ensures a straightforward deployment because a standard 5G-NR receiver can properly demodulates the BF-OFDM signal without any modification.

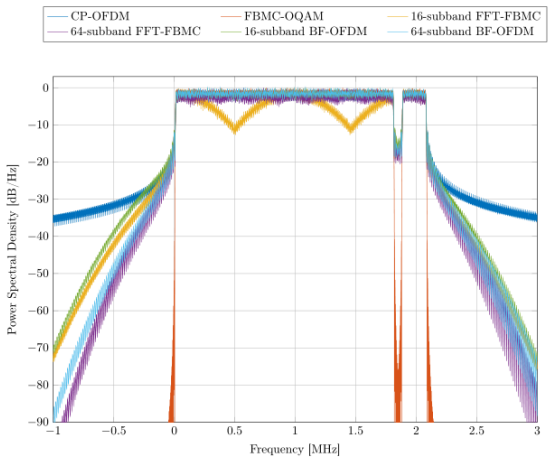

Figure 13: Comparison of the spectrum confinement

Perspectives

The proposed study focuses on the complex orthogonality property and shows that it can be ensured for a FBMC waveform. Nonetheless, the complexity of the proposed precoding scheme prevents from an efficient implementation. Besides, the proposed design method of the prototype filter limits the obtained performance. Consequently, lowering the complexity of the precoding and designing a filter-bank prototype filter with side lobe rejection may be interesting for further studies.

RELATED PUBLICATIONS:
[1] D. Demmer, R. Zakaria, R. Gerzaguet, J. Doré and D. Le Ruyet, "Study of OFDM Precoded Filter-Bank Waveforms," in *IEEE Transactions on Wireless Communications*, vol. 18, no. 6, pp. 2889-2902, June 2019.

Hybrid Beamforming in the Presence of Bockers

RESEARCH TOPIC:
Next wireless technologies, beyond 5G

AUTHORS:
Mohamed Reda. BEKKAR, Benoit MISCOPEIN, Serge BORIES

Densification of mobile networks using small cells is a promising approach to achieve the forecasted 1000x growth in capacity for 5G systems. However, a major impediment of dense networks is the low signal-to-interference-plus-noise ratio (SINR) regime, notably in uncoordinated time-division duplexing (TDD) systems in sub-6GHz bands. To tackle this issue, hybrid beamforming solutions involving both analog and digital stages are necessary. In such architectures, RF circuitry could be further simplified by the use of phase-shifters in the analog stage. However, this would be at the cost of making the SINR optimization problem non-convex. In this paper, we propose a relaxation approach to phase-only beamforming which allows for a straightforward solution using off-the-shelf interior point algorithms. We show by means of simulations that this approach provides promising results.

Context and Challenges

A consensus has emerged in the scientific and industrial community that 5G networks will be able to meet the demand for improved capacity by playing on at least three levels: the use of more spectrally efficient waveforms, the exploitation of new spectrum bands, and a densification of the network through the deployment of "small cells". The main challenge in such dense networks is the management of the high interference which arises because small cells and macro cells share the same spectral resources. More specifically, this work assumes the uncoordinated deployment of small cells operating in TDD (Time Division Duplex) mode, where a small cell in reception may be interfered by a transmitting neighboring small cell, resulting in a particularly high signal-to-noise and interference ratio (SINR). An effective way to manage this interference is spatial filtering using beamforming. In this work, we focused on hybrid beamforming, where the analogue part is composed of RF phase shifters only, as shown in Fig. 1.

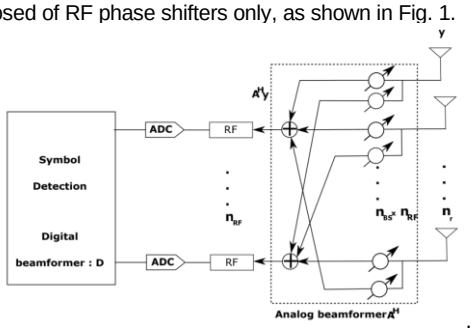

Figure 1: Hybrid beamforming architecture

Main Results

This contribution addresses the problem of hybrid beamforming by maximizing the received SINR with phase constraints only in a multi-user uplink scenario. The choice to having only phase-shifters in the analog stage makes the SINR maximization problem non-convex. This led us to use a so-called "relaxation" approach, allowing to formulate the problem in a much simpler way and solve it with a semi-defined programming method. The algorithm, called SDR, has been compared to algorithms in the literature, including the optimal Capon algorithm in digital and hybrid versions and a local convergence algorithm found in the literature and denoted "Zhang" in Fig.2. The comparison is made in terms of sum-capacity, which takes into account an analytical model of the analog-to-digital converter. The performance is shown in Fig.2, as a function of the power of the blocker relative to the wanted signal. These curves are plotted for 2 values of the number of bits of the converters: 4 and 8 bits.

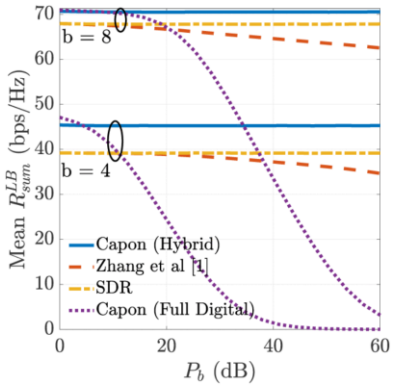

Figure 2: Sum capacity simulation results

Fig. 2 shows first the contribution of the hybrid approach, as full-digital solution collapses at blocker power regimes, due to the saturation of the converters. Also, the hybrid Capon and the SDR algorithm do not depend on the power of the blocker thanks to the perfect spatial filtering in the radiation diagram. The acceptable loss between the two is due to the fact that using phase shifters only does not allow to apodise the radiation pattern and therefore mitigate grating lobes. In comparison, the local convergence algorithm implies imperfect zero alignment and therefore sensitivity to high power blockers.

Perspectives

Further work will focus on studying the complexity of the algorithm in the perspective of its implementation on a

RELATED PUBLICATIONS:
[1] M. R. Bekkar, C. Siclet, L. Ros, B. Miscopein and S. Bories, "On the use of semidefinite relaxation for uplink phase-only hybrid beamforming with blockers," 2019 IEEE Wireless Communications and Networking Conference Workshop (WCNCW), 2019, pp. 1-6.
[2] M. R. Bekkar, C. Siclet, L. Ros, B. Miscopein and S. Bories, "Sur l'utilisation de la relaxation semidéfinie en lien montant pour la formation de voies hybride avec bloqueurs", Colloque GRETSI 2019, Août 2019, Lille.

Network Energy Efficient Mobile Edge Computing with Reliability Guarantees

RESEARCH TOPIC:
5G and beyond, edge cloud networks, energy efficiency, computation offloading

AUTHORS:
Nicola DI PIETRO, Emilio CALVANESE STRINATI

This work proposes a novel algorithmic solution for *dynamic computation offloading*, aimed at reducing the energy consumption of a mobile network endowed with multi-access edge computing. The dynamic evolution of the system is modeled here through three queues: a local queue of data to be offloaded by the user, a computation queue at the edge server, and a queue of results at the network's access point. The optimization problem is cast as the *minimization of the long-term average energy consumption* of the system, comprising users, servers, and access points. Quality of service constraints are imposed in terms of probability that the *sum of the queues* exceeds a given threshold. Via stochastic optimization tools, the problem is solved through a dynamic optimization algorithm, which does not assume any knowledge on the task input and output random sizes and the radio channel statistics.

SCIENTIFIC COLLABORATIONS: Mattia Merluzzi, Paolo Di Lorenzo, Sergio Barbarossa ("La Sapienza" University, Rome, Italy)

Context and Challenges

Mobile networks are facing a drastic evolution with the advent of 5G technologies. A key 5G enabler are small cells, whose deployment increases the capacity of mobile systems, but also implies a higher energy consumption at the network Access Points' (APs) sites. A solution to save energy is to use a sleep operation mode whenever the AP is not receiving or transmitting, an idea known as Discontinuous Transmission (DTX). Moreover, 5G systems are developed to enable new delay-critical services, which require storage and computation resources very close to end users. In this direction, Multi-access Edge Computing (MEC) is a key technology enabler, bringing cloud functionalities at the network's edge. However, MEC network architecture requires the energy-demanding presence of Mobile Edge Hosts (MEHs). In such a context, the overall energy consumption of 5G edge cloud networks depends on both APs and MEHs. Radio and computation aspects must be jointly orchestrated to improve the overall *energy efficiency* while guaranteeing the strict 5G requirements. In this work, we focus on energy saving in the framework of *computation offloading* services, through which computationally intensive applications are offloaded from mobile devices to MEHs. In this way, resource-constrained devices have sophisticated programs run on their behalf within strict latency constraints and with reduced energy consumption.

Main Results

The novelty of the present contribution is to consider a mixed user- and network-centric strategy for dynamic computation offloading with *reliability guarantees* on the service delay, based on *joint AP and MEH sleep control*. Our strategy also optimizes the radio and computing resource allocation with the ultimate goal of minimizing the long-term average energy consumption of the network, comprising contributions from the UEs, an AP and a MEH. We model the system evolution (arrival of data to offload and to treat at the MEH) with queues at the UEs', AP's, and MEH's sides. Moreover, we impose a reliability constraint on the service outage probability, meant as the probability that the sum of the queue lengths exceeds a predefined threshold. We also allow both the AP and the MEH to switch into sleep state in order to reduce their power consumption, whenever possible.

More details about our system model and the formalization of the related optimization problem are available in [1]. Hinging on stochastic optimization tools, we find therein *the optimal solution* to our complex dynamic long-term problem, through an algorithm that solves in real time a simpler deterministic convex problem. This makes it applicable to realistic implementations. Moreover, our algorithm does not need prior knowledge neither on the input and output sizes of the offloaded computational tasks nor on the wireless channel statistics.

The advantages of the proposed method for energy-efficient dynamic computation offloading over MEC networks are illustrated by the results of our numerical simulations [1], summarized in the table below for a scenario with 5 UEs:

Sleep time (AP)	Sleep time (MEH)	Overall network's energy reduction	UEs' transmit energy reduction
80.24%	80.24%	25.13%	99.27%

In particular, our offloading scheme requires the AP and the MEH to be active (in alternating time slots) for less than 20% of the overall network operation time, still guaranteeing the reliability requirements imposed by the UEs. This allows an overall energy reduction of more than 25% compared to an optimal resource allocation strategy devoid of sleep mode control. Finally, it is crucial to note that the optimization of the radio transmission power at the UE's side, integrated in our optimization strategy, yields great energy gains for UEs (a reduction of a factor ~100 of the radio transmission energy).

Perspectives

Future work will extend the proposed method to more complex network topologies, including more APs and MEHs. Moreover, sleep mode can be quite straightforwardly included in the UEs' architecture too, thus adding a further degree of freedom for the research of an improved optimal solution.

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[1] M. Merluzzi, N. di Pietro, P. Di Lorenzo, E. Calvanese Strinati, and S. Barbarossa, "Network energy efficient mobile edge computing with reliability guarantees," in *Proc. IEEE Globecom*, Waikoloa, HI, USA, 2019, pp. 1-6.

Multi-Agent Deep Reinforcement Learning based User Association for Dense mmWave Networks

RESEARCH TOPIC:
Machine Learning, Resource Allocation in 5G Network, Network Resource Optimization

AUTHORS:
Mohamed SANA, Antonio DE DOMENICO, Emilio CALVANESE STRINATI

Finding the optimal association between user equipments (UEs) and base stations (BSs) that maximizes the network sum-rate is a complex task. This problem is combinatorial and non-convex, and is even more challenging in millimeter-wave networks due to blockages and severe path loss. Despite the interest that this problem has gained over the last years, the various solutions proposed so far in the literature still fail at being flexible, computationally effective, and suitable to the dynamic nature of mobile networks. This work addresses these issues with a novel distributed algorithm based on multi-agent reinforcement learning. More specifically, each UE is empowered with an artificial intelligence (AI) system and learns at each time step to maps its observations to an association request to a base station in its coverage range. We show that the proposed solution offers near optimal performance and thanks to its flexibility, provides large sum-rate gain with respect to the state-of-art approaches.

Context and Challenges

The fifth generation (5G) and beyond mobile communication systems promise to meet the increasing demand for ultra-high-speed communications. To achieve this goal, among the different technologies currently under consideration, millimeter-wave (mmWave) communication has attracted a particular attention due to the large and mostly unlicensed spectrum resources available between 24 and 86 GHz. However, transmissions at mmWave frequencies suffer from severe attenuation, blockage, and deafness. Benefiting from the short wavelength characteristic of mmWaves, directional beamforming enables to overcome part of these issues. With the dense deployment of mmWave small cells, though, inter-beams interference resulting from simultaneous UEs communication can be detrimental for the network performance. In this context, optimally associating UEs with BSs is an important task to reduce co-channel interference and to take full advantage of network densification (see Fig. 1). Yet, it is a combinatorial problem whose complexity exponentially increases with the number of UEs and BSs. In [1], we propose to tackle this issue with an AI-based approach by using multi-agent deep reinforcement to address the association problem. A salient feature of the proposed solution is that it is distributed, thus limiting the computation complexity and signaling overhead.

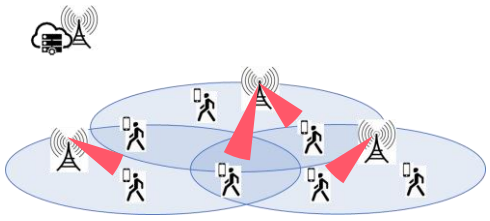


Fig. 1: Example of user association

Main Results

In the proposed framework, each UE (agent) learns its association policy based only on its local observations to maximize the total network sum-rate. These local observations are the received signal strength indicator (RSSI), the perceived rate when it gets connected to a BS, and acknowledgement signal sent by the BS to notify the UE of the acceptance or the rejection of its connection request. We show that despite the few information available to each agent, UEs successfully learn an association policy. We compare our method to two **centralized** solutions from the state-of-the-art called max-SNR and a heuristic algorithm. With the max-SNR, a UE gets associated with the BS providing the maximum signal-to-noise ratio (SNR). The max-SNR strategy does not consider the interference and accordingly it has limited performance. In contrast, the heuristic method considers the inter-beams interference but it is also sub-optimal by construction. Fig. 2 shows that our solution can achieved up to 98% of the optimal performance. Despite being distributed, our method outperforms the two aforementioned centralized benchmarks.

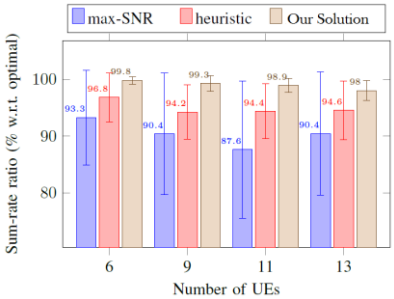


Fig. 2 Performance comparison with different number of UEs

Perspectives

This work is a first attempt to demonstrate the feasibility of the proposed solution in a static mmWave network. In future work, we will focus on dynamic scenarios, taking into account the time varying nature of wireless communication channels and considering UEs' mobility.

RELATED PUBLICATIONS:

[1] M. SANA, A. DE DOMENICO, E. CALVANESE STRINATI, "Multi-agent deep reinforcement learning based user association for dense mmWave networks", IEEE Global Communication Conference (GLOBECOM), Waikoloa, USA, 2019, PP. 1-6.

Towards Massive MIMO In-Band Full-Duplex Radio

RESEARCH TOPIC:
In-Band Full-Duplex, Hybrid SIC, Massive MIMO

AUTHORS:
Patrick ROSSON

In-band Full Duplex (IBFD) is a promising wireless transmission technology based on simultaneous transmission and reception in the same frequency band. This technique allows to increase the data rates up to a factor of two. The main function of IBFD is the Self Interference Cancellation (SIC). To reach the required high level of SIC, several techniques have to be combined, such as antenna isolation, analogue and digital SIC. It is known that analogue SIC does not scale well when the number of antennas is getting large. This work considers hybrid SIC (HSIC) for massive MIMO systems, which is realized with a number of SIC branches that scale linearly with the number of antennas.

Context and Challenges

In-Band Full-Duplex (IBFD) is a promising technique for future cellular network (beyond 5G). By avoiding the use of two independent channels for bi-directional communication, IBFD wireless systems open the way to (i) improve spectral efficiency by a factor of 2, (ii) allow more flexibility in spectrum utilization, (iii) improve data security and (iv) reduce the air interface latency. The challenge of IBFD transceivers is to transmit and receive simultaneously at the same frequency. In order to be able to detect and decode signals with very low received power while transmitting signal at very high power, it is necessary to cancel the Self-Interference (SI) signal, which is due to the leakage of the transmitter (Tx) onto the receiver (Rx). SI cancellation (SIC) is done thanks to the combined effects of interference cancellation at different levels. First, antenna isolation can provide decoupling between Tx and Rx antenna ports. Then, an analogue cancellation is used to avoid low noise amplifier saturation and to allow the converter (ADC) to convert the useful signal within the adapted power range. Finally, a Digital SIC (DSIC) after the ADC can be applied to remove the remaining part of the SI. In the MIMO context, IBFD wireless radios suffer from SI induced by the combination of the NTX transmission and NRX reception branches, leading to a (NTX x NRX) dimensionality. Hence, complexity is a well-known challenge for upcoming massive MIMO IBFD communication scenarios [1].

Main Results

Fig 1 shows a novel Hybrid SIC (HSIC) architecture for 2x2 MIMO transceiver, which is straightforwardly extendable to (N_{TX}, N_{RX}) MIMO configuration. This HSIC proposal consists in the regeneration of the SI thanks to additional RF transmitter chains. In a MIMO transceiver framework, the HSIC must therefore regenerate the SI for each receiver, where such SI are combinations of SIs coming from each transmitter. To do so, every single equivalent SI channels must be estimated, and the HSIC coefficients are directly derived from those estimations [1]. The filtering is done in the digital domain whereas the cancellation is done in the analogue domain thanks to auxiliary Tx chains and couplers. Note that the MIMO SI channel estimation does not require the time-frequency synchronisation as the transmission and the reception are on the same transceiver. Contrarily to RF SIC based on broadband analogue filters, whose complexity increases with the squared number of antennas, this new architecture has a complexity which scales linearly with the number of antennas.

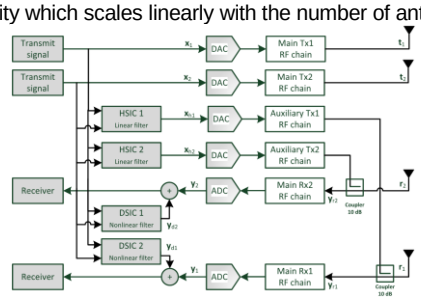


Figure 1. Architecture overview.

Fig. 2 shows several Power Spectral Densities (PSD): transmitted PSD on both Tx antennas (t1 and t2), received PSD after antenna isolation (r1 and r2, see [2]) and PSD after HISC1&2 (yr1 and yr2). Antenna isolations and HSIC allow 60 dB cancellation on the 2 received signals up to the noise floor.

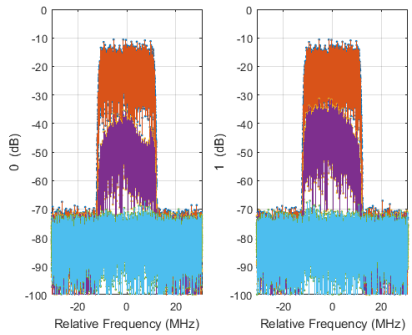


Fig. 2: HSIC MIMO Cancellation performance

Perspectives

The HSIC algorithm is based on linear estimation. Real measurements show that the remaining SI after HISC is due to nonlinear contributions. Nonlinear cancelation techniques into the HSIC might be an interesting perspective to improve performance.

RELATED PUBLICATIONS:

[1] P. Rosson, C.Kumar Sheemar, N. Valecha and D. Slock "Towards massive MIMO in-band full-duplex radio", ISWCS 2019, 16th International Symposium on Wireless Communication Systems, Full Duplex Radio Communications for 5G and Beyond Workshop (FDB5G), 27-30 August 2019, Oulu, Finland

[2] C. Jouvaud, D. Dassonville, P. Rosson, "High self-interference mitigation achieved thanks to significant antenna isolation and advanced RF frontend for In-Band Full-Duplex communications", Conference: 49th European Microwave Conference (EuMC), 2019

Purely Quantum Polar Codes

RESEARCH TOPIC:
Quantum error correction, entanglement assisted codes, quantum channel polarization, coherent information.

AUTHORS:
Valentin SAVIN

We provide a purely quantum version of polar codes, achieving the symmetric coherent information of any quantum channel. Our scheme relies on a recursive channel combining and splitting construction, where random two-qubit Clifford gates are used to combine two single qubit channels. We further show that a Pauli channel polarizes if and only if a specific classical channel with four symbol input set polarizes. We exploit this equivalence to prove fast polarization for Pauli channels, and to devise an efficient successive cancellation based decoding algorithm for such channels. Finally, we present a code construction based on chaining several quantum polar codes, which is shown to require a rate of preshared entanglement that vanishes asymptotically.

SCIENTIFIC COLLABORATIONS: F. Dupuis (Montreal University), A. Goswami and M. Mhalla (Grenoble Alpes University, CNRS)

Context and Challenges

Classical polar codes are the first explicit construction of a family of codes that provably achieve the capacity for any binary-input, symmetric, memoryless channel. They have been generalized for the transmission of quantum information, by using a Calderbank-Shor-Stean (CSS)-like construction, which essentially exploits classical polarization, in either amplitude or phase basis.

Main Results

In our work [1],[2], we explore the question of a *quantum polarization* phenomenon, which is answered in the affirmative. As a consequence, we give a purely quantum version of polar codes, *i.e.*, a family of polar codes where the good channels are good as quantum channels, and not merely in one basis. Our construction relies on a channel combining and splitting procedure (Fig. 1), where a two-qubit gate chosen randomly from the Clifford group is used to combine two instances of the quantum channel. We show that the synthesized quantum channels tend to become either noiseless or completely noisy as quantum channels, and not merely in one basis. Similar to the classical case, information qubits are transmitted through good (noiseless) channels, while the inputs to the bad (noisy) channels are frozen by sharing Einstein-Podolsky-Rosen (EPR) pairs between the sender and the receiver. We show that the proposed scheme achieves the coherent information of the quantum channel, for a uniform input distribution. Further, we show that polarization can be achieved while reducing the set of two-qubit Clifford gates, used to randomize the channel combining operation, to a subset of 9 Clifford gates only. We also present an efficient decoding algorithm for the proposed quantum polar codes for the particular case of Pauli channels. To a Pauli channel, we associate a classical symmetric channel, with both input and output alphabets given by the quotient of the 1-qubit Pauli group by its centralizer, and show that the former polarizes quantumly if and only if the latter polarizes classically. This equivalence provides an alternative proof of the quantum polarization for a Pauli channel and, more importantly, an effective way to decode the quantum polar code for such channels, by decoding its classical counterpart. Finally, we present a code construction based on chaining several quantum polar codes (Fig. 2), which is shown to require a rate of preshared entanglement that vanishes asymptotically.

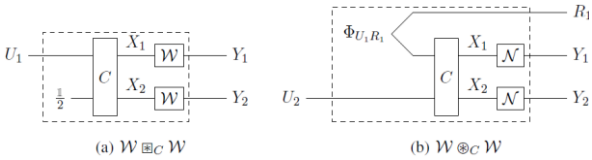


Fig.1: Channel combining and splitting: (a) bad channel: we input a totally mixed state to the second input, (b) good channel: we input half of an EPR pair into the first input, and the other half becomes the output R_1.

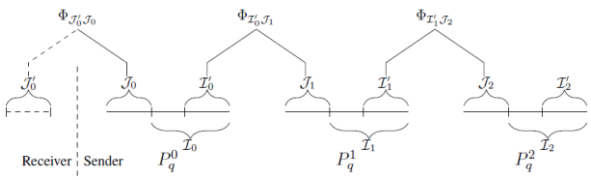


Fig. 2: Chaining construction with 3 copies of a quantum polar code P_q. The initial preshared entanglement acts as a catalyst, in that it produces new shared EPR pairs, which can be used for the next transmission.

Perspectives

The quantum polarization phenomenon opens new perspectives that may complement or extend the classical CSS-based viewpoint. First, our approach yields a family of quantum codes, whose construction does not rely on the stabilizer formalism. This invites the study of quantum decoding algorithms that might achieve the symmetric coherent information for non-Pauli channels. Second, while our work focused on the polarization of qubit-input channels, most of the employed techniques admit a natural generalization to the case of qudit-input channels. Therefore, it would be interesting to extend the quantum polar code constructed here to quantum channels with qudit input.

RELATED PUBLICATIONS:
[1] F. Dupuis, A. Goswami, M. Mhalla, V. Valentin Savin, "Purely Quantum Polar Codes", *IEEE Information Theory Workshop (ITW)*, Visby, Sweden, August 2019.
[2] F. Dupuis, A. Goswami, M. Mhalla, V. Valentin Savin, "Purely Quantum Polar Codes", *Quantum Information Processing (QIP)*, Shenzhen, China, January 2020.

05 WIRELESS SOLUTIONS FOR IOT, VEHICULAR & LOCALIZATION APPLICATIONS

- Low power wide area networks
- Narrow band - IoT
- V2X, V2V / V2I
- Wireless localization
- Car navigation & autonomous driving

LPWA Deployment for Factories of the FUTURE: Lora or Turbo-FSK based technology

RESEARCH TOPIC:
Low Power Wide Area, LoRa, Turbo-FSK, IoT, PHY, MAC, Adaptive networks

AUTHORS:
Moises NUNEZ OCHOA, Arturo GUIZAR, Valerian MANNONI, Mickaël MAMAN

Advanced wireless connectivity has gained increased interest for Factories of the Future (FoF). In this study, we evaluate and compare the benefits of LPWA technologies, LoRa and Turbo-FSK, in the FoF context for massive Machine-Type Communication (mMTC) applications, where low power consumption and high reliability are key objectives. To do so, we evaluate reliability, network capacity, latency, and battery lifetime according to three axes of research: FoF propagation models, flexibility of the PHY layer configurations and different gateway architectures. Finally, we propose some strategies to improve LoRa networks by considering parameters such as device heterogeneity, network topology, deployment density, and traffic intensity

Scientific collaborations: Laboratoire d'Informatique de Grenoble (LIG)

Context and Challenges

"Factories of the Future" (FoF) and "Industry 4.0" refer to a new factory model born of the 4th Industrial Revolution. It introduces Internet of Things (IoT) and Cyber-Physical System (CPS) concepts in industrial scenarios to make factories highly efficient, connected and flexible. One important challenge is how to efficiently support massive Machine Type Communications (mMTC) in FoF environments, i.e. how to support low-energy operation and provide deep indoor penetration for thousands of IoT devices per square kilometer. Low-Power Wide-Area (LPWA) networks already address this market and offer interesting connectivity to low-power devices distributed over very large geographical areas. Among the several competing LPWAN technologies, we select the widely adopted LoRa system and a proprietary solution based on Turbo-FSK, which requires lower energy-per-bit-to-noise ratio to achieve the same level of performance.

Main Results

First, we investigate the advantages and drawbacks of using LPWA technologies (i.e. LoRa and Turbo-FSK) in the FoF context for mMTC applications focusing on high reliability and low power consumption. We evaluate the impact of three factors, FoF propagation models, flexibility of the PHY layer configurations and three different gateway architectures, on Turbo-FSK. The industrial environment has a significant influence on the performance. Thus we show how network densification (i.e. increasing the number of gateways) and link adaptation (i.e. exploiting higher spectral efficiency configurations) can provide interesting performance gains. In particular, we show how Turbo-FSK flexibility (e.g., bandwidth, modulation order) can improve the reliability and the energy consumption.

Secondly, we compare LoRa and Turbo-FSK under the same FoF conditions using equivalent configurations in terms of data rate and bandwidth. The results show the trade-offs of both technologies in terms of reliability, network capacity, end-to-end latency and battery lifetime. Turbo-FSK is the best solution to increase reliability and the network capacity in dense networks, while LoRa is interesting for larger bandwidth to increase the battery lifetime. As an example, Fig. 1 shows the reliability as a function of the number of nodes in the network, each node generating a 100 Bytes packet every minute

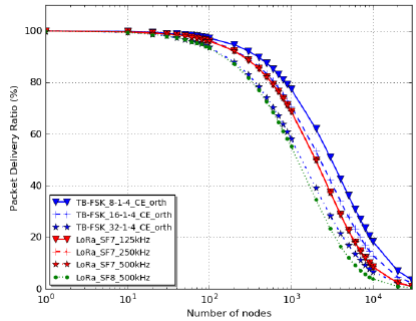


Fig. 1: Reliability as a function of number of nodes in the network

Lastly, we propose three approaches to enhance LoRa networks: link adaptation, network densification, and joint optimization. Our scheme first selects the configuration according to the network parameters (e.g., network congestion) and the radio environment (e.g., link budget), and optimizes single gateway capacity according to the current load and the capacity of each Spreading Factor (SF). This looks suitable for more complex layouts and provides a fairer distribution of SFs compared to LoRaWAN solution only based on the link budget. Multi-gateway adaptation considers the required number of gateways and the optimal SF configuration to assure sufficient reliability for different network sizes. Finally, the proposed joint strategy improves the reliability by exploiting SF orthogonality, spatial reuse of communications, and optimized gateways capacity.

Perspectives

In the future, we will validate these simulations with practical deployments in factories and we will investigate algorithm enhancements with machine learning techniques and gateway negotiation to exploit spatial diversity in harsh environments.

RELATED PUBLICATIONS:

[1] Moises Nunez Ochoa, Arturo Guizar, Mickael Maman and Andrzej Duda, "Toward a Self-Deployment of LoRa Networks: Link and Topology Adaptation", 15th International Conference on Wireless and Mobile Computing, Networking and Communications (WIMOB 2019).

[2] Arturo Guizar, Moises Nunez Ochoa, Valerian Mannoni and Mickael Maman, "LPWA Deployment for Factory of the Future: LoRa or Turbo-FSK Based Technology?", IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC 2019)

Beyond LoRa and NB-IoT: PHY Layers for Future LPWA Systems

RESEARCH TOPIC:
Low Power Wide Area (LPWA), Internet of Things (IoT), Physical layer, low sensitivity

AUTHORS:
Valerian MANNONI, Vincent BERG, Jean-Baptiste DORE, François DEHMAS

A significant amount of connectivity for the Internet-of-Things now relies on Low-Power Wide Area systems. These new standards are continuously evolving to provide low cost and low power connectivity notably within the 3GPP Standard (5G). The physical layer should be improved particularly its energy efficiency to provide low power consumption and connectivity range. Turbo-Frequency Shift Keying (FSK), the combination of M-ary orthogonal FSK modulation and coding in the same process has been shown to be a promising candidate when associated with an iterative receiver (turbo principle). Implementation and evaluation in the context of the FIT/CorteXlab, a cognitive radio experimentation platform, brings the new waveform to new experimentation opportunities by the research community.

SCIENTIFIC COLLABORATIONS: G. Vivier, Sequans, L. Moureh, ISEP, J.-M. Gorce, Univ. de Lyon, CITI

Context and Challenges

Recent forecast estimates that the number of Internet of Things (IoT) connections will reach 22 billion units worldwide. Over the past few years, new approaches often referred as Low Power Wide Area (LPWA) networking technologies have emerged including Narrow Band IoT (NB-IoT) to provide direct connectivity between the objects and the Network. These standards are continuously evolving to provide low cost low power connectivity within the 3GPP Standard (5G).

However, from a theoretical standpoint, these LPWA systems apply very simple mechanisms to reliably transmit information. Physical layers notably rely on well proven and somehow basic technologies. The spectral efficiency is relatively far from optimal and the energy per transmitted information bit is relatively high.

Main Results

Turbo-FSK waveform was introduced by Roth et al. and described in [1], it combines an orthogonal modulation FSK with a powerful channel coding based on the Turbo principle. The main motivation of this scheme is to operate close to the Shannon capacity while using a constant envelop modulation (or a PAPR close to 0dB).

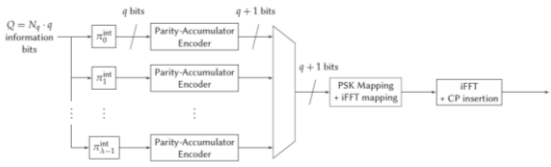


Fig 1: Transmitter architecture of Turbo-FSK

The structure of the Turbo-FSK transmitter (Fig. 1) is composed of λ repetition stages, a differently interleaved version of the same input information bit sequence and fed to a simple parity accumulator.

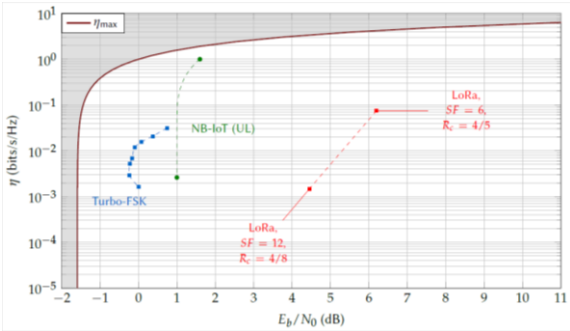


Fig 2: Performance of the Turbo-FSK waveform versus the maximum achievable spectral efficiency and comparison with NB-IoT and LoRa

The Turbo-FSK receiver relies on turbo decoding to iteratively estimate the information bits given both the observation of the channel and the a priori information coming from the decoding of the coded branches. Fig. 2 shows the performance of the Turbo-FSK waveform with the evolution of the spectral efficiency for different configurations as a function of the required E_b/N_0[2][3]. These results clearly demonstrate that the Turbo-FSK fulfills its original purpose (energy efficiency) and exhibits promising performance for the low spectral efficiencies compared to NB-IoT or LoRa.
This proposal has been recently implemented and evaluated in the context of FIT/CorteXlab and is being made openly available to the research community [3].

Perspectives

Further works include development, evaluation of the waveform along with new non-orthogonal multiple access (NOMA) schemes in a theoretical context but also experimental through FIT/CorteXlab.

RELATED PUBLICATIONS:
[1] Y. Roth, The Physical Layer for Low Power Wide Area Networks : a Study of combined modulation and coding associated with an iterative receiver. Theses, Université Grenoble Alpes, July 2017.
[2] Yoann Roth, Jean-Baptiste Doré, Laurent Ros, and Vincent Berg, "Coplanar Turbo-FSK: A Flexible and Power Efficient Modulation for the Internet-of-Things," Wireless Communications and Mobile Computing, vol. 2018, Article ID 3072890, 17 pages, 2018
[3] G. Vivier, V. Mannoni, F. Dehmas, V. Berg, L. Mroueh, et al.. Beyond LoRa and NB-IoT: Proposals for Future LPWA Systems. EuCNC 2019 - European Conference on Networks and Communications, Jun 2019, Valencia, Spain. pp.523-527

Narrowband LPWA Physical Layer accurate Ranging Technologies

RESEARCH TOPIC:
Localization, Low Power Wide Area (LPWA), Internet of Things (IoT), Deep Neural Network (DNN)

AUTHORS:
Florian WOLF, François DEHMAS, Sébastien DE RIVAZ

Localization in the context of the Internet of Things (IoT) is a strong enabler for many applications, but accurate localization for Low Power Wide Area (LPWA) networks remains challenging because LPWA signals are narrowband and significantly degraded by multipath propagation channels. To address this issue, we propose a coherent multi-channel ranging approach that provides improved temporal resolution without modifying the physical layer parameters. A hardware testbed has been developed to evaluate performance in the framework of a field trial, where comparison with existing solution (SX1280 from Semtech) has been made. Improvement using deep learning approaches provide precision down to 45m in 90% of the cases in a semi-urban environment.

SCIENTIFIC COLLABORATIONS: Jean-Pierre Cances, Université de Limoges, CNRS, XLIM

Context and Challenges

Internet of Things (IoT) connections are rapidly increasing and among them, low power wide area (LPWA) networks, such as LoRa, Sigfox or NB-IoT, designed to directly connect the objects to the network has emerged. Accurate geolocalization of the objects is an enabler and provides a significant added-value for many applications including for instance forest fire detection or location of vulnerable elderly people.

This location feature remains challenging in many contexts or environments. For example, Global Navigation Satellite Systems (GNSS) can be inefficient for indoor applications or consume unnecessary amount of energy. LPWA radio based location has the advantage to rely on the same hardware for localization and communication with limited amount of additional energy. However, narrowband signals considered for long range communications are very limited to provide accurate positioning.

Main Results

Theoretical bounds show that Time of Arrival (ToA) estimation error is inversely proportional to the bandwidth. To increase the bandwidth without modifying the physical layer of an LPWA system, we successively transmit packets at different frequencies. The idea is to make an estimation of the propagation channel by sampling it in the frequency domain. For C different frequencies f_c, we estimate the phase and the amplitude of the propagation channel (i.e. its sampled complex response). Phase rotation due to the channel is not straightforward to estimate due to the initial phase of the oscillators in the transmitter and the receiver. Thus, a round trip is used (as in classical two-way ranging for Time of Flight estimation) to cancel these initial phases.

A testbed based on a software-defined radio platform has been developed to make laboratory experimentations and field trials. Thus we were able to compare the ranging accuracy with the commercial ranging solution proposed by Semtech (SX1280 chip) in the 2.4 GHz band based on ToAs estimation [1]. In the urban canyon scenario, Figure 15 shows the perfromance comparison.

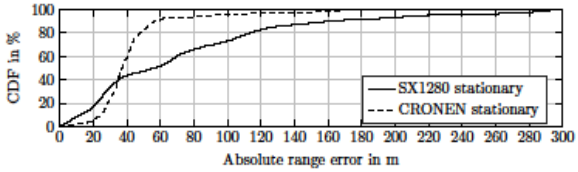


Figure 15 : LoRa 2.4GHz SX1280 and designed range error CDF for the urban canyon scenario.

Furthermore, to get the channel impulse response and the ToA of the first path, instead of a simple inverse Fourier transform, we explore advanced signal processing solutions based on MUSIC and deep neural networks (DNN) [2]. If the first does not give significant improvement, DNN does: with a training dataset based on a mix of simulated data and field measurements (allowing to have a large dataset with only few measurements), 25m accuracy gain is obtained (Table 1).

Table 1 : Ranging precision from field trial experimentation (semi-urban scenario)

TOA estimation method	IDFT	MUSIC	DNN
Error @ 90%	70m	70m	45m

Perspectives

In the framework of LPWA, a phase difference of arrival technique, based on multi-channel processing, that allows localization thanks to uplink only transmissions should be considered. The advantages are numerous notably a shift of complexity towards the base stations where strict synchronization is required.

RELATED PUBLICATIONS:

[1] F. Wolf, K. Le Déroff, S. de Rivaz, N. Deparis, F. Dehmas and J. Cances, "Benchmarking of Narrowband LPWA Physical Layer Ranging Technologies," 2019 16th Workshop on Positioning, Navigation and Communications (WPNC), Bremen, Germany, 2019, pp. 1-6.

[2] F. Wolf, M. Sana, S. de Rivaz, F. Dehmas, J. Cances. "Comparison of Multi-Channel Ranging Algorithms for Narrowband LPWA Network Localization." 2019 The 5th International Symposium on Ubiquitous Networking (UNet), Nov 2019, Limoges, France.

Smartphone-Based indoor localization using Multi-Modal Fusion and map-matching

RESEARCH TOPIC:
Indoor localization, multi-modal fusion, map-matching, particle filtering

AUTHORS:
Christophe VILLIEN, Anne FRASSATI, Bruno FLAMENT (Invensense)

Pedestrian Indoor localization based on modalities available in modern smartphones have been widely studied in the literature and many of the specific challenges have been addressed. However, very few approaches considered the whole problem and the proposed solutions are very often evaluated for very limited scenarios. We propose a fusion engine for localization that makes use of various data provided by a smartphone (Inertial sensors, pressure sensors, Wi-Fi, BLE, GNSS, map etc.) to provide a fused localization that is robust under harsh conditions (low RSS coverage, device position change etc.). Moreover, our solution has been evaluated for hardware integration and tested over a large database including more than 250 experiments representing different scenarios, showing feasibility of lightweight implementation and good results over various conditions.

SCIENTIFIC COLLABORATIONS: Invensense (FR)

Context and Challenges
Pedestrian Indoor localization based on modalities available in modern smartphones have been widely studied in the literature and many of the specific challenges have been addressed. However, very few approaches consider the whole problem and the proposed solutions are very often evaluated for very limited scenarios. We propose a fusion engine for localization that makes use of various data provided by a smartphone (Inertial sensors, pressure sensors, Wi-Fi, BLE, GNSS, map etc.) to provide a fused localization that is robust under harsh conditions (low RSS coverage, device position change etc.).

Main Results
A positioning algorithm based on a particle filter that fuses the various data available in a smartphone (IMU sensors, Wi-Fi, BLE, GNSS, pressure) and performs map-matching has been developed. This algorithm also addresses some of the most challenging use cases like the Device Position Change (DPC), outdoor to indoor transitions, step-length estimation, and is intended for a lightweight, always-on, hardware integration. Implementation on a 32bit fixed-point platform (i.e. BlackFin processor) has shown a hardware footprint requiring a processing power of 45MIPS, and a memory size of 150kB (code+data), which is suitable for integration In a low power processor.
Field trials have been conducted over 3 years divided into 8 campaigns of acquisition, resulting 580 files, 240km of walk, about 100 users and 7 different devices. One typical experiment lasts about 10 minutes or more and the user is asked to follow a predefined path and, for some experiments, he is also asked to do some additional actions such as making a phone call, changing the smartphone position, or locating a specific information on a poster (i.e. to have some trampling behavior). All the classical device positions have been tested (portrait, landscape, call, pocket, chest, waist, backpack and swinging in hand). Typical density of radio beacons (when present) is equal to 1 per 300m², placed at positions that are independent of the algorithm performances.
Results computed over the entire database, gives an overall accuracy of 9m RMSE, which improves to 4.3m under favorable scenario conditions. Analysis of those two figures reveals that the developd algorithm is efficient for some environments (e.g. narroew corridors, good Wi-Fi / BLE coverage) even with DPC, but deteriorates under one of these factors: (i) without any RSS measurements, (ii) in large open spaces, (iii) during stairways transitions.

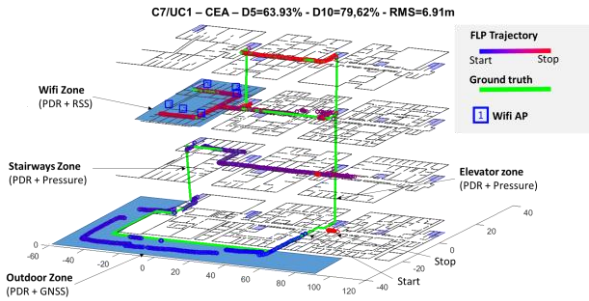


Fig. 1. Example of test conducted in a 4 floors building

Fig. 2. Android demonstrator of the indoor localization engine

Perspectives
As this approach, as many other localization techniques (e.g. fingeprinting), makes use of maps which are difficult to survey, current work is focusing on map reconstruction through machine learning from crowd-sourcing data. The focus of this is particularly relevant to large scale Internet of Things (IoT) localization.

RELATED PUBLICATIONS:
[1] Villien, Christophe & Frassati, Anne & Flament, Bruno. (2019), "Evaluation of An Indoor Localization Engine" 2019 Intenational Conference on Indoor Positionning and Navigation (IPIN.2019). pp. 1-8.

A Comparison of the V2X Communication Systems: ITS-G5 and LTE-V2X

RESEARCH TOPIC:
Vehicle to Everything (V2X) communication system, LTE-V2X, ITS-G5, Physical layer, MAC layer

AUTHORS:
Valerian MANNONI

Vehicular communications, known as V2X (Vehicle to Everything), are expected to grow quickly in the coming years. These technologies have a significant role to play in optimizing road traffic and improving road safety. Currently, two standards: ITS-G5 (standardized in Europe by ETSI and derived from WiFi IEEE communication standards) and LTE Vehicle to Everything or LTE-V2X (developed by 3GPP and derived from LTE) consider the use of the 5.9 GHz ITS band for their deployment. While different countries are well advanced in their choice of Intelligent Transport System (ITS), it seems clear a single standard solution will not be deployed worldwide. It is therefore important to have a good understanding of both technologies and to be able to assess their respective performance.

SCIENTIFIC COLLABORATIONS: P. Roux (LIST/DIASI), S. Sesia (Renault Software Labs), E. Perraud (Renault Software Labs)

Context and Challenges

Vehicular communications have been identified as a key enabler for improving vehicular safety, traffic and energy efficiency as well as the quality of the user experience, for automated and autonomous vehicles. Two competing vehicular communication standards using the specially allocated 5.9GHz unlicensed band have emerged in recent years: ITS-G5 protocol (ETSI) and LTE-V2X (3GPP) notably the so called modes 3 and 4, based on the interface 'PC5' without or with any involvement of the eNB (respectively). PC5 interface have been designed to satisfy bounded low latency requirements and accommodate a given level of density of vehicles combined with the support of high speed. Although the vehicular protocol stack has been defined with IEEE 802.11p in mind, it can be adapted to the LTE-V2X access layer.

In order to maximize the emergence of this type of technology, it is essential to evaluate both communication systems through different scenarios and to identify their respective working point by considering the physical and upper layers.

Main Results

The performance of the physical layer for both standards was first derived considering a point-to-point link [1]. These simulations showed (Fig. 1) that for the same data rate, LTE-V2X has a better performance than ITS-G5. The wide variety of parameterization of the C-V2X allows to further accentuate this gain with an improvement of the communication range of up to 600m when in Line of Sight (LOS), particularly when retransmission is considered. However, in this case, the performance gain is at the expense of the time and frequency resources that have been utilized.

Secondly, the complete protocol (lower layers and protocol stack) has been evaluated for different scenarios using system level simulations with NS-3, a network simulator [2]. Results comparison between ITS-G5 and LTE-V2X PC5 mode 4 shows that LTE-V2X outperforms ITS-G5 (Fig. 2). Furthermore, when considering latency maximum tolerance, the performance gap is even larger because ITS-G5 introduces extra latency when the traffic is high. However, we may have to mitigate this conclusion considering that LTE-V2X relies on GNSS synchronization to operate.

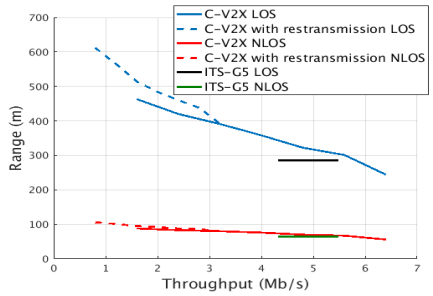


Fig 1: Communication range as a function of the throughput for LTE-V2X and ITS-G5

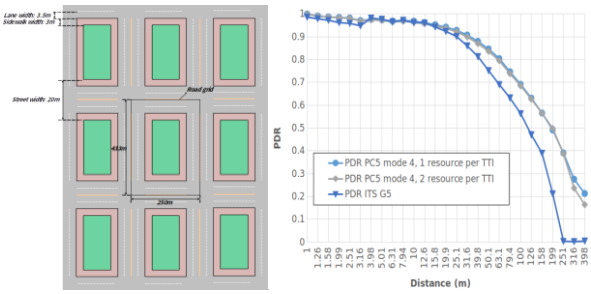


Fig 2: LTE-V2X and ITS-G5 PDR performances for the Manhattan scenario, speed=60 km/h.

Perspectives

Further work includes investigations on the coexistence scenarios between both technologies and on the impact of the V2X communication system on the cooperative collision avoidance (based on occupancy maps) mechanism.

RELATED PUBLICATIONS:

[1] V. Mannoni, V. Berg, S. Sesia and E. Perraud, "A Comparison of the V2X Communication Systems: ITS-G5 and C-V2X," in 2019 IEEE 89th Vehicular Technology Conference (VTC), Kuala Lumpur, Malaysia, April 2019.

[2] P. Roux, S. Sesia, V. Mannoni, E. Perraud, "System Level Analysis for ITS-G5 and LTE-V2X Performance Comparison," in 2019 IEEE 16th International Conference on Mobile Ad-Hoc and Smart System (MASS), Monterey, USA, Nov. 2019.

Resource Budgeting for Joint Localization and Communication Services in Multi-user Multi-carrier mmWave Systems

RESEARCH TOPIC:
Beamforming optimization, fairness strategies, multi-user resource allocation, mmWave radio, wireless localization, (B)5G

AUTHORS:
Remun KOIRALA, Benoît DENIS

Despite the claimed synergies between directional communications and intrinsic localization capabilities in millimeter-wave (mmWave) systems, allocating too much radio resource for data services can dramatically harm the estimation of user's position and orientation, and vice versa. Relying on localization-oriented beamforming optimization and on the analysis of theoretical performance bounds, we have thus addressed and characterized non-trivial operating trade-offs between data and localization services in a multi-user multi-carrier mmWave context, from a resource budgeting standpoint (over time/frequency/power, users, services…).

SCIENTIFIC COLLABORATIONS: Univ. Rennes 1 (Rennes, France), Univ. of Bologna (Cesena, Italy), Chalmers Univ. of Technology (Gothenburg, Sweden)

Context and Challenges
In the context of (beyond) 5G communication networks ((B)5G), the millimeter wave (mm-Wave) radio technology, which operates at high frequencies (i.e., above 20 GHz), is expected to fulfill unprecedented needs in terms of data rates and channel load. Benefitting from both directional antenna systems and sparse multipath channels, mmWave systems also claim unprecedented localization capabilities. However, smart resource allocation strategies (i.e., over time/frequency, users and services…) still need to be defined to optimize localization performance depending on application needs, while keeping acceptable communication performances.

Main Results
Leveraging former studies on theoretical positioning performance bounds and heuristic localization-oriented beamforming strategies adapted to mmWave multi-carrier systems [1], we have first derived a tunable application-dependent localization error cost [2]. The latter combines the Cramér-Rao lower bounds of delay, angle of departure and/or angle of arrival estimates over the downlink. Then, a convex reformulation of the beamforming optimization problem has been proposed, along with multi-user resource sharing schemes (based on proportional and min-max fairness criteria).

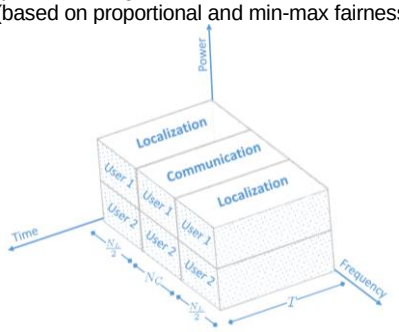


Fig.1: Ex. of frequency division framework for joint localization and communication services in a multi-user context.

Finally, based on the latter optimization results in both single-user and multi-user contexts, we have analyzed system-level trade-offs between communication and localization performances (resp. in terms of the average data rate and the position error bound) for various resource sharing strategies (in particular, over time and frequency; See Fig. 1 and 2) [2], [3].

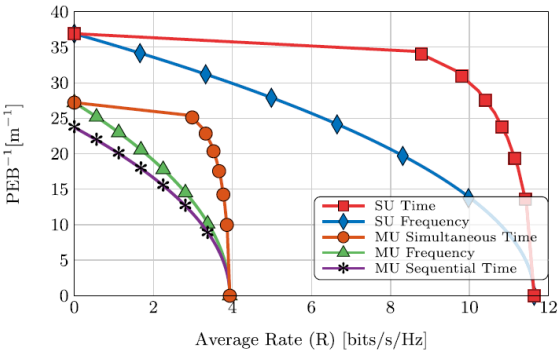
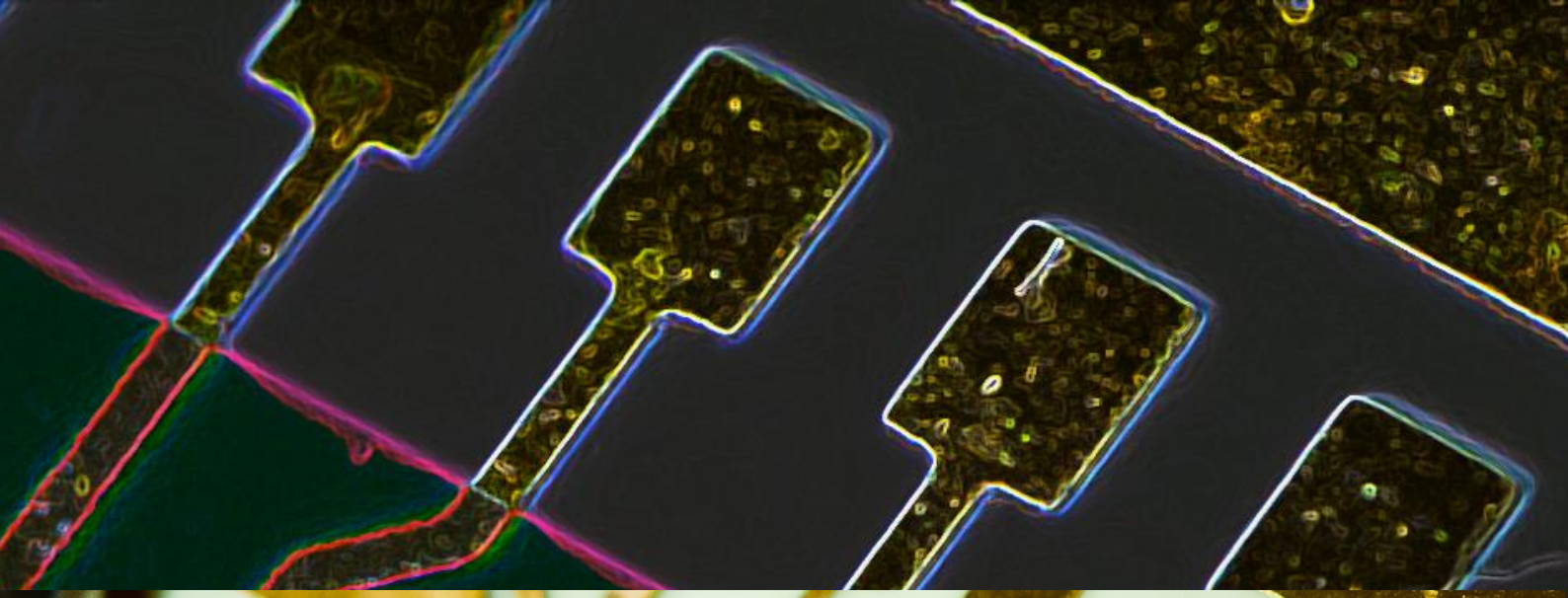


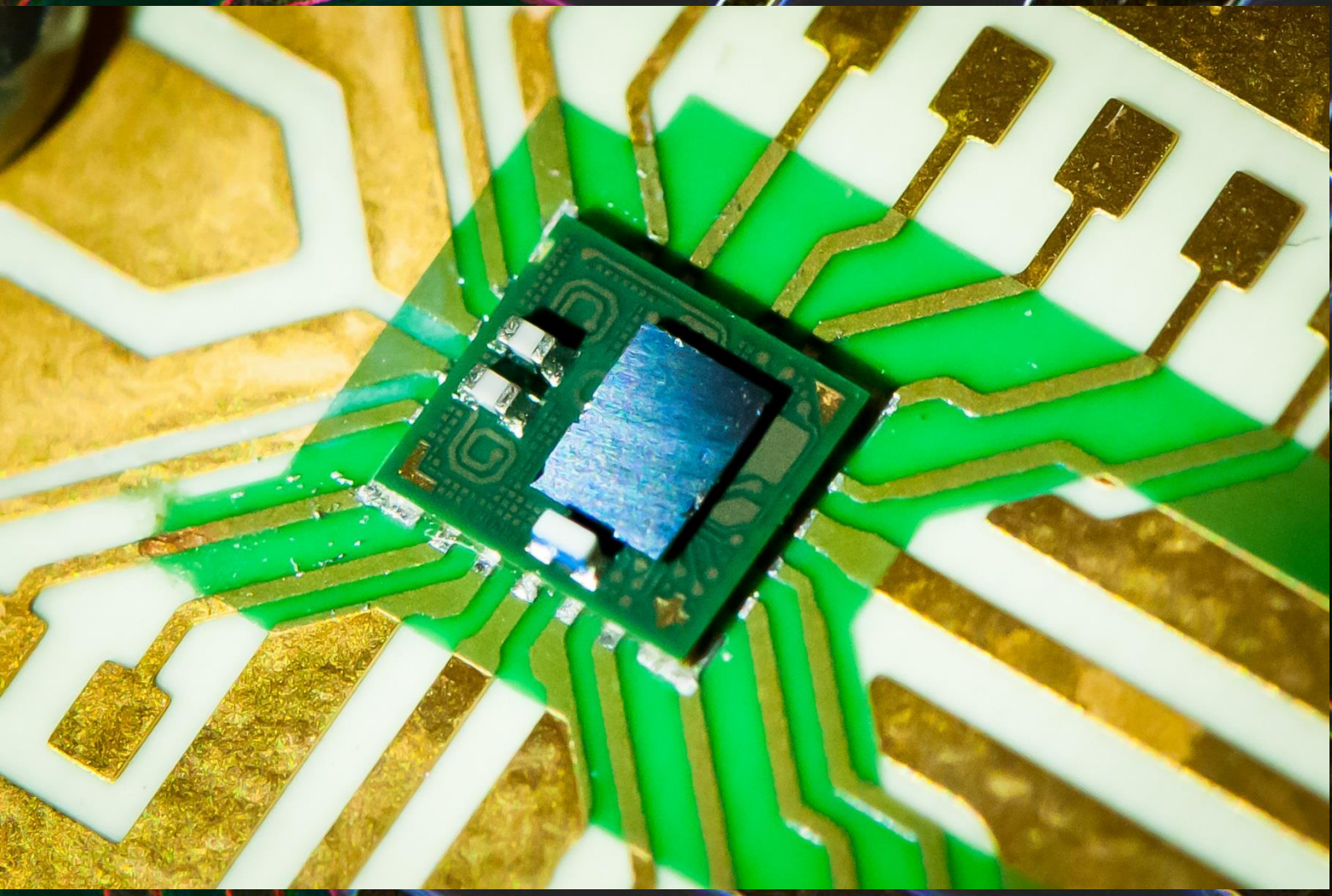
Fig.2: Inverse of position error bound vs. average rate trade-off for both time and frequency division strategies among 3 users.

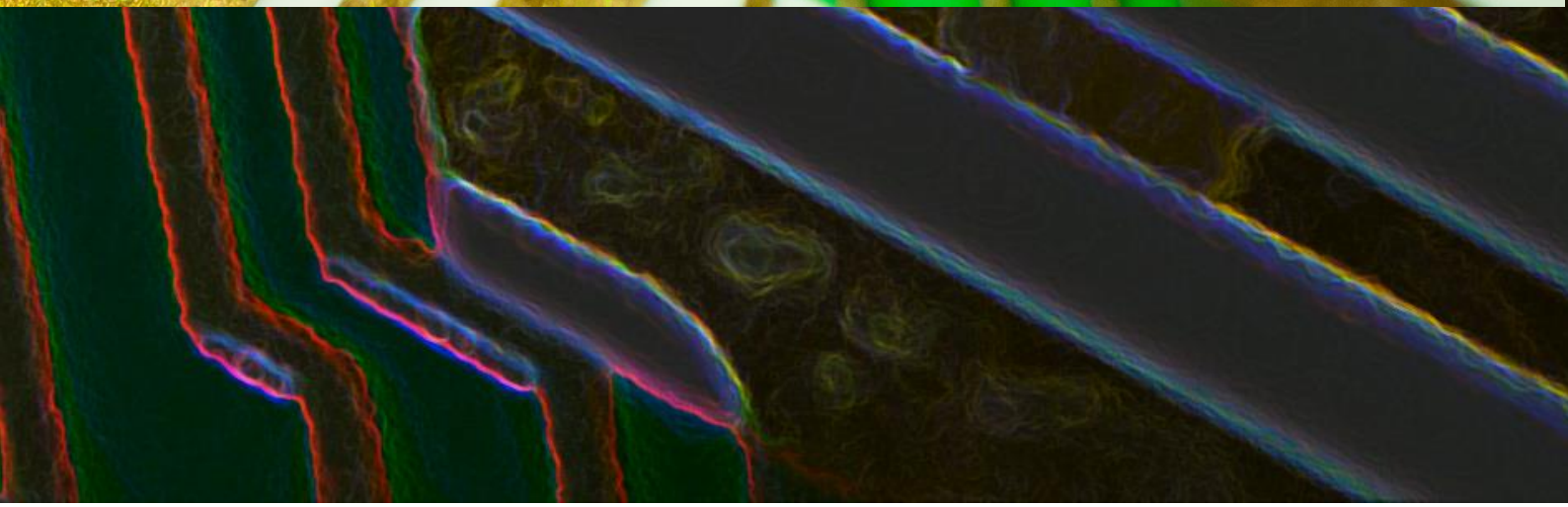
Based on the obtained set of trade-off curves, given a total resource budget and a particular scenario, one can thus identify a feasible region that satisfies simultaneously the Quality of Service requirements of both localization and communication and find the optimal resource splitting in terms of time and frequency division [2].

Perspectives
Leveraging the angular information obtained during the localization service phase, extensions to the previous work have been considering the location-assisted estimation of sparse multipath channels, as well as simultaneous localization and mapping applications within the same mmWave system.

RELATED PUBLICATIONS:
[1] R. Koirala, B. Denis, B. Uguen, D. Dardari, H. Wymeersch, "Localization Optimal Multi-user Beamforming for Multi-Carrier mmWave MIMO Systems", Proc. IEEE Personal, Indoor, and Mobile Radio Communications 2018, Bologna, Sept. 2018.
[2] R. Koirala, B. Denis, B. Uguen, D. Dardari, H. Wymeersch, "Localization and Throughput Trade-off in a Multi-User Multi-Carrier mm-Wave System", IEEE Access, Vol.7, Is.1, Dec. 2019
[3] R. Koirala, B. Denis, B. Uguen, D. Dardari, H. Wymeersch, "Localization and Communication Resource Budgeting for Multi-user mmWave MIMO", Proc. IEEE Workshop on Positioning, Navigation and Communications 2019, Bremen, Oct. 2019







06 CIRCUITS & SYSTEMS FOR WIRELESS APPLICATIONS

- 5G high speed mmW network
- RF/mmW front-end module
- RF analog to feature processor
- IoT

5G and Beyond 5G Roadmap: what is forecast in the next decades for mmW and tHz communications

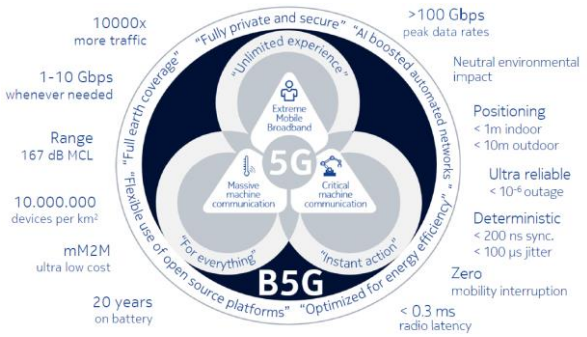
RESEARCH TOPIC:
5G High speed mmW Network, THz Communications

AUTHORS:
J.L. Gonzalez-Jimenez, A. Siligaris, C. Dehos, N. Cassiau, A. Clemente, F. Foglia Manzilla, A. Hamani, F. Chaix, B. Martineau, F. Hameau, A. Boulmirat, P. Courrouve, J.B. David, J.B. Doré.

With the fifth generation (5G) of mobile networks currently under deployment, researcher start to look at the next generation. One of the axes of evolution of wireless communications services is driven by the increase in data-rate. Another axe is driven by increase in number of devices connected to the network. Both evolutions will require increasing the maximum data rate of the transport and access segments of the network. With increasingly dense wireless cell requirements in terms of number of connections and data rate per connection, most of these links will need to be wireless, at least in the access and front haul/backhaul sections. This trend opens an unprecedented demand of available spectrum, which is only found at sub-THz and THz frequencies.

Context and Challenges

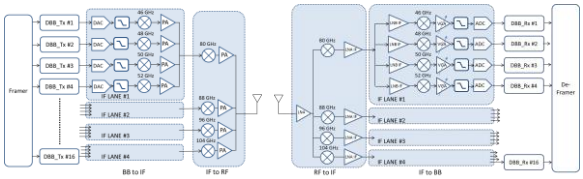
5G has been developed to bring a new class of services pushing the capabilities of mobile network across three axis: extreme mobile broadband access, critical machine communication, and massive machine communication. Beyond 5G (B5G) is currently envisaged as an extension of the key performance indicators (KPI) that were defined as a goal for 5G systems, as shown in the following figure.



In order to implement higher data rate, access to new spectrum is needed. Frequencies beyond 90GHz are under consideration by many regulatory bodies in Europe, Asia and the Americas. In addition, new circuits and device technologies able to operate at those new frequencies bands are currently under research at Leti and many other research labs of industry and academia. At Leti the focus is put on providing solutions with a reduced power consumption, since the development of B5G and future 6G systems and services would not happen if societal concerns such as environmental impact and energy efficiency were not taken into account.

Main Results

A first wave of circuits and systems operating at frequencies between 90 and 300 GHz is based on existing silicon technologies such as CMOS, FDSOI, PDSOI and SiGe. Nevertheless, innovative RF architectures are required to optimize spectrum and energy efficiency. Leti has been working since the last three years in channel bonding transceivers able to cover large RF bands with reasonable power consumption and baseband interfaces data rate. One of example of this architecture is shown in the next figure.



This RF radio is able to provide 100Gb/s and even higher data rates by bonding up to 16 base-band channels and up-convert them up to D-band covering a total of 32GHz of band with only 8 LO frequencies. Some of the critical building block are being developed by the RFIC lab and some other have been already demonstrated [1],[2]. This transceiver has been demonstrated in the lab with up to 64QAM modulation.

Other innovative approaches are targeting increasing even further the spectral efficiency target specific signal modulation schemes that are more resilient to some of the RF impairments, such as phase noise, that become a limiting issue for large frequencies and large bandwidth [3].

Perspectives

The quest for even higher data-rates and bandwidth will continue and frequencies beyond 300GHz, in the THz range, are starting to be considered. For these frequencies, the combination of classical silicon based CMOS and BiCMOS technologies with other semiconductor technologies such as GaN or InP or some other based on new materials will be required to combine the high frequency capabilities of these other technologies with the low power and low cost of silicon based processes. Leti is actively collaborating with other research actor to make this heterogeneous integration a possibility, for example in the framework of the 5GGaN-2 project.

RELATED PUBLICATIONS:

[1] F. Barrera, A. Siligaris, B. Blampey and J. L. Gonzalez-Jimenez, "A D-band 4-ways power splitter/combiner implemented on a 28nm bulk CMOS process," 2019 14th European Microwave Integrated Circuits Conference (EuMIC), Paris, France, 2019, pp. 314-317.

[2] F. F. Manzillo, J. Luis Gonzalez-Jimenez, A. Clemente, A. Siligaris, B. Blampey and C. Dehos, "Low-cost, High-Gain Antenna Module Integrating a CMOS Frequency Multiplier Driver for Communications at D-band," 2019 IEEE Radio Frequency Integrated Circuits Symposium (RFIC), Boston, USA, 2019, pp. 19-22.

[3] S. Bicaïs, J. Doré and J. Luis Gonzalez Jimenez, "Adaptive PSK Modulation Scheme in the Presence of Phase Noise," 2018 IEEE 19th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC), Kalamata, 2018, pp. 1-5..

Recent advancement in SOI-CMOS PA design for LTE-A, 5G and Wifi6 applications

RESEARCH TOPIC:
Power Amplifier, SOI, LTE-A, 5G, Wifi

AUTHORS:
Alexandre GIRY, Ayssar SERHAN, Patrick REYNIER, Clément PARAT

The need for smaller form factor and reduced cost is driving research towards integrated Power Amplifier (PA) modules with multimode multi-band capabilities. Linear amplification of high peak-to-average power ratios (PAPR) signals is traditionally achieved by operating the PA in back-off where conventional PA architectures show limited efficiency. This calls for an important shift towards advanced PA architectures capable of handling signals with high PAPR while maintaining high efficiency and linearity on a broad frequency range. LETI has recently demonstrated state-of-the-art SOI-CMOS PA modules for LTE-A, 5G and Wifi6 applications.

SCIENTIFIC COLLABORATIONS: Huawei Technologies Research & Development, Belgium; Amkor Technology, Portugal

Context and Challenges

As shown on Figure 1, recent broadband wireless standards make use of high frequency bands and high order modulated signals with high instantaneous bandwidth (IBW) in order to achieve high data rates. The increasing signal peak-to-average power ratio (PAPR) and Error Vector Magnitude (EVM) requirements are pushing the PA to operate at higher back-off levels to stay within the regulatory limits. This creates serious challenges for the integration of high efficiency linear PA.

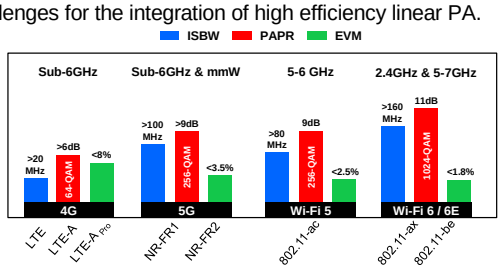


Figure 16. Evolution of ISBW, PAPR and EVM with recent 3GPP and WiFi standards

Main Results

SOI technology offers new opportunities for advanced PA integration and LETI has recently demonstrated high performance SOI-CMOS PAs for LTE-A, 5G and Wifi6 applications [1]. One key 5G feature is enhanced mobile broadband using sub-6GHz frequency carriers in C-band. A SOI-CMOS Doherty PA (DPA) targeting Ultra High Band (UHB) applications was developed [2] as shown in Figure 2.

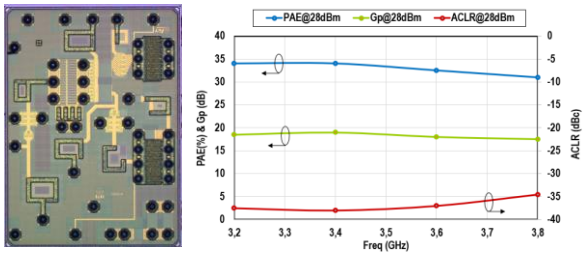
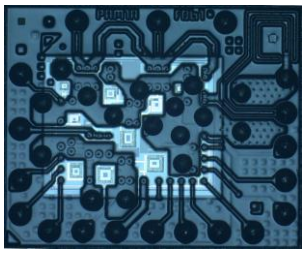


Figure 2. SOI PA for UHB: die photo and measured LTE performance vs Frequency

The DPA architecture represent an attractive solution for efficient linear amplification of modulated signals with PAPR in the range of 4dB to 8dB. The proposed SOI-CMOS DPA makes use of high breakdown SOI-LDMOS devices to enable robust and reliable operation [3]. With a 3.4V voltage supply, the two-stage DPA achieves a measured peak output power and PAE of 32dBm and 48% respectively at 3.4GHz. With a 10MHz LTE-uplink signal, the linearized DPA exhibits a measured ACLR-EUTRA of less than -35dBc from 3.2GHz to 3.8GHz.

Doherty PAs generally have a limited band of operation and require precise phase control to maintain high linearity and efficiency over frequency. A state-of-the-art reconfigurable broadband SOI-CMOS DPA module targeting Mid-High Band (MHB) applications was developed using a laminate package [4]. From 1.9GHz to 2.7GHz, the PA module achieves significant linearity improvements compared to a non-tunable DPA, without using digital predistortion (DPD).

In the context of REFERENCE project [5], an ultra-thin and compact Doherty PA module leveraging an advanced Wafer-Level Fan-Out (WLFO) packaging technology was demonstrated as shown in Figure 3. At 2.3GHz, the PA achieves a measured peak PAE of 55% at 32dBm of output power. At 1dB compression point, output power and PAE are 31.8dBm and 54.5% respectively. With a 10MHz LTE-uplink signal, the PA achieves 42.5% of PAE and -35dBc of ACLR at 28dBm of output power without using DPD.



Packaging technology		WLFO
Module size (mm2)		3.2x2.6
Module thickness (mm)		0.45
IC technology		SOI-CMOS
Freq. (GHz)		2.3
VDD (V)		3.4
CW	Psat (dBm)	32
	Max. PAE (%)	55
LTE	Modulation	QPSK
	BW (MHz) / RB	10/50
	Pout (dBm)	28
	PAE (%)	42.5
	ACLR (dBc)	-35
	DPD	No

Figure 3. SOI PA for MHB: module photo, characteristics and measured performance

Perspectives

SOI-CMOS technology represents a cost-effective platform paving the way to high efficiency linear PA integration. LETI is actively working on next generation SOI-CMOS PAs for future wireless broadband applications.

RELATED PUBLICATIONS:
[1] A. Giry et al., "Recent advancement in RFSOI PA design for LTE-A and 5G", in IEEE EuMW Workshop, 2019
[3] S. Boutayeb et al., "A 3.2-3.6GHz SOI-LDMOS Dual-Input Doherty Power Amplifier", in IEEE S3S, 2019
[2] X. Garros et al., "A Very Robust and Reliable 2.7GHz +31dBm Si RFSOI Transistor for Power Amplifier Solutions", In IEEE IEDM, 2019
[4] A. Serhan et al., "A Reconfigurable SOI CMOS Doherty PAM for Broadband LTE High-Power User Equipment Applications," in IEEE RFIC, 2020.
[5] Electronic Component Systems European Leadership (ECSEL) Joint Undertaking, Grant agreement n°692477 (REFERENCE)

Reconfigurable SOI CMOS Doherty Power Amplifier Modules for Broadband LTE/LTE-A applications Supporting High-Power User Equipment mode

RESEARCH TOPIC:
Doherty, High-Efficiency, Power Amplifier, Reconfigurability, 5G

AUTHORS:
Ayssar SERHAN, Alexandre GIRY, Damien PARAT, Pascal REYNIER

RF power amplifier (PA) design has significantly increased in complexity over the last decade due to the ever-increasing signal bandwidth (BW), PAPR (peak-to-average-power-ratio), and number of frequency bands that need to be supported. Moreover, new power classes such HPUE (High Power User Equipment) have been introduced to preserve cells coverage and channel capacity in TDD bands, which increases the output power requirements in cellular UEs. To address these challenges, LETI has developed highly integrated reconfigurable PA Modules combining high-efficiency architectures, SOI-CMOS technology, and advanced packaging in order to achieve state of the art efficiency, linearity and power levels over an extended range of operating frequency.

SCIENTIFIC COLLABORATIONS: Huawei Technologies Research & Development, Belgium NV

Context and Challenges

High PAPR signals used in today's cellular communication systems require the PA to be backed-off from its peak power in order to meet the linearity specifications. In conventional PAs, the power back-off drastically degrades the average efficiency of the PA (Figure 16). Hence, PA architectures that use supply modulation (Envelope Tracking) and load modulation (Doherty, Outphasing) are used to improve the efficiency at BO. Yet, compared to ET and outphasing, Doherty PAs require less interaction with the baseband to be linearized [1-2]. However, Doherty PAs are generally narrow band and require precise phase control to maintain their performance over frequency. To overcome the BW limitation, LETI developed a reconfigurable Doherty PA module using STMicroelectronics H9SOIFEM platform. The low R_{on}×C_{off} SOI transistors enables low-loss matching networks tuning, leading to wider PA BW.

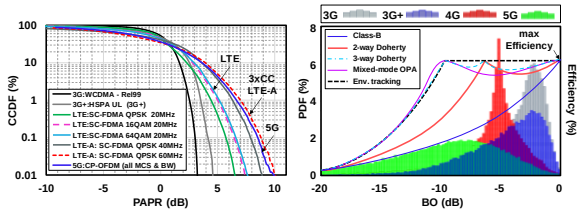


Figure 17. (right) CCDF profiles, (left) PDF and DE profiles versus BO power.

To improve channel capacity and cell coverage in TDD bands, HPUE mode doubles the linear output power (P_{out}) of the PA from 28dBm to 31dBm. This requires the PA to operate at higher Vdd making the PA reliability more challenging. LETI's reconfigurable Doherty PA uses high breakdown LDMOS devices to enable robust and reliable operation in HPUE mode.

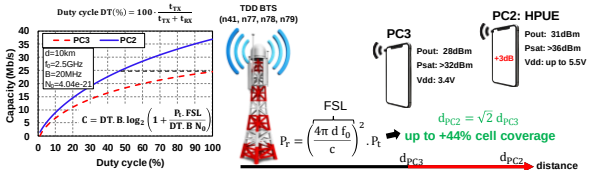


Figure 18. Illustration of the benefits of HPUE mode.

Main Results

The photo of the SOI die and the laminate package is shown on Figure 16. At the nominal frequency (2.3GHz), and for the temperature range from -40°C to 80°C, the PA exhibit an ACLR lower than -36.5dBc and a PAE higher than 42% at P_{out}=28dBm using 10MHz QPSK LTE uplink signal and Vdd=3.4V. For HPUE mode, the PA achieves 31dBm of P_{out} and a PAE of 42.6% while having an ACLR lower than -35.7dBc using 10MHz QPSK LTE uplink signal and Vdd=5V.

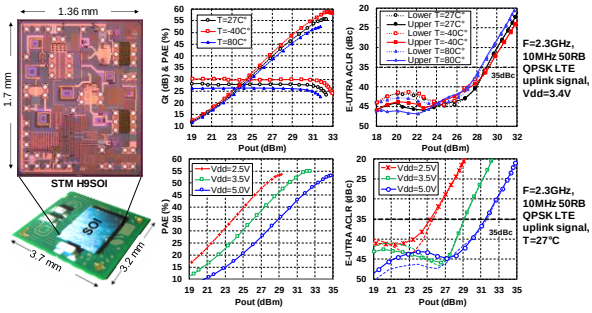


Figure 16. Photo of the SOI die and laminate package, LTE performance vs. power.

The benefit of the PA reconfiguratbility is demonstrated by the measuring the ACLR, EVM, and PAE, at P_{out}=28dBm, for several operating frequency with and without reconfiguring the PA. As highlighted by the measurements, the EVM and ACLR are significantly improved when reconfiguring the PA, while delivering the same output power, without degrading the PAE. All performance are measured without using pre-distortion [2].

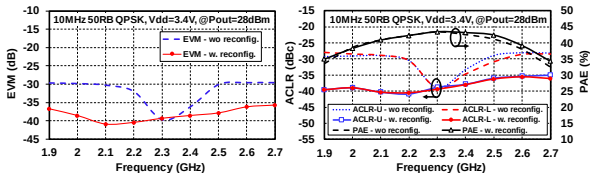


Figure 16. Performances versus frequency (LTE 10MHz QPSK, Vdd=3.4V, 27°C).

Perspectives

LETI is working on next generation high-efficiency reconfigurable PA solutions supporting an increased number of 5G bands and wider modulated signal bandwidth.

RELATED PUBLICATIONS:
[1] A. Serhan et al., "A Reconfigurable SOI CMOS Doherty PAM for Broadband LTE High-Power User Equipment Applications," in IEEE RFIC, 2020.
[2] A. Serhan et al., "A Broadband High-Efficiency SOI-CMOS PA Module for LTE/LTE-A Handset Applications," in IEEE RFIC, 2019.
[3] A. Giry et al., "A 2.5GHz LTE Doherty Power Amplifier in SOI-CMOS Technology," in IEEE NEWCAS, 2019.

Design opportunities exploiting FDSOI technology For RF power amplifier and LNA design

RESEARCH TOPIC:
IoT, Wake-Up Radio, Ultra Low Power, FD-SOI, Power Amplifier

AUTHORS:
Frédéric HAMEAU, Dominique MORCHE, Patrick AUDEBERT

The key advantages of FDSOI technology has already been used in digital design. In Literature, power consumption versus speed performances has been reported. However, few has been done regarding RF design blocks. We propose to prove the ability of FDSOI to enable high performance RF design blocks though the design of two RF critical blocks: a Power Amplifier targeting the stringent 802.11ac wifi specification and form the receiver side an ultra-low power LNA targeting compliant 802.15.4 zigbee specifications.

SCIENTIFIC COLLABORATIONS: IMS laboratory Bordeaux, France

Context and Challenges

While the CMOS FD-SOI technology is mostly associated with low power, high performance digital implementation, two critical radio frequency blocs have been designed taking benefits of the key advantages of the 28nm UTBB FD-SOI technology. First, a Power Amplifier (PA) targeting 802.11ac Wifi standard has been design to demonstrate the technology benefits in term of design compactness for high output swing and high error verctor magnitude (EVM) performance. Then a low noise amplifier (LNA) targeting ultra-low power application for IOT has been design taking benefits of intrinsic high gain of the technology and ultra-low power supply ability thanks to the backgate control.

Main Results

The challenge with power amplification is implied by the need to handle large output voltage swing which may cause transistor breakdown. The FDSOI technology proposes 4 different MOS transistors types: regular Vt (RVT) NMOS and flip well (LVT) PMOS have a P-well backgate. RVT PMOS and LVT NMOS have a N-well backgate. Thanks to this 4 active devices a compact, area optimized stacked structure has been proposed to enable 2*vdd power supply and high output swing while preventing any breakdown. A pushpull version of this structure (Figure 1) has been used which offer significant advantage of cancelling the AM-PM distortion for EVM improvement. The Power amplifier has been measured under probe and shows 23dm Psat output power and 18dBm, 8% EVM under 3.7v power supply (Figure 2).

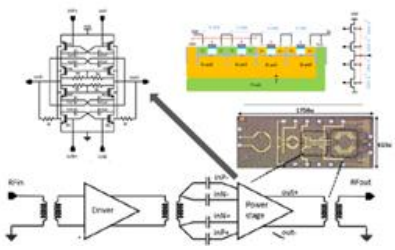


Figure 1: Pushpull cascoded structure of the power amplifier

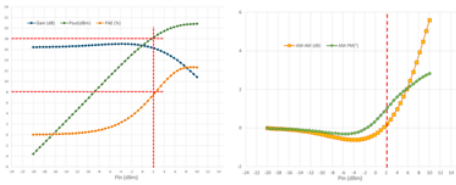


Figure 2: FDSOI 802.11ac compatible PA performance

With the proliferation of the Internet of Things (IoT) the battery lifetime is getting a great concern in design consideration. An LNA, as one of the main critical receiver block, has been design to prove the ultra-low power ability of the technology. An inductorless active gm boosted topology has been design for its silicon area compactness and high performance under low power supply. To reduce power consumption, either, the current consumption and the voltage supply need to be lowered. But the current is mainly responsible of RF performances thus reducing the power supply is mandatory. At constant RF performance (good input matching, 15dB gain, <7dB noise which is good enough for low power zigbee receiver) classical MOS technology is limited due to MOS transistor threshold limitation. Thanks to the back gate control of the FDSOI, the threshold voltage of the MOS transistor can be lowered thus enabling the use of ultra-low power supply. 30% of power supply can be saved as shown on figure 3.

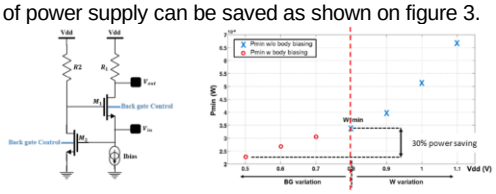


Figure 3: Minimum Power Consumption versus Vdd supply to fulfill LNA targeted performances reduction

Perspectives

Through the design of these two most critical blocs of the transmitter and the receiver, the intrinsic advantages of FDSOI for RF design has been pointed out. It paves the way for new RF design opportunity. Power scalable design are ongoing to exploit flexible power consumption regarding the highly environment dependent link budget especially in IoT

RELATED PUBLICATIONS:

[1] F. Hameau, J. Zaini, T. Taris, D. Morche, P. Audebert and B.Martineau, "New Design Opportunities exploiting FDSOI technology for RF Power Amplifier nd LNA design," 2019 17th IEEE International New Circuits and Systems Conference (NEWCAS), Munich, Germany 2019, pp. 1-4

[2] B. Martineau, E. Mercier, P. Vincent "Opportunity of CMOS FD-SOI for RF Power Amplifier" in 2017 IEEE SOI-3D-Subthreshold Microelectronics Technology Unified Conference (S3S), Burlingame, CA, 2017, pp. 1-2.

[3] J. Zaini, F. Hameau, T. Taris, D. Morche, P. Audebert and E. Mercier, "A tunable Ultra Low Power inductorless Low Noise Amplifier exploiting body biasing of 28 nm FDSOI technology," 2017 IEEE/ACM International Symposium on Low Power Electronics and Design (ISLPED), Taipei, 2017, pp. 1-6.

Benefits of Joint Optimization of Tunable Wake-up Radio Architecture and Protocols

RESEARCH TOPIC:
IoT, Wake-Up Radio, Ultra Low Power, FD-SOI, Protocols

AUTHORS:
Dominique MORCHE, Mickaël MAMAN, Baudouin.MARTINEAU, Clément JANY

With the massive deployment of IoT, Wake-up Radio, which represents the ultimate frontier in low power communication, has received an increased interest. However, when considering the different applications, the requirements are widely spread in terms of range, energy consumption, latency or protocols. This results in a large panel of wake-up radio hardware solutions. At the same time, advanced submicron technologies such as 28nm FD-SOI technologies offer the opportunity to develop improved solutions. We have proposed a new wake-up radio architecture exploiting highly tunable building blocks. Then, based on a simplified model of the wake-up, we have analyzed the capability of the protocol to exploit this flexibility to improve the performance and to answer the requirements of the different applications.

SCIENTIFIC COLLABORATIONS: Columbia University, IRISA Lannion

Context and Challenges

With the massive deployment of IoT applications, long lifetime networks are mandatory and very challenging. To optimize the network lifetime, it is crucial to design ultra-low power communication systems. Several technologies are competing for low power uplink communications (e.g., LoRa, Sigfox, Bluetooth, Thread, Zigbee and WiFi). But when interaction with IoT devices is mandatory, ultra-low power as well as predictable latency Downlink communications are missing. Traditionally, this problem has been addressed by low-power radios and duty-cycling protocols. The proposed approach to drastically reduce the power consumption is to switch off the main receiver, while introducing a new wake-up circuitry capable of detecting an incoming transmission that has only little information to transmit

Main Results

To justify its interest, the wake-up module cannot limit its compatibility to a single use case, it should cover a wide range of applications. Tunability is therefore requested for all building blocks to extend the application range. Lastly, the impact of the wake-up module should be negligible on to the system cost. It should therefore avoid any additional component and occupy a limited area. Our proposed wake-up module [1] follow these requirements, as depicted in Figure 1.

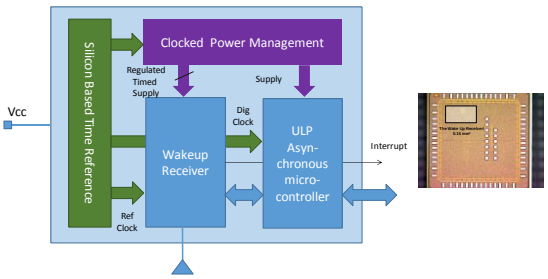


Figure 1 : Description of the Wake Up Module

The module integrate the wake-up receiver, the dedicated power management, a silicon RC based Time Reference for duty cycling and an asynchronous microcontroller for potentially processing the datas collected from the wake-up radio. As a function of the chosen protocol, one block or the other could be the more critical and is therefore tuned accordingly. To analyze the impact of the protocol, we have developed some simplified models of the wake-up module which are activated by the chosen protocol in an event-driven approach. It becomes possible to evaluate the power of the whole system for different parameters, as described in the figure 2. It shows that that WuR offers a better latency while consuming negligible power but at the cost of the sensitivity.

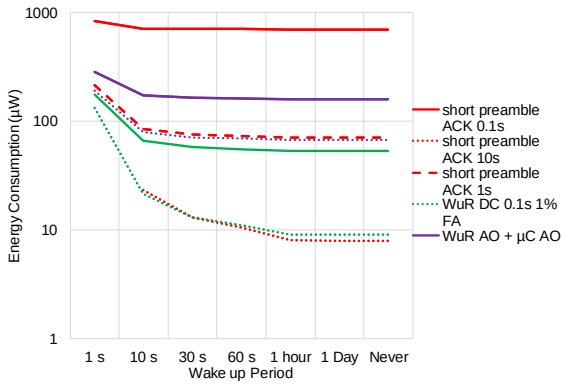


Figure 2 : Description of the Wake Up Module

Perspectives

Thanks to the proposed approach, further optimization is possible, especially by achieving a tradeoff between the energy consumption of the low power clock and the impact of its imperfection in DC (DutyCycled) WuR. A two steps wake-up protocol can also be exploited to have a more efficient wake-up sequence. Last but not least, some analysis are ongoing to exploit the wake-up mode to collect some Information on the spectrum occupancy and signal availability, paving the way for new applications of the wake-up module.

RELATED PUBLICATIONS:

[1] S. Patil, A. Ratiu, D. Morche and Y. Tsividis, "A 3–10 fJ/conv-step Error-Shaping Alias-Free Continuous-Time ADC," in IEEE Journal of Solid-State Circuits, vol. 51, no. 4, pp. 908-918, April 2016,

[2] B.Martineau, C.Jany, "Towards Fully Integrated 28nm UTBB FD-SOI IoT Node: the sub-50µW RF Receiver" 2016 IEEE S3S Conference, October 10 - 13, 2016 San Francisco,

[3] M.Maman, D.Morche, B.MArtineau, C.Jany et al. "Benefits of Joint Optimization of Tunable Wake-up Radio Architecture and Protocols " 25th IEEE International Conference on Electronics, Circuits and Systems (ICECS), December 2018, pp. 789-792

Energy Efficient Channel State Classification and Low Complexity Interference Detection for LPWA IoT Networks

RESEARCH TOPIC:

Internet of Things, Low Power Wide Area networks, Channel State Information, Ultra-Low Power transceivers, SDR

AUTHORS:

Chhayarith Heng UY, Carolynn BERNIER, Sylvie CHARBONNIER

Energy efficient and accurate channel state classification is a desired property for long-lifetime IoT LPWA applications. Identifying channel state is useful for selecting the optimum trade-off between transceiver performance and amount of saved energy, without impacting transmission quality. In addition, with the development of Low Power Wide Area (LPWA) wireless networks deployed over shared ISM (Industrial, Scientific, Medical) RF bands, the probability of interference and frame collisions has significantly increased.
This work uses an experimentation-based machine learning approach to develop indicators and classifiers that can be used for these tasks while considering the limited ressources of ULP LPWA transceivers.

SCIENTIFIC COLLABORATIONS: GIPSA-LAB (UGA)

Context and Challenges

Current Low Power Wide Area Network (LPWAN) RF transceivers are designed, or configured at deployment time, to function assuming a worse-case application scenario. Most of the time, they thus waste a significant amount of energy when operated under favorable channel conditions. In addition, many LPWA applications are deployed over shared ISM (Industrial, Scientific, Medical) bands. With the recent and widespread development of these networks, the probability of interference and frame collisions has significantly increased. In this context, real-time channel quality and interference monitoring provides precious information for network planning, base-station installation site selection, congested area detection, etc.

Main Results

Since COTS transceivers do not allow access to DBB algorithms, a software radio (SDR) platform is needed to generate realistic data for classifier training and testing. Physically, the SDR platform is composed of three (an emitter, a receiver and an interference source) universal software radio peripherals (USRP) placed in a 5 m x 4 m room. Modem algorithms for IEEE802.15.4-2015 LECIM FSK physical layer are implemented in Matlab. Our approach consists in designing a low complexity Channel Analysis Signal (CAS) based on existing DBB signals, as well as a set of low complexity Channel State Indicators (CSI), such as Average Crossing Count (ACC), illustrated in Fig. 1. Thanks to a single CSI value computed per correctly received frame, channel quality can be assessed using simple threshold-based classifiers.

In [1], a low complexity channel state indicator and a simple mono-feature classifier for channel state recognition are proposed. The classifier is trained using the experimental data acquisitions and has a 96% accuracy. Specially designed for LPWA applications, the classifier is capable of distinguishing undisturbed channels from those suffering from both mobility-induced fading and interference, while operating at low to medium SNR (Fig.1).

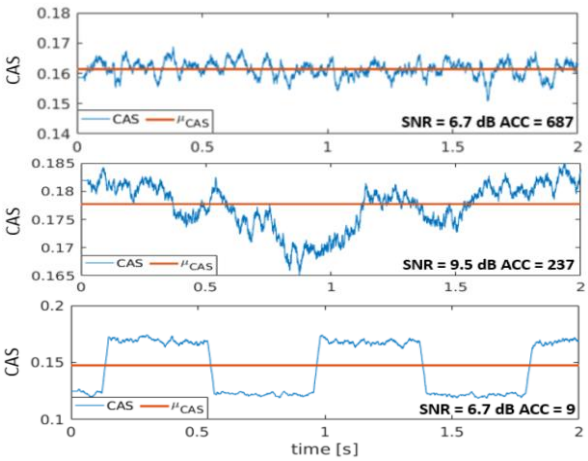


Fig. 1 CAS and ACC for frames labelled as 'undisturbed' (top), 'fading' (center) and 'interference' (bottom)

In [2], our experimental USRP framework is also used to design a low complexity interference detector for mobile LPWA nodes. A first classifier is used to detect the presence of interference and shows a detection accuracy of 94%. If interference is detected, a second classifier is used to classify the interference's relative strength into ten classes with a correct classification rate up to 97%.

Perspectives

As in most machine learning approaches, one of the main challenges observed during this work concerned the generation and labelling of data. In future work, incremental learning approaches will be experimented even during the data acquisition phase of our experiments. In addition, seeing that the wireless medium is unpredictable, future work will address the online learning of new interference scenarios.

RELATED PUBLICATIONS:

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[2] C. Heng Uy, C. Bernier, S. Charbonnier, "Design of a Low Complexity Interference Detector for LPWA Networks," IEEE International Instrumentation and Measurement Technology Conference (I2MTC), May 2019.

Localization system in GPS-denied environments using radar and IMU measurements: application to a smart white cane

RESEARCH TOPIC: t
Radar, sensor fusion, localization and autonomous navigation

AUTHORS:
Jeremy BARRA, Suzanne LESECQ, Mykhailo ZARUDNIEV, Olivier DEBICKI, Nicolas MAREAU, Laurent OUVRY

This overview presents the development of a localization system in GPS-denied environments using an Inertial Measurement Unit (IMU) and a Pulse-Doppler radar. A ground speed estimation from radar measurements is first proposed. This estimation is combined with noisy measurements from an IMU in a Luenberger observer, allowing accurate dead-reckoning. The methodology proposed provides short-term position of the sensors embedded in a white cane, the ultimate goal being obstacle detection through the computation of a model of the surroundings. The results show that this solution allow to obtain an error rate up to hundred times better than conventional techniques.

Context and Challenges

According to the World Health Organization, 1.3 billion people are estimated to be visually impaired worldwide. For these people, the risks of falls and collisions in unknown environments is increased. In this context, Electronic Travel Aids (ETA) could help to improve the statistics of accidents by providing to the information about the surroundings. In the context of the INSPEX project [1], several sensors including a Pulse-Doppler radar and an IMU are embedded on a white cane Figure 21. The IMU contains 3-axis accelerometer, gyroscope and magnetometer. In the context of localization and accurate computation of the occupancy grids the precise knowledge of the sensors position and their orientation over the observation time is researched.

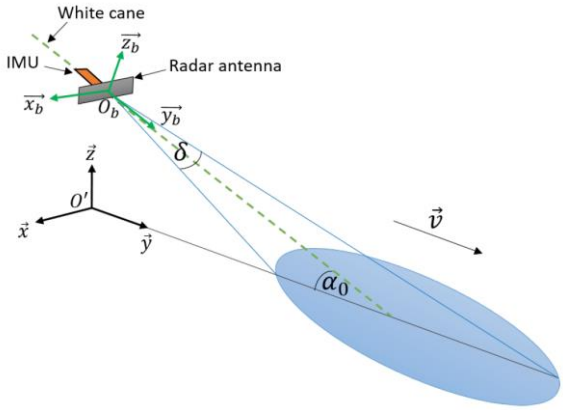


Figure 21 White cane sensors configuration

The white cane motion is unconstrained in 3D space and there are different situations in which the user can be found other than stable walk. The solutions proposed in the literature often rely on strong assumptions on the motion of the mobile, e.g. on the step length of the user or the swing motion of the white cane. However, these assumptions can easily be unsatisfied. For example, the step of a user walking in a crowded environment will be shorter than in normal situation. For this reason a hypothesis-based dead-reckoning approach such as a white cane adapted SHS or ZUPT-INS algorithm is not suitable in the white cane localization approach. We suggested to extend the hypothesis of the white cane dynamics to the unconstrained motion and to use radar sensor allowing unbiased and more precise ground speed estimation than IMU sensor.

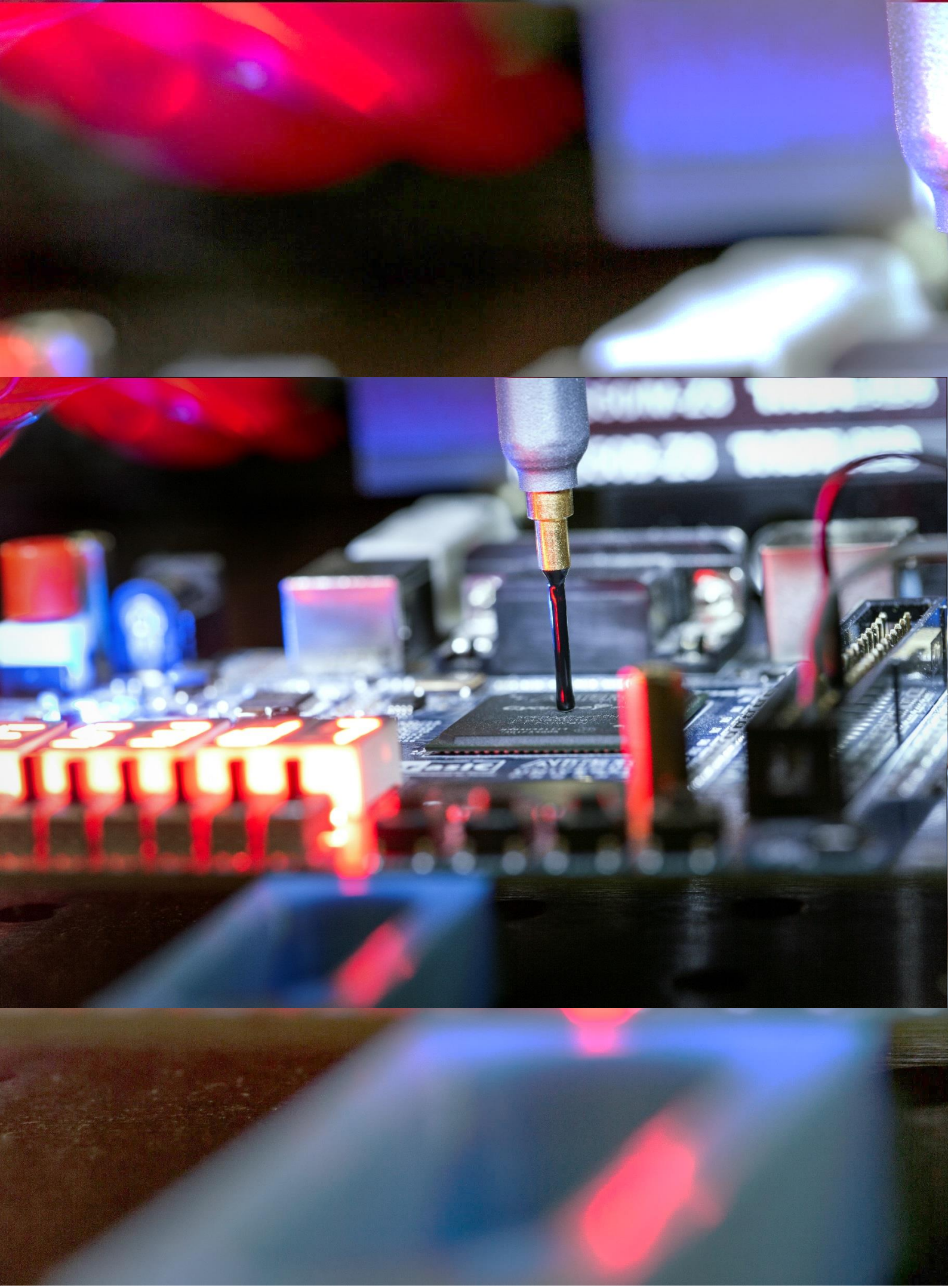
Main Results

Coupling the ground-speed estimate from the radar range-Doppler measurements with the information extracted from IMU measurements allows to address a large variety of movements of the white cane and reduce the error of estimation compared to the only IMU approach [2]. The variety of possible movements of the white cane is considered with a general model of the sensor motion derived from the standard dynamics equations. In this model, the linear acceleration of the white cane is considered constant over the sampling period. This assumption is valid because the IMU measurements are acquired at frequency of 100Hz which is much higher than the motion dynamics. In the literature, the localization problem using on-board sensors such as an IMU is usually solved with a Kalman filter. Such a solution has been also implemented and the results obtained are similar in terms of final precision. The main drawback of the Kalman filter, is that it requires more computational workload. Since the proposed solution is targeted to be integrated on a low computing capability microcontroller with fixed-point arithmetic, the Luenberger observer seems to be a better option from a computational and the stability point-of-view. The main interest of the radar coupling with IMU and the chosen sensor fusion approach is shown in Table 1.

Table 1

	Radar/IMU Luenberger	Radar/IMU Kalman	Adapted SHS	Naive INS
Error max	$2.7m$	$2.7m$	$3.9m$	$246m$
Error sd σ	$0.5m$	$0.4m$	$0.9m$	$74m$
Error mean	$1.3m$	$1.3m$	$1.9m$	$132m$
Error growth rate	$0.026m/s$	$0.026m/s$	$0.038m/s$	$2.64m/s$

RELATED PUBLICATIONS:
[1] INSPEX H2020 project. Integrated smart spatial exploration system, accessed in november 2018. www.inspex.com.
[2] J. Barra, S. Lesecq, M. Zarudniev, O. Debicki, N. Mareau and L. Ouvry, "Localization system in GPS-denied environments using radar and IMU measurements: Application to a smart white cane," 2019 18th European Control Conference (ECC), Naples, Italy, 2019, pp. 1201-1206.



07 SECURITY OF EMBEDDED SYSTEMS

- Attacks
- Characterizations
- Trusted components

Deep Learning to Evaluate Secure RSA Implementations

RESEARCH TOPIC:
Side-Channel Attacks, RSA, Deep Learning, Security Evaluation

AUTHORS:
Marie-Angela CORNELIE, Cécile DUMAS

Side-channel analysis (SCA) is a class of cryptanalytic attacks that exploits the physical environment of a cryptosystem implementation to recover some leakage about its secrets.
This paper shows the high potential of deep learning attacks against secure implementations of RSA. The analyses have been conducted by three experts' teams, each working on a specific attack path and exploiting information extracted either from the electromagnetic emanation or from the power consumption.
This work raises the need for dedicated countermeasures for asymmetric cryptography against deep learning attacks.

SCIENTIFIC COLLABORATIONS: **ANSSI, SERMA SAFETY AND SECURITY, THALES ITSEF**

Context and Challenges

Side-channel attacks (SCA) exploit secret information which leaks from the physical implementations of cryptographic algorithms. They are often much more efficient than cryptanalysis mounted in the so-called black-box model where no leakage occurs, and dedicated countermeasures are usually implemented to protect the execution of cryptographic algorithms on embedded systems. This is especially true for RSA implementations where resistance against side-channel attacks is achieved by defining a secure exponentiation algorithm based on a secure arithmetic coprocessor.
When it comes to assessing the robustness of an RSA implementation against the SCA threat, several attacks are performed by experts, usually after a leakage characterization step. Among them, the so-called family of profiled SCA is recognized as the most effective one since the underlying adversary is assumed to priorly use an open copy of the final target to precisely tune all the parameters of the attack.
This attack strategy where the adversary precedes the attack by a supervised training phase may be viewed as a classical Machine Learning problem and a recent line of work [1] has started to build connections between the world of side-channel analysis and the world of Machine Learning (with a particular focus on Deep Learning). Few works have been published on secure asymmetric cryptographic implementations [2,3,4]. The main challenge when attacking secure RSA implementations is that the attack must be able to recover more than 90 % of the secret parameter from a single execution.

Main Results

This paper presents the first full profiled attack against an RSA implementation running on a certified arithmetic coprocessor and equipped with classical side-channel countermeasures. Three different teams have co-jointly done the work, each working on a specific attack path. For completeness, and because this information is often missing in the literature while being of important practical interest, we have detailed all the attack steps (identification of the attack paths, acquisitions, pre-processing, attacks) that are usually followed to evaluate the security of an implementation in a security laboratory. These attacks results, which exploit different kinds of leakages measured either through the power consumption or the electromagnetic emanation of the devices, show the high potential of deep learning attacks (and in particular CNN models) against secure implementations of RSA. The architectures of the best-trained models are given for information, as seen in figure 1. The figure 2 shows the efficiency of the training, as the accuracy reaches the maximal value.

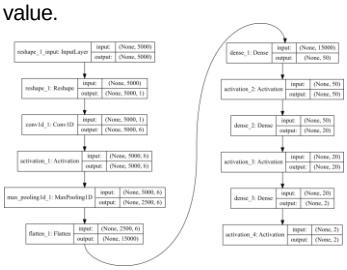


Fig 1: best-trained models

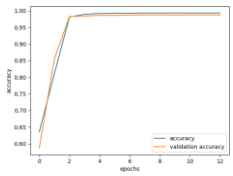


Fig 2: results

Perspectives

A careful analysis of the security and efficiency of these countermeasures and/or the design of new ones are open avenues for further research. Replacing the exponentiation algorithm by another one is not a solution since collisions are still exploitable (as argued in [3]). A possible approach is to frequently re-randomize the internal state as proposed in [3] or to re-randomize the output of each modular operations as proposed in [5]. Another possibility is to mix (in a random order) several exponentiation routines.

RELATED PUBLICATIONS:
[1] E. Cagli, C. Dumas, E. Prouff: Convolutional neural networks with data augmentation against jitter-based countermeasures. CHES 2017.
[2] L. Lerman, G. Bontempi, O. Markowitch: Power analysis attack: an approach based on machine learning. IJACT 2014.
[3] A. Bauer, É. Jaulmes, E. Prouff, J. Wild: Horizontal and vertical side-channel attacks against secure RSA implementations. CT-RSA 2013.
[4] R. Poussier, Y. Zhou, F.-X. Standaert. A systematic approach to the side-channel analysis of ECC implementations with worst-case horizontal attacks. CHES 2017.
[5] V. Dupaquis, A. Venelli: Redundant modular reduction algorithms. CARDIS 2011.

Deep Learning for Side-Channel Analysis and Introduction to ASCAD Database

RESEARCH TOPIC:
Side-Channel Attacks, Convolutional Neural Networks, Deep Learning, Evaluation tool, Trace Misalignment

AUTHORS:
Eleonora CAGLI, Cécile DUMAS

Deep learning algorithms are known to be efficient to conduct security evaluations of embedded systems. Unfortunately, their hyper-parametrization has often been kept secret by the authors who only discussed on the attack efficiencies in some specific contexts. We propose here a comprehensive study of deep learning algorithms when applied in the context of side-channel analysis, and address in particular the question of the choice of the hyper-parameters. To enable perfect reproducibility of our tests, this work also introduces the first open platform, named ASCAD, including all the sources of the target implementation together with the campaign of electromagnetic measurements exploited in our benchmarks in order to serve as a common basis for further works.

SCIENTIFIC COLLABORATIONS: ANSSI (Ryad Benadjila, Emmanuel Prouff, Rémi Strullu)

Context and Challenges

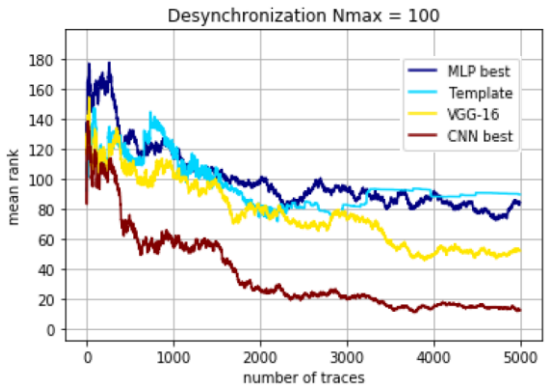
Side-channel attacks (SCA) exploit information which leaks from the physical implementations of cryptographic algorithms. Among SCA, the family of so-called *profiling* attacks is actually the most powerful one since the underlying adversary is assumed to primarily use an open copy of the final target to precisely tune all the parameters of the attack. It includes Templates Attacks [1] and Deep Learning (DL) algorithms like multi-layer perceptron (MLP) or convolutional neural networks (CNN) [2]. While DL offers a promising alternative to the state-of-the-art attacks, especially when the measurement dimension is high and/or the measured signal suffers from deformation like jittering, the application context of the previous works is too weak or the amount of information on the involved Deep Learning techniques is too limited to draw solid conclusions for challenging contexts (i.e. where the target implementations include state-of-the-art countermeasures) and/or to improve these first attempts. This is clearly an important limitation of previous works since (1) the latter parametrization is known to be a challenging question in Machine Learning and (2) it does not allow for the reproducibility of the presented results and (3) it does not allow to draw general conclusions.

Main Results

We conduct a comprehensive and in-depth study of the application of DL theory in the context of SCA. In particular, for the first time, we discuss several parametrization options and we present a large variety of benchmarks which have been used to either experimentally validate our choices or to help us to take the adequate decision.

Our study also shows that CNNs are almost as efficient as MLP networks in the context of perfectly synchronized observations, and outperform them in presence of desynchronization/jittering. This suggests that CNN models should be preferred in the context of SCA.

When it comes to choosing a base architecture for the latter models, our study shows that, surprisingly, the 16-layer network VGG-16 used by the VGG team in the ILSVRC-2014 competition [3] is a sound starting point. It allows us to design architectures which, after training, are better than classical Templates Attacks even when combined with dimension reduction techniques like Principal Component Analysis [4]. By training our CNN *best* architecture on the ASCAD database, we outperformed the other tested models on highly desynchronized traces while we achieved one of the best performances on small desynchronized traces as seen on the following figure, where the true key will be ranked first faster for CNN best (i.e. the true key is recovered with less traces).



Perspectives

The methodologies followed for the hyper-parameters selection may be viewed as a proposal to help researchers to make their own choice for the design of new deep learning models. They also open the way for further research in this domain.

We think that this published ASCAD database may serve as a common basis for researchers willing to compare their new architectures or their improvements of existing models.

RELATED PUBLICATIONS:
[1] Chari S., Rao J., Rohatgi P.: Template Attacks. CHES 2002.
[2] Cagli E., Dumas C., Prouff E.: Convolutional neural networks with data augmentation against jitter-based countermeasures. CHES 2017.
[3] Simonyan K., Zisserman A.: Very deep convolutional networks for large-scale image recognition. arXiv preprint arXiv:1409.1556 (2014).
[4] Pearson K.: On Lines and Planes of Closest Fit to Systems of Points in Space. Philosophical Magazine 2(11), 559-572 (1901)

Gradient Visualization for General Characterization in Profiling Attacks

RESEARCH TOPIC:
Side-Channel Attacks, Convolutional Neural Networks, Deep Learning, Evaluation tool, Trace Misalignment, Masking

AUTHORS:
Loïc MASURE, Cécile DUMAS

In Side-Channel Analysis, neural networks have been shown to efficiently extract sensitive information from implementations running on embedded devices. Yet, those techniques are seen as black box, which raises problems in a security evaluation context.
This paper introduces a new tool called *Gradient Visualization* that aims to proceed a *post-mortem* information leakage characterization after the successful training of a neural network.
The efficiency of the proposed method does not depend on the particular countermeasures that may be applied to the measured traces.

SCIENTIFIC COLLABORATIONS: ANSSI, Emmanuel Prouff

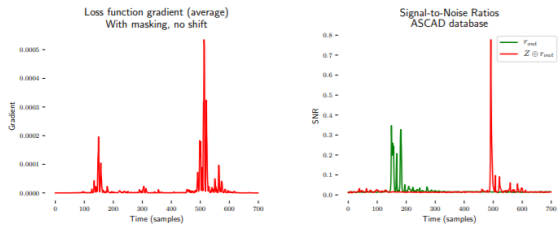
Context and Challenges

Side-Channel Attacks (SCA) aim at recovering secret-key dependent information based on physical measurements of the chip. To prevent these attacks, chip manufacturers commonly implement countermeasures, for example misalignment in the measurement sets or information masking.
Over the past few years, convolutional neural networks (CNN) have become a standard tool for evaluating side-channel attacks on embedded devices. In particular, a previous work conducted by ITSEF in CEA [1] has drawn a great interest of the SCA community about the use of such tools, since they can overcome the usual countermeasures.
Yet, a part of this community remained sceptical. Indeed, these tools were seen as black-box models, which prevent the evaluator from clearly knowing which vulnerability is exploited by the neural network. This issue is part of a more general problematic in Deep Learning based systems, namely their explainability and interpretability.

Main Results

In this paper, we propose to apply a method called Gradient Visualization (GV) in order to better understand how a CNN can predict the true information based on the analysis of a single measurement. The main claim is that CNN succeed in localizing inside the measurement the relevant information from the noise, by computing a specific gradient with respect to the input traces.
This gradient can be visualized and interpreted by a human. We theoretically show the soundness of this technique. The efficiency of the proposed method does not decrease when the usual countermeasures like masking or misalignment are applied. In addition, the characterization can be made for each trace individually.
We empirically show that Gradient Visualization is at least as good as state-of-the-art characterization methods, in presence or not of different countermeasures.

The following figure shows results obtained for a device protected by masking.



The left part presents a GV, compared with a state-of-the-art characterization method in the right part. It may be observed that the peaks obtained with both methods are identical. More generally both methods target the same clock cycles.
However, the right visualization has been obtained by using *privileged knowledge* about the target device, whereas the GV method did not require such knowledge. In that sense, GV outperforms state-of-the-art characterization techniques.
This visual information constitutes a useful argument for the evaluator in order to help the developer to localize and understand where the vulnerability comes from in order to remove or at least reduce it.

Perspectives

Further work would study such a technique in presence of both desynchronization and masking, or in presence of higher order masking scheme. More generally, this work is part of a growing field of interest in the SCA community [3,4].

RELATED PUBLICATIONS:
[1] Cagli, E., Dumas, C., Prouff, E.: Convolutional neural networks with data augmentation against jitter-based countermeasures. CHES 2017.
[2] Montavon, G., Samek, W., Müller, K.R.: Methods for interpreting and understanding deep neural networks. Digital Signal Processing 2018.
[3] Hettwer, B, Gehrer, S, Güneysu, T, : Deep Neural Network Attribution Methods for Leakage Analysis and Symmetric Key Recovery. SAC 2019.
[4] Timon, B, : Non-Profiled Deep Learning-based Side-Channel attacks with Sensitivity Analysis. TCHES 2019.

Analyzing Software Security against Complex Fault Models with Frama-C Value Analysis

RESEARCH TOPIC:
Software analysis of hardware fault attacks

AUTHORS:
Johan LAURENT, Christophe DELEUZE, Vincent BEROULLE, Florian PEBAY-PEYROULA

As technology evolves, digital systems are becoming more vulnerable to hardware faults, while also increasing in complexity. Analyzing the security of a program hence requires powerful techniques such as static code analysis. The methods developed so far usually apply these techniques with a specific software fault model. However, the effects a fault can occur on a program are very diverse, and are not fully considered by representative software fault models. In this paper, we present a method to instrument a code with complex fault models, and we use it with a tool based on abstract interpretation to verify that some security properties are preserved whatever the user inputs. The tool allowed us to find vulnerabilities (validated with RTL simulation) that would be difficult to find with other tools. Finally, we discuss the benefits and drawbacks of the method.

Context and Challenges

Various methods are used to analyze the security of programs against hardware fault attacks [1], [2]. These methods are based on software fault models such as instruction skip, test inversion or register corruption. However, as shown in previous works [3], it is possible, by analyzing the microarchitecture of a processor, to find unexpected faulty behaviors that can defeat typical countermeasures and lead to successful attacks on actual applications. Since these behaviors are not taken into account in typical software fault models, they are also not detected by the aforementioned analysis methods.

To enhance the security of programs, it is thus required to find a way to represent microarchitecture-specific software fault models, and to analyze programs according to this representation.

Main Results

The software representation needed to satisfy several requirements. It needed to be sufficiently generic to represent faulty behaviors that are very different from one another. It should also be able to represent the behavior of a processor pipeline; and to be easily integrated into existing tools to analyze the security of applications.

The chosen solution was to first represent the assembly code of the application at the C level: each assembly instruction was taken separately and replaced by an equivalent sequence of C instructions. Then, a software fault model described in a configuration file could be inserted in the resulting C program. This tool thus created mutants of the original program, according to a user-specified fault model. The decision to use C-level representation was motivated by the fact that it is used in many analysis methods.

In particular, we decided to use static analysis methods because these are used to statically deduce properties about a program. We intended to use these tools to verify if some security properties in a given program were preserved even when attacked by one of our fault models.

We focused on Frama-C value analysis. It is a method based on abstract interpretation, i.e. it abstracts the semantics of an application. More specifically, it can analyze the state of a program using intervals of values instead of concrete values. We used this method to check if a PIN verification was secure for all users and secret PINs.

With this tool, we were able to show that certain combinations of PIN were more vulnerable than others when using specific fault models. The attacks were simulated at the Register-Transfer Level to demonstrate that these vulnerabilities were indeed exploitable by injecting single-bit faults.

Finally, we also discussed some of the limitations of our approach, including the fact that the analysis proves that there is no possible or convincing attack, in this case a manual analysis is required. It can also be difficult to find the right security assertions to use.

Perspectives

A first perspective would be to find a way to automatically extract counter-examples to help in the manual analyses when the analysis does not conclude. Another perspective would be to experiment with other analysis tools. In this paper we only focused on Frama-C value analysis, but the mutation tool we presented is sufficiently general to be used with other analysis approaches.

This work was funded thanks to the French national program "Programme d'Investissement d'Avenir IRT Nanoelec" ANR-10-AIRT-05.

RELATED PUBLICATIONS:

[1] M. Christofi, B. Chetali, L. Goubin, and D. Vigilant, “Formal verification of an implementation of CRT-RSA algorithm,” presented at the Security Proofs for Embedded Systems (PROOFS), 2012, pp.28–48.

[2] M. L. Potet, L. Mounier, M. Puys, and L. Dureuil, “Lazart: A Symbolic Approach for Evaluation the Robustness of Secured Codes against Control Flow Injections,” in Verification and Validation 2014 IEEE Seventh International Conference on Software Testing, 2014, pp. 213–222.

[3] J. Laurent, V. Beroulle, C. Deleuze, F. Pebay-Peyroula, and A. Papadimitriou, “Cross-layer analysis of software fault models and countermeasures against hardware fault attacks in a RISC-V processor,” *Microprocessors and Microsystems*, vol. 71, p. 102862, Nov. 2019, doi: 10.1016/j.micpro.2019.102862.

Cross-layer Analysis of Software Fault models and Countermeasures Against Hardware Fault Attacks in a RISC-V Processor

RESEARCH TOPIC:
Hardware fault attacks, RISC V

AUTHORS:
Johan LAURENT, Vincent BEROULLE, Christophe DELEUZE, Florian PEBAY-PEYROULA, Athanasios PAPADIMITRIOU

Fault injection is a powerful technique for attacking digital systems. Software fault models have been developed to attempt to predict these faults. However, these models are often designed independently of any hardware consideration and therefore introduce the problem of realism. The generality of these models often cannot account for the specificities of each architecture. Consequently, software countermeasures based on such software fault models do not guarantee an adequate protection against fault attacks. A cross-layer approach can then be developed, using conjointly hardware and software characteristics to design stronger software countermeasures with reasonable overheads. To illustrate this assumption, this paper shows actual faulty behaviors observed in a RISC-V processor RTL simulation, and shows that they can bypass countermeasures designed to protect against faults predicted by typical software fault models.

Context and Challenges

To protect software programs against hardware fault injection, developers use various software countermeasures. These countermeasures are designed to thwart software fault models [1] that aim at representing the behavior of faults at the software level. However, these models are often applied independently from the processor microarchitecture on which the program will be executed. Why would an attack on processor A lead to the same faulty behaviors as processor B? Typical software fault models are useful for their simplicity, but they cannot take into account the specificities of each processor. This lack of accuracy from software fault models in turn leads to potential attacks undetected by typical software countermeasures. This paper illustrates these facts by analyzing the microarchitecture of a RISC-V processor.

RTL simulations were used to inject faults in the processor, using single bit-flips as the RTL fault model. The Attacks focused on processor pipeline, excluding faults in the memory or the register-file. Indeed, the structure of the pipeline is the main feature that changes between different processors, and it is therefore a good candidate to detect unexpected faulty behaviors.

Main Results

The microarchitecture analysis has revealed some interesting faulty behaviors that were not predicted by typical software fault models. In particular, optimization structures in the processor, such as forwarding, need to be studied carefully: they are one reason why there are inaccuracies between the software view and reality. Typical software fault models often result from a simplistic view of a processor while in reality various optimizations make the microarchitecture complex. As an example, we found that it is possible to skip instruction i without affecting instruction i+1 nor its result, even if instruction i+1 depends on the result of instruction i. While this makes no sense with a purely software point of view, it is actually possible by exploiting the forwarding optimization in the processor.

We could also show that in our processor, some values and registers seem more sensitive to faults than others, and some attacks depend on the context of execution. Most of these attacks are difficult to predict without undertaking an accurate analysis of the microarchitecture of the processor.

After demonstrating these various behaviors, we also used them to bypass various countermeasures [2] based on instruction duplication, and a control-flow integrity. This shows once again that not taking into account the microarchitecture of a processor during a security analysis leads to unmitigated attack vectors.

Perspectives

This work demonstrates that there is still a lot to learn about possible faulty behaviors in a processor by studying its microarchitecture. However, we only showed examples of these behaviors and how they can impact some typical software countermeasures. One perspective would then be to develop an appropriate approach to model these behaviors more exhaustively, and to find a way to analyze programs with these new, microarchitecture-specific, software fault models.

This work was funded thanks to the French national program "Programme d'Investissement d'Avenir IRT Nanoelec" ANR-10-AIRT-05.

RELATED PUBLICATIONS:
[1] Joint Interpretation Library, “Application of attack potential to smartcards.”Jan-2013.
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SPN-DPUF: Substitution-Permutation Network-based secure circuit for digital PHYsical Unclonable Function

RESEARCH TOPIC:
Physical Unclonable Function, Robust PUF, Digital PUF, Security Evaluation, Substitution Permutation Network

AUTHORS:
Johan MARCONOT, David HELY, Florian PEBAY-PEYROULA

We focus on the conception of efficient Physical Unclonable Functions, hardware primitives that are used to generate for instance a chip's signature or cryptographic keys. Such primitives are being intensively studied in order to integrate them in processing architecture to provide efficient security services. We studied in this publication [1] a novel category: a digital PUF (DPUF) that exploits structural variation in the silicon layers of the chips to generate signatures. We present the DPUF proposals from the current PUF literature. We identify the limits and weaknesses of the logical circuits that are used to generate the responses from the random structures. Then we propose new models of extraction circuits combining the random structure with a Substitution-Permutation Network to enhance the security properties of the DPUF responses. We present our “SPN-DPUF” primitive and implementation model that offers a security-cost trade-off, reducing the constraints on circuit size and structure randomness.

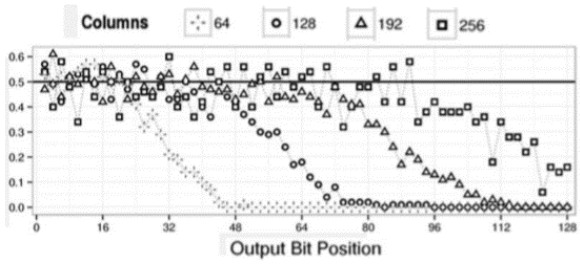
Context and Challenges

Physical Unclonable Functions (PUFs) are known as efficient authentication mechanisms for Integrated Circuit (IC). Generally, PUFs measure a chosen physical variable (e.g. time, frequency …) to extract a unique chip signature. However, the conventional PUFs are usually based on continuous physical or analogical measurements that are sensitive to external parameters (temperature, humidity …) and to ageing. A PUF response could then not be extracted without errors leading to a wrong authentication.

In recent years, Digital PUFs (DPUFs) primitives have been proposed: they exploit structural variations – interconnections randomly interrupted – obtained by fluctuations of a customized manufacturing process. Since the structures are inherently robust, they can be used as measurable robust parameters. However, for digital PUFs, an adequate extraction circuit is required. Such a circuit must comply to low cost implementations and secure scheme for the challenge-response mechanism generation, in order to respect both performance and security objectives.

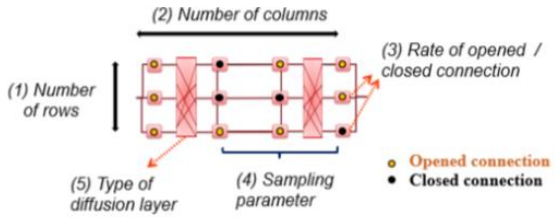
Main Results

We first review the existing DPUF fabrication processes and associated extraction circuits from the literature, then we discuss possible optimizations in terms of cost and security. We deploy a platform for the modelization and evaluation of extraction circuit scheme.



In our review, we point out the lack of diffusion of the previous extraction circuits proposed in the literature (the XOR extraction circuit from the SD-PUF). This diffusion property aims at characterizing similarities between signatures generated for authentication protocols. Weak diffusion can lead to a risk of usurpation through the generation of incorrect signatures. The previous figure illustrates this issue for the XOR extraction circuit: one-bit variation submitted to the DPUF cannot be entirely diffused to the extracted signature.

We propose a new model, which integrates a substitution-permutation network to enhance the diffusion. We used 4-bits SBOX that reduces the surface cost of the circuit. This primitive is named “SPN-DPUF” and is defined by several parameters that are described in the next figure. The main challenge here is to identify the parameters that limit the required circuit surface, especially with regard to the dimension of the physical structure. Using adequate sampling rate for the diffusion layer we can find a trade-off between size and diffusion property. We also conducted a study to optimize the configurations in order to reduce size constraints while preserving DPUF randomness.



Perspectives

Our results can be used by designers to build an efficient extraction circuit. Additional evaluation on simulated hardware architecture should be realized to take into account performances factors such as frequency and energy consumption.

This work was funded thanks to the French national program "Programme d'Investissement d'Avenir IRT Nanoelec" ANR-10-AIRT-05.

RELATED PUBLICATIONS:
[1] « Motivation and Contribution for Novel Digital Disorder based Strong PUF Design”, J. Marconot, D. Hely, F. Pebay-Peyroula, ISVLSI.

Adaptive Masking: a Dynamic Trade-off between Energy Consumption and Hardware Security

RESEARCH TOPIC:

Side channel attacks, hardware counter-measures, cryptography, Trivium, adaptative masking

AUTHORS:

Maxime MONTOYA, Thomas HISCOCK, Simone BACLES-MIN (LIST), Anca MOLNOS (LIST), Jacques FOURNIER

As IoT devices process and communicate an increasing amount of sensitive data, the confidentiality of these data is a growing concern. Hardware side-channel attacks pose a threat against the implementation of encryption commonly used to ensure this confidentiality. Traditional countermeasures against such side-channel attacks, like masking, usually introduce a high energy overhead, which might pose problems to resource-constrained IoT devices. Furthermore, the energy or security constraints may vary between devices or over time, depending on, e.g., the remaining battery level or data sensitivity. In this work, we introduce a new paradigm whereby hardware masking is applied on demand to increase the energy efficiency and allow users to have a dynamic trade-off between security and power consumption. We illustrate this concept by applying it to the stream cipher Trivium.

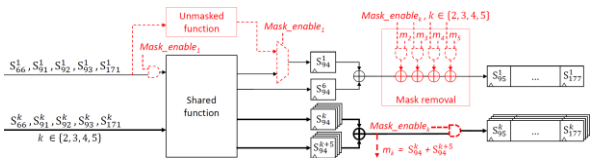
SCIENTIFIC COLLABORATIONS: CEA-LIST

Context and Challenges

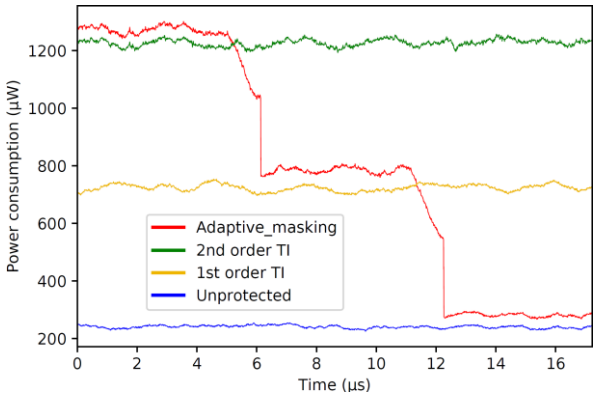
As the Internet of Things (IoT) devices process and communicate an increasing amount of sensitive data, the confidentiality of these data is a growing concern. Hardware side-channel attacks pose a threat against the physical implementation of encryption, which is commonly used to ensure this confidentiality. Traditional hardware countermeasures against such side-channel attacks, like masking, usually introduce a high energy overhead. However, IoT devices are typically resource-constrained and have a small energy budget. Furthermore, the energy or security constraints may vary between devices or over time, depending on, e.g., the remaining battery level or data sensitivity. Therefore, a dynamic trade-off is needed between security, power consumption and performance. We hence introduce a new paradigm whereby hardware masking is applied on demand to increase energy efficiency. We illustrate this concept by applying it to the stream cipher Trivium, one of the three finalists of the ECRYPT stream cipher competition.

Main Results

Taking as exemplar case that of a lightweight stream cipher called Trivium, we have studied and illustrated this novel approach of adaptive masking, to dynamically tune the protection level and thus optimize the security and energy consumption of encryption. We have implemented and validated a second-order threshold implementation of Trivium and made the necessary modifications to make it adaptive as illustrated in the following figure (where we show the modified "update" function of Trivium, the red part corresponding to the "adaptative" part).



With this configuration, one can select among a protection against first-order attacks, resistance to second-order attacks or no protection at all. Reducing the protection level also reduces significantly the power consumption (by up to 76.2%) when a high level of security is not necessary. This solution is resistant to higher-order univariate and multivariate side-channel attacks with up to 200,000 traces. The cost is a small area (13.5%) and power (4.6%) overhead, when compared to a static second order threshold implementation.



Perspectives

This approach of adaptive masking can be generalized to other stream ciphers, and the approach could be extended to other algorithms as well. Future work includes the integration and validation of this solution on ASIC, and the study of the security of the control mechanism for adaptive hardware security, which is critical to ensure that this adaptive security does not create new attack paths.

RELATED PUBLICATIONS:

[1] "Sécurité adaptative et énergétiquement efficace dans l'Internet des Objets"? Maxime Montoya, PhD thesis, Mines Saint Etienne, December 2019.

[2] "Adaptive Masking: a Dynamic Trade-off between Energy Consumption and Hardware Security" by M. Montoya, T. Hiscock, S. Bacles Min, A. Molnos & J. Fournier in the proceedings of IEEE ICCD 2019, Abu Dhabi, United Arab Emirates, November 17-20, 2019.,

An Open-Source Hardware-In-The-Loop Virtualization System for Cybersecurity Studies of SCADA Systems

RESEARCH TOPIC:
Cybersecurity, SCADA, Industrial Systems, Simulation

AUTHORS:
Stéphane MOCANU, Maxime PUYS, Pierre-Henri THEVENON

Industrial control systems are targeted by cyberattacks since Stuxnet in 2010 and attacks have increased in the past years with respect to interconnection with IT systems. Due to their exposure to the real world, industrial systems need to be protected and engineers need to be trained accordingly. In this paper [1], we present a scalable physical process virtualization platform for cybersecurity study of SCADA systems. Our virtualization platform includes electronic interfaces and a software physical processes simulator, directly connected with the input/output cards of industrial control system hardware. Our system is entirely open source including electronic card schematics, printed circuit boards, embedded software and physical process simulation software and provides a reasonable real-time performance.

Context and Challenges:
Industrial control systems (ICS), also called SCADA are used to monitor and control physical industrial processes. They are composed of hardware and software elements interconnected by communication networks and interacting with the physical world via sensors and actuators. ICS cybersecurity became one of the fastest growing cybersecurity fields after the Stuxnet attack in 2010. The consequences of cyber-attacks on SCADA systems are very costly not only in terms of money but also in terms of the environment and the integrity of citizens. This requires government agencies, hardware manufacturers, and researchers to develop cybersecurity measures once the vulnerability of ICS has been revealed by media events. There are two main challenges when dealing with ICS cybersecurity:

1. Industrial systems are a proprietary world. Thus, working on a programmable logic controller (PLC) and protocols requires to obtain the actual controller as the hardware. Operating system and hardware have yet to be reproduced in software.
2. Impact on physical process. A threat can use legitimate communications to send malicious commands to the physical process. In other words, there is no violation of the security policy, however the safety properties of the process are violated.

Main Results
Our main goal is to provide a physical process simulation testbed [3] that allows the use of real control devices in a realistic environment. Our hardware and software are therefore similar to the material used in Factory Acceptance Test. Hence, we provide electronic cards able to connect the software process simulator to PLCs. We also intend to reproduce SCADA systems of a size close to real industrial cases. Our symbolic target is one hundred industrial equipment and one thousand sensors and actuators. Thus, the interfacing board needs to scale up to targeted number of inputs and outputs. Therefore, a network communication with the process simulation allows to easily add more boards. The boards are custom-built integrated circuits relying on STM32 microchips. They communicate with industrial equipment's using 32 0/24 V digital signals and 8 -10/+10 V analogs. On the other hand, they serve the values of GPIOs over UDP to allow the simulation to read PLC inputs and write outputs. The overall cost of the board is around 400€.

Fig. 1: Interface board (left), demonstrator (right)

The simulation is coded in Python and allows to implement any industrial process (chemistry, electricity production and distribution, etc.). Rather than implementing precise simulation using complex equations, it focuses on being able to communicate and be included in tests-beds rather than simply simulating on its own. Thus, it can be deployed on any operating systems, including on embedded systems for integration within demonstrations. Notably, the simulator was used as part of a demonstrator for the FIC2020 forum. The interface board and the simulator are currently implemented as part of a cybersecurity test-bed for the PULSE program of IRT Nanoelec.

Perspectives
Future works include the deployment of the test-bed as part of the IRT Nanoelec PULSE program, the development of new scenarios for the simulator and conduct stress tests to evaluate its scaling capability.

This work was funded thanks to the French national program "Programme d'Investissement d'Avenir IRT Nanoelec" ANR-10-AIRT-05.

RELATED PUBLICATIONS:
[1] Mocanu S, Puys, M, and Thevenon P-H. An Open-Source Hardware-In-The-Loop Virtualization System for Cybersecurity Studies of SCADA Systems. C&esar 2019 - Virtualization and Cybersecurity, Nov 2019, Rennes, France. pp.1-16.
[2] Puys, M and Thevenon, P-H. L'internet des objets industriels, une révolution à sécuriser. INDUSTRIES & TECHNOLOGIES N°1026-1027.
[3] Holm, H., and al.: A survey of industrial control system testbeds. In: Secure IT Systems. pp.11–26 (2015).

A large-area curved pyroelectric fingerprint sensor

RESEARCH TOPIC:
Fingerprint sensors, printed electronics, IGZO TFT, biometrics, pyroelectricity, thermal sensing

AUTHORS:
Jean-François MAINGUET, Didier GALLAIRE, Audrey MARTINENT, Amélie REVAUX, Mohammed BENWADIH, Simon CHARLOT

We present a thin, flexible and large 500 dpi fingerprint sensor for security applications providing better usability than existing sensors with a similar performance. A new process flow, using PVDF-TrFE pyroelectric capacitors on top of an IGZO TFT backplane on a flexible polyimide (PI) foil is implemented to create an active thermal fingerprint sensor. The system measurements fit well with the simulation of the thermal operation. Biometric performances show comparable results to regular optical sensors. The associated demonstrator was awarded the "Best Publicly-Funded Project Demonstrator Award" at the LOPEC2019 conference.

SCIENTIFIC COLLABORATIONS: CEA-LETI / LITEN, TNO Holst Centre, IDEMIA, Bioage, Irlynx, UC3M, Autoliv, imec

Context and Challenges
Biometric sensors for personal identification undergo a huge evolution since a few years, being not only reduced to governmental and enterprise markets anymore. Nowadays, fingerprint sensors are found in consumer electronics such in smartphones and laptops. Basically, two main technologies can be mostly found in fingerprint sensors: one based on optical devices and another based on silicon devices. The first one is a robust and mature technology, which enables a high acquisition/ high resolution surface at a reasonable price, and allows to capture multiple fingerprints concurrently. However, prism-based optical sensors demonstrate some limitations: they are heavy, thick, bulky, non conformable and raise concerns regarding integration, product design, portable uses and cost. On the other hand, silicon devices, i.e. mostly capacitive, pressure or thermal devices, are used for consumer electronics, due to their small size and easiness for integration. However, when large sensing areas are required, it is not a possible solution for cost reasons.

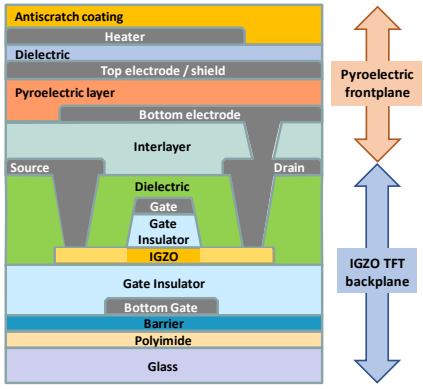
Main Results
The PYCSEL project aims at developing a low-cost thin and large area fingerprint sensing surface enabling the personal identification via the development of a TOLAE (Thin and Organic Large Area Electronics) technology, combining an organic sensor with a TFT matrix on a plastic foil. Based on the fact that personal recognition requires high resolution (500 dpi / 50µm pitch) and large sensors (1 up to 4 fingers), the project focused on the design, development and integration of a printed pyroelectric PVDF-based sensor layer on a IGZO TFT active matrix on foil.

We simulated and developed a manufacturable process, compliant with the 500 dpi high-resolution requirements, including encapsulation (mechanical protection and shielding) and specific sensor poling methods. We designed two sensors, the first one is 256x256 pixels corresponding to a '1 finger' imager, and the second one is 1600x1500 pixels, enabling a '4-fingers' image capture, with their associated demo boards.

Fingerprint acquisition campaigns showed similar performances compared to regular optical acquisition devices.

Perspectives
Compared to other technologies, active thermal sensing offers many more advantages regarding integration ability, high quality image and 'fake or difficult' fingers detection. Moving flexible and wearable electronics to a next level of applications addressing the growing worldwide biometrics market is the ambition of PYCSEL. The biometrics market is expected to be worth more than 20 billion € by 2020. The project is expecting impact not only in governmental market but also in high volume automotive (personalized HMIs), machine tool (user-restricted HMI), buildings (access control), consumer electronics and in enterprise market like banking applications, expected to be a huge lever in the future

The PYCSEL project is funded by the European Union under the Horizon H2020 GA N° 732423 thematic priority ICT-02-2016 – RIA, Advanced Thin, Organic and Large Area Electronics (TOLAE) technologies. https://www.pycsel-project.eu/



RELATED PUBLICATIONS:
[1] J. Mainguet *et al.*, "A large-area curved pyroelectric fingerprint sensor," *2019 IEEE International Electron Devices Meeting (IEDM)*, San Francisco, CA, USA, 2019, pp. 26.5.1-26.5.4. https://ieeexplore.ieee.org/document/8993475
[2] LOPEC 2019 / Best Publicly-Funded Project Demonstrator Award: PYCSEL H2020 - Thin Thermal Fingerprint Sensor, https://oe-a.org/viewer/-/v2article/render/30330399
[3] Pycsel innove avec la biométrie flexible / Les défis du CEA #240 http://www.cea.fr/multimedia/Documents/publications/les-defis-du-cea/making-of_240.pdf

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08 PHD DEGREES AWARDED IN 2019

- Benjamin POLLET
- Victor SARAIVA-PARAHYBA
- François BEATO DE LA SALLE
- Gaëtan LIEB
- Taoufik BOUGERA
- David DEMMER
- Remun KOIRALA
- Ludovic CHANDESRIS
- Gourab GHATAK
- Tien TU VO
- Alexandre ADOMNICAI
- Antoine LOISEAU
- Maxime MONTOYA
- Meriem SMACHE
- Mounia KHARBOUCHE

BENJAMIN POLLET

DC-DC PIEZOELECTRIC CONVERTERS USING TRANSIENT MECHANICAL ENERGY STORAGE

The increasing demand for power convertors in various application fields implies specific constraints and specific technological solutions. In this context, working with piezoelectric materials constitutes an excellent alternative of classical inductor-based converter. Indeed, these materials enable a high-power density, thin and planar geometry and can be integrated on silicon more easily than popular wire-wound magnetic components. A new kind of piezoelectric inductorless converters with a new topology, in which the piezoelectric material acts as an energy storage element, was studied. Soft switching was performed to ensure very high efficiencies even for high frequencies. The study of five different size piezoelectric resonators enabled to understand the impact of geometric parameters of the resonator on the converter performances. Alternative topologies were also described and routes towards improvement possibilities and perspectives to get a complete and industrialized converter are discussed.

VICTOR SARAIVA-PARAHYBA

OPTIMIZATION OF AN INFRARED MCT-APD BASED FLASH LIDAR SYSTEM FOR SPACE LANDING AND 3D IMAGING

Planetary exploration missions require some challenging phases during landing. Extraterrestrial body exploration is expected to be performed in the near future by unmanned missions and therefore an autonomous procedure is essential for precise and fast navigation operations. The support of a 3D vision for the Guidance Navigation and Control (GNC) system allows the creation of a Digital Elevation Map (DEM) of the target terrain, used to identify and avoid dangerous sites and adapt the course of the spacecraft to a safe location. Flash Light Detection and Ranging (LiDAR) systems are a key technology in the future of relative proximity navigation. These systems are constituted by a detector composed by a large array of Avalanche PhotoDiode (APD) and a LASER. In the Flash LiDAR, the light pulse emitted by the LASER illuminates the entire target terrain without employing a scanning device, making the system compact and reliable. This thesis describes the optimization of a Flash LiDAR system based on a Mercury Cadmium Telluride (MCT)-APD detector developed by CEA-LETI. MCT-APDs have characteristics that allow the fast detection of the returned LASER pulse with a good Signal-to-Noise Ratio (SNR). The Read-Out Integrated Circuit (ROIC) responsible for controlling the detector was designed to output two frames per pulse: a 2D (intensity) image corresponding to the integration of the light pulse and a 3D (Time-of-Flight) image that can be translated into a range measurement. The optimization phase included the integration of a new and powerful pulsed LASER, the design of an optical system and the development of a dedicated electronic control board, aiming the miniaturization of the system. This prototype was used to investigate the major faults that corrupt the quality of the image. A set of imaging processing algorithm and methods were developed in order to improve the performance of the range measurements in terms of accuracy and precision.

FRANCOIS BEATO DE LA SALLE

A STUDY ON THE HIGH-SENSITIVITY MAGNETOMETERS BASED ON METASTABLE HELIUM-4 OPTICAL PUMPING

This work presents a detailed study of helium 4 optically pumped magnetometers based on atomic alignment. Although their physical behavior is restricted to low magnetic fields ($B \lesssim$ 150 nT), the dynamic range of such sensors may easily be extended using a back-action loop on the magnetic field. We explicitly derived analytic expressions of the optical signals of helium magnetometers based on atomic alignment for the three atomic transitions $D0$, $D1$ and $D2$. By doing so we wer able to specifically study the different possible sensor architectures. We carefully presented the two different ways of measuring a signal atomic alignment: absorption and linear birefringence. We highlighted new architectures of Hanle magnetometers, notably the possibility of measuring a field with only one optical access. We took a particular interest also in parametric resonance magnetometers to write their driving equations either in absorption and birefringence. We systematically completed our theoretical studies with experimental verifications. We finished by studying the intrinsic sources of imperfections (pumping of the probe beam, lightshift…) and noise of the sensors. Thus, we discussed pros and cons of the architectures and analyzed their theoretical sensitivity.

GAETAN LIEB

ALL-OPTICAL ATOMIC MAGNETOMETERS FOR SPACE, GEOPHYSICS AND MEDICAL APPLICATIONS

The measurement of the Earth magnetic field, using satellites of reduced volume –so called cube-sats or nano-sats– requires optically pumped magnetometers of strongly reduced size that can be operated as gradiometers without crosstalk between different sensors. In order to fulfill these conditions we developed an architecture for all-optical magnetometers. In this work, we present an all-optical isotopic solution for a scalar helium-4 magnetometer based on atomic alignment. This architecture originates in the combination of an optically created radiofrequency magnetic field realized by a vector light-shift and of an intensity modulation of the pump light. The first experimental tests of this configuration proved the existence of a working point that allows isotropic operation. First estimations of noise and precision using this configuration let us hope to obtain equivalent performance than that of scalar isotropic magnetometers that were realized by the CEA-Leti for the mission Swarm. Additionally, the all-optical architectures respond to the needs that exist in the field of medical magnetic imaging. In fact, building a matrix of commonly used sensors involves problems of cross-talk between proximate magnetometers. The second focus of this thesis lies on all-optical magnetometers designated for the measurement of magnetic fields with small amplitudes. Exploring the configurations of Hanle magnetometers that are based on atomic alignment, we identified a technique which gives access to two magnetic field components while using only one single optical access to the gas cell, a solution that was experimentally tested. We theoretically investigate an extension of this configuration that enables the measurement of all three components of the magnetic field, using a partially depolarized light as optical pump.

TAOUFIK BOUGUERA

AUTONOMOUS COMMUNICATING SENSORS FOR IOT

Researchers aim to develop entirely autonomous sensors. By ensuring an important autonomy, the use of batteries solves part of the energy problem with relatively low costs. However, batteries introduce different problems such as maintenance and environmental pollution. Harvesting thermal, mechanical, electromagnetic, solar or wind energy present in the environment is an attractive solution. Using harvested energy from their surroundings, wireless sensor nodes can significantly increase their typical lifetime. Nevertheless, the harvested energy depends on the surrounding conditions of the device and can vary periodically or randomly. It seems important to adapt the system (measurement and data transmission) to the harvesting energy constraints. The thesis objective was to provide an autonomous sensor solution based on a multisource energy harvesting and management system (solar and wind energies), which can be used in different IoT applications. First, we were interested in modeling and optimizing the sensor node energy consumption. Then, the multiple harvesting system was modeled according to the energy needs of the sensor node. Besides, we focused on the power management of the autonomous system. This management part was based on predictions of both available and consumed energies. Finally, the proposed modeling and optimization studies were validated experimentally in order to develop an Autonomous Communicating Sensor platform for IoT applications.

DAVID DEMMER

OFDM PRECODING FOR FILTER-BANK BASED WAVEFORMS

New use cases for wireless communications recently emerged, ranging from massive sensor networks to connected cars. These applications highly differ from typical signals supported by already deployed mobile technologies which are mainly high data rate pipes. The forthcoming generation of mobile technology, 5G New Radio, introduces the new concept of signal numerology so as to properly serve the requirements of the diverse applications it will support. Indeed by considering different numerologies, the time/frequency signal allocation is made more flexible which allows to shape the transmitted signal according to its needs. However, multiplexing signals with different numerologies generates interference and therefore signal distortion. Spatial filtering, such as beamforming, is envisioned for 5G above 6-GHz communications to limit inter-user interference. However, this issue still holds for sub-6 GHz systems where spatial filtering is not considered in 5G. In this work, we considered side lobe rejection techniques to ease service multiplexing in sub-6 GHz bands. Not only does it provide inter-user interference mitigation but it also improves the bandwidth use efficiency. A novel solution, mixing filter-bank for confined spectrum and complex orthogonality for a straightforward re-use of 4G/5G known-how, was proposed. The complex orthogonality was restored thanks to an OFDM precoding substituting the commonly used Offset QAM signaling which limits the orthogonality to the real field. Moreover, the Block-Filtered Orthogonal Frequency Division Multiplexing (BF-OFDM) solution relies on a simple 5G receiver scheme which makes it backward compatible with already deployed technologies. The BF-OFDM system model was fully described and adapted to cellular standards. Different prototype filter design methods were proposed to either improve the intrinsic interference attenuation or to better confine the spectrum of the transmitted signal. Finally, the proposed waveform was compared with state-of-the-art solutions for both typical and 5G oriented evaluation scenarios such as multi-service coexistence.

REMUN KOIRALA

JOINT LOCALIZATION AND COMMUNICATION IN 5G MILLIMETER WAVE NETWORKS

In this thesis, we explored different facets of the inherent synergies between localization and communication functionalities in fifth generation (5G) millimeter wave (mm-Wave) wireless networks. First, after deriving the theoretical performance of wireless localization in terms of the Cramér-Rao lower bound (CRLB), we showed how beamforming (intended in a precoding sense) could be optimized in a multi-carrier and multi-user context so as to improve the estimation of intermediary location-dependent radio variables (namely, the delay, angle of departure (AoD) and angle of arrival (AoA) of transmitted signals) and accordingly, the estimation of end-users' positions. Then, we considered the co-existence of both communication and localization services in a unique system from a time-frequency resources budgeting standpoint, while characterizing non trivial operating trade-offs. We subsequently proposed a joint dynamic resource allocation and beam optimization scheme capable of addressing the latter trade-offs. Finally, we investigated different features of the mm-Wave system that could benefit from such refined location information, namely initial network access, sparse multipath channel estimation, or simultaneous localization and communication (SLAM) applications. In particular, we showed that the performance of the proposed location-aided solutions was clearly enhanced in terms of estimation quality, latency and/or complexity in comparison with more conventional methods.

LUDOVIC CHANDESRIS

CONTRIBUTION TO THE CONSTRUCTION AND DECODING OF POLAR CODES

In a context of intensive numeric dataflow, the use of error correcting codes has become an essential aspect of telecommunication systems. Unavoidable alteration of the messages during the transmission can be compensated by means of additional redundancy to the initial message. Last family of codes to be discovered, in 2008, polar codes have soon experienced a large interest of the community, due to their ability to achieve the Shannon capacity, namely the theoretical limit of the information rate, defined by Shannon in 1948. Very recently, these codes were adopted in the fifth generation of cellular mobile communications (5G). This thesis concentrates on the analysis of this family of codes regarding constraints of practical systems, including in 5G, through the two major issues of the construction of the code and the decoding in finite length. After reviewing the definition and the characterization of polar codes and addressing the question of the spectrum distance, we considered the issue of the flexibility of the codes as function of the codelength, using either puncturing or shortening techniques, and described a new method to select the pattern so as to minimize the error rate under successive cancellation decoding (SC). Then, a new bit-flipping decoding algorithm was proposed, improving significantly the performance compared to the state-of-the-art, while offering a reduced average complexity, close to the one of the SC decoder. Finally, the issue of using polar codes with high order modulation was considered. On one hand, the case of coded modulations, where a high order modulation is combined with binary codes, was considered through the bit-interleaved coded modulation and the multilevel coded modulation, and it was shown that the second one is very much suitable for polar codes. On the other hand, the case of non-binary codes, which can be mapped directly to the constellation, was studied and revealed that they were able to surpass their binary counterpart at the cost of additional decoding complexity.

GOURAB GHATAK

MILLIMETER WAVE MULTI-RAT SMALL CELLS FOR HETEROGENEOUS MOBILE SERVICES: PERFORMANCE ANALYSIS AND OPTIMIZATION

Future wireless applications anticipate an explosion of use-cases and services, which cannot be sustained by incremental improvements of the existing communication schemes. Two research directions are particularly attractive: network densification using small cells and millimeter wave (mm-wave) communications. In this thesis, we modeled and evaluated cellular networks consisting of multi-radio access technique (RAT) mm-wave small cells. First, we mathematically modeled a homogeneous deployment and characterized the user and network performance in terms of signal to interference plus noise ratio (SINR), coverage probability, downlink throughput, and cell overloading probability. Then, we studied user association to different tiers and optimal selection of different RATs, to optimize these performance metrics. Cellular network models that assume homogeneous deployments of small cells generally fail to take into account the nuances of urban blockage characteristics. We modeled the small cell locations along the roads of a city, including signal blockage due to buildings or moving vehicles. We assumed that the operator supported three types of services; ultra-reliable low-latency communications (URLLC), massive machine-type communications (mMTC), and enhanced mobile broadband (eMBB) with different requirements. We studied the optimal RAT selection for these services with varying vehicular blockages. Finally, based on the on-road deployment model of mm-wave small cells, we studied a network designed to support positioning and data services simultaneously. We characterized the positioning accuracy based on the localization bounds and then studied optimal resource partitioning and beamwidth selection strategies to address varied positioning and data-rate requirements.

TIEN TU VO

SPACE, TIME AND FREQUENCY DIVERSITY FOR RANGE AND ANGLE OF ARRIVAL MEASUREMENT IN UWB

Detection and ranging with electromagnetic waves (Radar) are used in a number of domains such as aeronautics, automotive industry or even medicine. In this thesis, we were particularly interested in use cases of Radar for the wellness sector and the general public: sleep pattern tracking sensors, smart glasses or white cane with obstacle detection for visually impaired people. This thesis aimed at adding functionalities to the existing Radar solutions and to serve these applications in particularly: tracking of the displacement of the rib cage and abdomen during breathing and up to millimeters, and measurement of the backscattered signals direction from obstacles. The technological starting point is the ultra-wideband (UWB), which is capable of measuring distances within few meters and with centimeter precision, and enables discrimination of backscattered signals from multiple obstacles. In order to meet these criteria, the research focused on the backscattering propagation channel of the human body. Signal processing techniques were also analyzed for the purpose of estimating breathing rate in the backscattered signals of the human body, and to estimate the direction of arrival of waves to an antenna array and with degree precision. Finally, the thesis investigated the system architecture, especially the receiver associated to the antenna array, in order to perform the angular measurement without notably increasing the receiver complexity, cost and consumption.

ALEXANDRE ADOMNICAI

SECURE IMPLEMENTATION AND INTEGRATION OF LIGHTWEIGHT CRYPTOGRAPHY FOR THE INTERNET OF THINGS

Université Grenoble Alpes (France)

While the internet of things (IoT) promises many advances for businesses, administrations and citizens, its deployment is a real challenge in terms of privacy and security. In order to ensure the confidentiality and the authenticity of information transmitted by these objects, numerous IoT protocols incorporate cryptographic algorithms within their specification. To date, these algorithms are the same as the ones used in traditional internet security protocols and thus, have not been designed with constrained platforms in mind. This thesis focuses on lightweight cryptography which aims at reducing as much as possible the cost of its implementation. Apart from the main goal of lightweight cryptography which is to consume fewer resources than traditional algorithms, it is also valuable to take into account the integration of countermeasures against physical attacks during the design phase in order to limit their impact. Although this kind of attacks require a physical access to the target, this can be a realistic scenario as connected objects might be deployed everywhere and thus, potentially accessible by malicious people. Our work focuses on the study of three lightweight cryptographic algorithms, each having a potential for industrial applications. Especially, we highlight the need of secure implementations by introducing two new side-channel attacks: one against ChaCha20, standardized by the IETF and now used in TLS 1.3, and another one against ACORN, an algorithm which is part of the CAESAR portfolio.

ANTOINE LOISEAU

LIGHTWEIGHT AND SECURE IMPLEMENTATION FOR ELLIPTIC CURVE CRYPTOGRAPHY FOR THE INTERNET OF THINGS

Université Grenoble Alpes (France)

This thesis deals with issues related to the implementation of cryptography on elliptic curves in a constrained environment such as the Internet of Things (IoT). Elliptic curves are widely deployed in cryptographic applications. These implementations are generally based on the NIST standard. However, since the development of this standard several advances in terms of performance and security have been made. In this thesis, we propose to construct a new set of elliptic curves for the Binary Edwards Curve model. These new curves incorporate a number of optimizations specific to 32-bit processor architectures. The efficiency of this curve model lies in the use of differential coordinates. However, this representation is difficult to integrate into signature protocols. We then propose two solutions to overcome this problem. In addition, the strong security constraints against side channel attacks lead us to evaluate our implementation against a set of physical attacks. This evaluation validates the intrinsic security properties inherent in this elliptic curve model and the implementation choices we have made. From this study, we propose a new physical attack combining fault attack and side channel attack. Template attacks are the subject of a special study. We show how we can use these attacks to find a key in a single attack trace, despite the use of countermeasure of coordinates randomization. We use dimension reduction methods (PCA, LDA) to perform this attack. We finally propose a new countermeasure to protect against this kind of attack.

MAXIME MONTOYA

ADAPTIVE AND ENERGY-EFFICIENT SECURITY IN THE INTERNET OF THINGS

Université Grenoble Alpes (France)

Integrated circuits for the Internet of Things have to address various demands, such as a low energy consumption and a high security level against several attacks. However, this high security usually introduces a high energy consumption. The goal of this work is to propose new methods that provide both a high security and a high energy efficiency for integrated circuits. On one side, we study the security of a mechanism dedicated to energy management. Wake-up radios trigger the wake-up of integrated circuits upon receipt of specific wake-up tokens, but they are vulnerable to denial-of-sleep attacks, during which an attacker replays such a token indefinitely to wake-up a circuit and deplete its battery. We propose a new method to generate unpredictable wake-up tokens at each wake-up, which efficiently prevents these attacks at the cost of a negligible energy overhead. On the other side, we improve the energy efficiency of hardware countermeasures against fault and side-channel attacks, with two different approaches. First, we present a new combined countermeasure, which increases by four times the power consumption compared to an unprotected implementation, introduces no performance overhead, and requires less than 8 bits of randomness. Therefore, it has a lower energy overhead than existing combined protections. It consists in an algorithm-level power balancing that inherently detects faults. Then, we propose an adaptive implementation of hardware countermeasures, which consists in applying or removing these countermeasures on demand, during the execution of the protected algorithm, in order to tune the security level and the energy consumption. A security evaluation of all the proposed countermeasures indicates that they provide an efficient protection against existing hardware attacks.

MERIEM SMACHE

DETERMINISTIC NETWORK SECURITY FOR THE INDUSTRIAL INTERNET OF THINGS (IIOT)

Université Grenoble Alpes (France)

Time synchronization is a crucial requirement for the IEEE802.15.4e based Industrial Internet of Things (IIoT). It is provided by the application of the Time-Slotted Channel-Hopping (TSCH) mode of the IEEE802.15.4e. TSCH synchronization allows reaching low-power and high-reliability wireless networking. However, TSCH synchronization resources are an obvious target for cyber-attacks. They can be manipulated by attackers to paralyze the whole network communications. In this thesis, we aim to provide a vulnerability analysis of the TSCH asset synchronization. We propose novel detection metrics based on the inner process of the TSCH state machine of every node without requiring any supplementary communications or any capture or analysis of the packet traces. Then, we design and implement novel self-detection and self-defense techniques embedded in every node with take into account the intelligence and learning ability of the attacker, the legitimate node and the real-time industrial network inter-actions. The experiment results show that the proposed mechanisms can defend against synchronization attacks.

MOUNIA KHARBOUCHE

CMOS/STT-MRAM HYBRIDIZATION OF INTEGRATED CIRCUITS FOR THE HARDWARE SECURITY OF THE INTERNET OF THINGS

In the last decade, the Internet of Things deployment highlighted new needs and constraints in terms of consumption and area for integrated circuits. However, the recent craze for connected objects and the extremely pressing time-to-market demand force the manufacturers to commercialize their products sometimes at the expense of their security. The main focus of the work undertook during this thesis consists in the hybridization of the CMOS technology with the emerging non-volatile memory technology STT-MRAM. This study aims to determine the assets and drawbacks of this hybridization. These innovating architectures must allow the development of low power applications and support the growth of secured connected objects. Thus, the design of a hybrid CMOS/STT-MRAM lightweight cryptographic algorithm based on the PRESENT cipher is achieved. The first study carried out consisted in investigating the robustness of STT-MRAM junctions facing physical attacks, before their integration in the cryptographic algorithm. Laser fault injections were performed in order to evaluate the integrity of the sensitive data stored in the cells. Following the experiments carried out on perpendicular STT-MRAM memories, a new physical attack detector based on this memory technology was proposed, designated by DDHP. This sensor allows simultaneous detection of photoelectrical and thermal attacks that can target integrated circuits.

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