

leti
cea tech

TECHNOLOGY
RESEARCH
INSTITUTE

```
public void getNumber() {  
    Scanner sc = new Scanner(System.in);  
    System.out.println("Start:");  
}
```

```
public void getNumber() {  
    Scanner sc = new Scanner(System.in);  
}
```

2020
SCIENTIFIC
REPORT

SYSTEMS

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

CEA-Leti is a technology research institute of France's CEA and a global leader in miniaturization technologies enabling smart, energy-efficient, and secure solutions for industry. Founded in 1967, CEA-Leti conducts pioneering micro and nanotechnology research and custom develops differentiating application-specific solutions for global companies, SMEs, and startups. CEA-Leti tackles critical challenges in healthcare, energy, and digital migration. From sensors to data processing and computing solutions, CEA-Leti's multidisciplinary teams deliver solid expertise, leveraging world-class pilot production lines to scale new technologies up. With a staff of more than 1,900, a portfolio of 3,140 patents, 10,000 sq. meters cleanrooms, and a rigorous IP policy, CEA-Leti has launched 69 startups and is a member of France's Carnot research network. based in Grenoble, France, the institute has offices in Silicon Valley and Tokyo.
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Technological expertise

CEA (the French Alternative Energies and Atomic Energy Commission) is a leading global research organization whose mission is to transfer new scientific knowledge and innovations to industry. With a focus on electronics and integrated systems from micro to nano, CEA innovations make businesses in transportation, health, safety, and telecommunications more competitive by helping them develop high-performance, differentiating products and novel solutions.

www.cea.fr/english



CEA-Leti at a glance

450
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

1,904
researchers

3,140 patents
in portfolio

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

69
startups created

SYSTEMS

Located on the Minatec Campus, the System Division gathers over 300 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.

Our'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 as well as from the signal and data processing domains; 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, our Division is particularly attractive for industrial partners who are facing the challenges of the Internet of Things (IoT) – also called Cyber Physical Systems (CPS) – associated with artificial intelligence at the system edge (edge AI), 5G and beyond-5G communications, 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.

Our's research and innovation activities span a wide panel of applications including – but not limited to – automotive, space and aeronautics, smart manufacturing and the factory of the future, smart energy and secure energy networks, smart transport, data centers, virtual reality, e-health.

Finally, we serves the foundational purpose of training the young generation of researchers by hosting a significant number of doctorates in these fields of excellence, which contributes to nourishing our learned-from-the-field and open vision of forthcoming challenges for the digital world.

CONTENTS

EDITO	03
KEY FIGURES	05
SCIENTIFIC ACTIVITY	07
01 / Telecommunication infrastructures of the future	09
02 / Antenna systems for future IoE applications	25
03 / Sensors: interacting with the electronic world	35
04 / Electronics for Energy	45
05 / IoT for industry, mobility, space and defense	53
06 / Security of embedded systems: the HARDWARE route	69
07 / News attacks on electronic systems	75
08 / PHD Degree awarded in 2020	85

SYSTEMS

FOREWORD



Sébastien Dauvé
Head of the Systems Division



Emmanuelle Pauliac-Vaujour
Scientific Director of the Systems Division

In this very peculiar year, all the teams from the System Division are immensely pleased and proud to present you a selection of the best scientific achievements of 2020. Despite the worldwide sanitary crisis, we have maintained its scientific production and collaborations to the highest level, while also actively contributing to projects and technological developments and bringing a stone to the fight against COVID-19.

In this scientific report, you will find about 60 of our main scientific contributions split in 7 chapters covering our main innovation areas, namely sensors, power conversion, telecommunication and cybersecurity.

In the field of telecommunications, our division has reaffirmed its leading position in designing, developing and evaluating innovative solutions for the forthcoming 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 as well as ground-breaking designs of antenna systems, among others (see chapters 1 and 2).

2020 was also an important year in terms of acquiring new strengths and know-hows from joining CEA teams in integrated circuit (IC) design for RF applications in particular, IC electronic testing, as well as characterization tools dedicated to the security of electronic systems. These transverse competences reinforce our positioning in all activity sectors, in particular RF communications (see chapter 1 for example), IoT (chapters 3 and 5), energy management (chapter 4) and cybersecurity (chapters 6 and 7).

Among the significant results and trends, 2019 had already seen the growing use of learning algorithms applied to hardware developments with a link to edge-AI applications for both communications and sensors applications. This expertise has matured in 2020 and quite naturally percolated in all our activity sectors – including cybersecurity – as evidenced in all the different chapters of this report.

In particular, in this time of major transitions towards the digital world, 2020 has offered an increasing number of opportunities for the System Division to converge with the medical sector, ranging from RADAR architectures for human vital sign measurement, to space-time-frequency multi-sensor analysis for motor cortex localization, and to optically-pumped magnetometers for medical imaging - the latter feeding a new CEA start-up company to be created in 2021. In chapter 3, you will discover some examples of how our division facets its multi-disciplinarity and versatility towards cyber physical systems which interface more and more seamlessly and ubiquitously with the medical and human-centred world.

Finally, the System Division has reached several new milestones in the field of energy, including the first industrialisation of an energy harvesting solution for the consumer goods market, with millions of products already announced and to be launched onto the market in April 2021 (see article on autonomous switch in chapter 4).

We would like to thank our industrial partners, institutional fellows and academic collaborators, who have worked closely with us in 2020 despite the uncertainty of the international context. 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.

We hope you will find in this 2020 Scientific Report inspiration for your future.

<https://www.leti-cea.com/cea-tech/leti/english/Pages/Applied-Research/Results/scientific-reports.aspx>

KEY FIGURES



220 permanent staff

58 PhD students and postdocs

38 temporary employees



38 M€ budget

84 % external funding

66 direct industrial partners

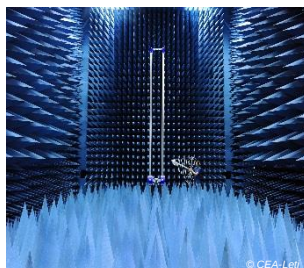


59 patents granted in 2020

480 patents in portfolio

39 book chapters and journals

121 conference communications



3 anechoic chambers

1 connectivity platform

1 IT Security Evaluation Facility

1 electronic test platform

SCIENTIFIC ACTIVITY

Publications

144 publications in 2020 including 38 top journals and over 100 international conference communications. These include: IEEE Internet of Things Journal, Applied Energy, IEEE Vehicular Technology Magazine, IEEE Transactions on Wireless Communications, IEEE Transactions on Communications, IEEE Transactions on Antennas and Propagation, Energy and Buildings, Smart Materials and Structures, Sensors, IEEE Transactions on Circuits and Systems, IEEE Transactions on Microwave Theory and Techniques, IEEE Access, IEEE Transactions on Network and Service Management, DATE, VTC Fall meeting, VLSI, RFIC, PIMRC, ISSCC, PCIM, GLOBECOM, EuMW, EuCNC, EuCAP, COSADE, CARDIS, BRAINS, IEEE APS URSI, POWERMEMS, IEDM etc.

Prize and awards

R. Berro, S. Boriès, C. Delaveaud, "Analysis of the Effects of Conductivity on Small Antenna Characteristics", IWAT Special Prize "Prof. Raj. Mittra" 2020.

V. Cristiani, M. Lecomte, P. Maurine, "Leakage assessment through neural estimation of the mutual information", ACNS workshops best paper award (AIHWS) 2020.

G. Gougeon, Y. Corre, M.Z. Aslam, S. Bicaïs, J-B. Doré, Assessment of sub-THz Mesh Backhaul Capabilities from Realistic Modelling at the PHY Layer, EuCAP Best Paper Award Nominee 2020.

F. Wolf, S. De Rivaz, F. Dehmas, V. Mannoni, V. Berg, "Accurate Narrowband LPWA Ranging: Principles, Performance in AWGN and Multipath Channels", EuCNC Best Student Paper Award 2020.

A. Serhan, D. Parat, P. Reynier, M. Pezzin, R. Mourrot, F. Chaix, R. Berro, P. Indirayanti, K. Han, M. Borremans, E. Mercier, A. Giry "A Reconfigurable SOI CMOS Doherty Power Amplifier Module for Broadband LTE High-Power User Equipment Applications", RFIC Top 3 Industrial Papers 2020.

R. Gerzaguet, N. Bartzoudis, L. Gomes Baltar, V. Berg, J-B. Doré, D. Kténas, O. Font-Bach, X. Mestre, M. Payaro, M. Färber, K. Roth, "The 5G candidate waveform race: a comparison of complexity and performance", EURASIP Journal on Wireless Communications and Networking, Best Paper Award 2020.

Experts

1 International Expert, 4 Research Directors, 20 Senior Experts, 24 Experts, 11 of them holding an HDR.

Scientific committees

Reviewing & Technical Program Committees or Jury members of: National Research Agency (ANR), RISC-V Week, DSD "AHSA Track", IEEE ISSCC, IEEE IEDM, IEEE RFIC, IEEE IMS, IEEE NEWCAS, IEEE PRIME, IEEE ESSCIRC, IEEE ICECS, EuCNC, 6G Summit, SSI, IEEE VTC Fall, IEEE PIMRC, IEEE ICC (ANLN workshop), IEEE VTC Spring (HMWC workshop), IEEE IWAT, MDPI journals (Sensors, Nanomaterials), CSAW, AsiaCrypt, JCEN, Nature Digital Medicine, Computer Methods & Programs in Biomedicine,

Member of: RISC-V International, Swarm ESL (Expert Support Laboratories) and DISC (Data, Innovation and Science Cluster) at the European Spatial Agency (ESA), MIAI Grenoble Alpes.

Conferences and

Workshops organizations

CrownCom Conference Organization in EuCAP 2020 Special Session "Recent advances on electronically steerable antenna arrays at mm-wave frequencies"

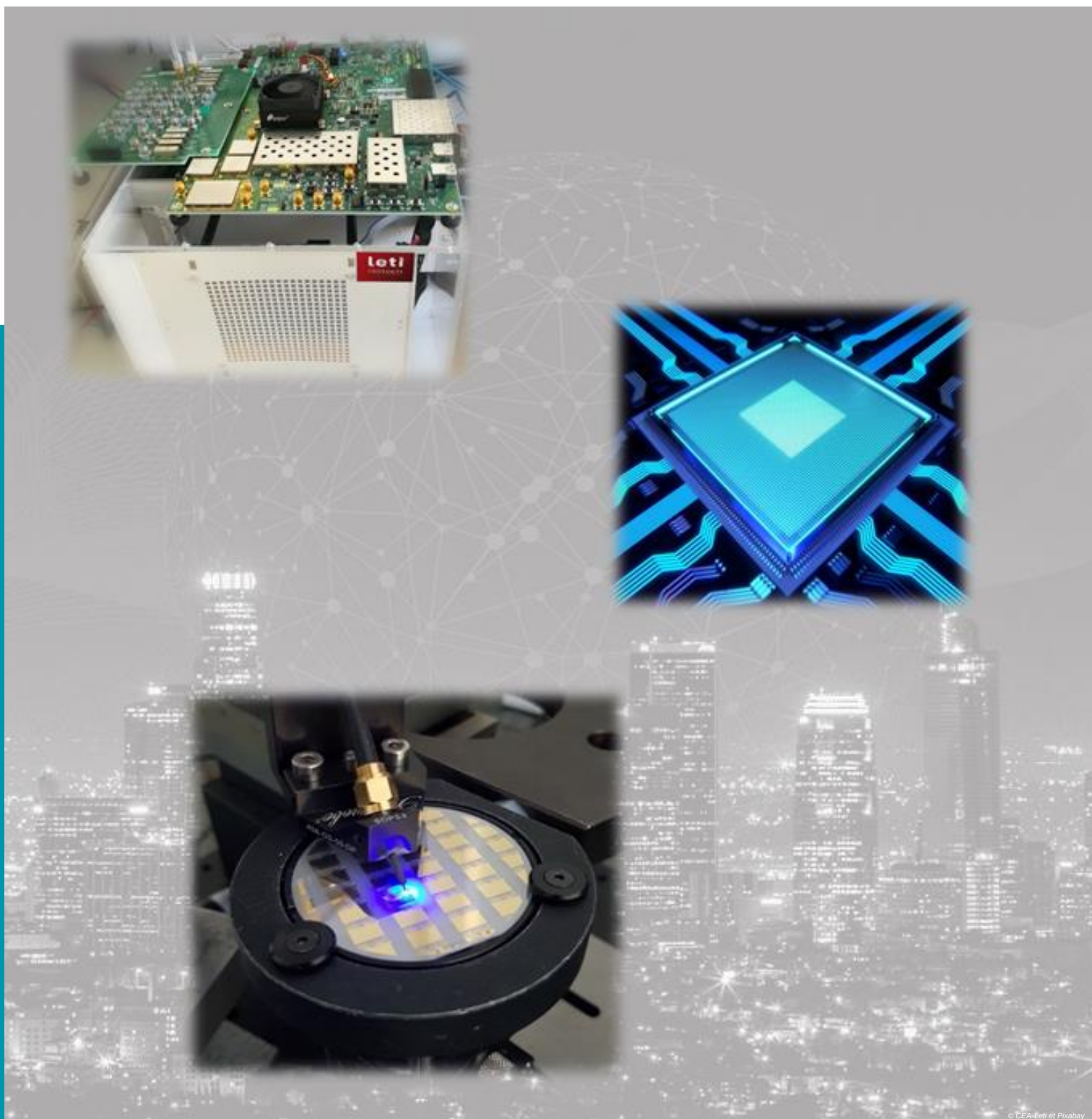
CSS 2020 Special Session "M-Sec: cross-border privacy between Europe and Japan"

National Day on Energy Harvesting and Storage JNRSE (organizing and technical committee)

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), Université Catholique de Louvain UCL (Belgium), University of Arizona (USA), MIT (USA), EPFL (Switzerland).



01

**TELECOMMUNICATION
INFRASTRUCTURES OF
THE FUTURE**

- **Future telecommunication infrastructures**
- **Sub-THz, millimeter wave communications**
- **5G and beyond 5G, 6G**
- **Antenna and transmitarrays**
- **Beam forming**
- **MicroLEDs**

MmWave spectrum above 90GHz for wireless connectivity: opportunities and challenges for future 6G

RESEARCH TOPIC:

System architectures, integrated circuits and process technologies for Millimeter Wave 6G Connectivity and Network

AUTHORS:

José Luis González Jiménez, Eric Mercier, Jean-Baptiste Doré, Didier Belot

The spectrum above 90 GHz is foreseen as a key enabler for the next generation of mobile networks. The large amount of spectrum paves the way of high capacity wireless links. Many challenges still need to be overcome to make this technology a success. This paper describes the scenarios and contemplated scenario for the spectrum above 90GHz, covered by cellular industry for 6G. A benchmark of semi-conductor technologies is discussed to highlight promising candidates. The final section demonstrates channel-bonding architectures as a suitable option for the implementation of extreme broadband RF radios with acceptable power consumption. Opportunities, challenges and some recent experimental results of D-band transceivers implemented in CMOS processes are discussed.

Context and Challenges

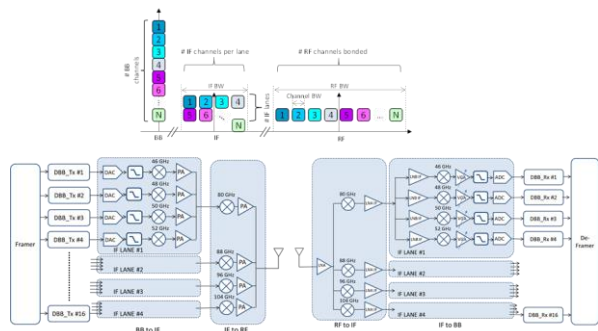
Next-generation wireless networks are imagined to be faster, more reactive, ultra-reliable and denser. Therefore, the exploitation of new and wider bandwidths at higher frequencies is a promising solution towards very high data-rates (100+Gbps) and ultra-low latency (sub-ms). The frequency from 90 to 300 GHz, and above, are definitively foreseen as key enablers for 6G communication systems. Several applications can already be imagined: high capacity back-haul/front-haul; short-range high data rate hot-spots and device-to-device Gbps ultrashort-range communications.

Main Results

Defining technology processes to answer mmW to THz applicative requirements for critical building blocks as Power Amplifiers and Low Noise Amplifiers, cost will be the main factor to earn market share. BiCMOS and RF CMOS processes have already proven to be adequate up to 140 GHz, providing better integration and overall cost than III-V InGaAs MHEMT or InP HBT. It is acknowledged that the beyond-5G and 6G applications will continue to benefit from CMOS improvements but new concepts should be proposed to efficiently address the THz band.

Radio front-end architecture for extremely broadband applications has to be selected considering both the large amount of bandwidth that is required at the RF section and reasonable sampling frequencies in the radio-to-digital baseband (BB) interfaces. An example of a Tx-and-Rx radio front-end based on such techniques has been studied the selected architecture is able to provide a total raw throughput of 102 Gb/s if 16-QAM modulation, and 156 Gb/s for 64-QAM modulation. Having this trade-off in mind, channel-bonding techniques seem a natural solution. Main challenge for such architectures is that they require many different local oscillator (LO) signals. The frequency plan can be optimized to minimize the number of distinct LO frequencies required as well as to relax the bandwidth requirement of the radio up-and-down conversion blocks. A Multi-frequency LO generator

architecture is proposed aiming very low phase noise LO signals which are required for high-order modulation schemes such as 64-QAM and beyond.



Perspectives

The spectrum above 90 GHz is foreseen as a key enabler for the next generation of mobile networks. The large amount of spectrum paves the way to high-capacity wireless links. Many challenges must be overcome to make this technology a success. First, whereas the design of CMOS RF modules is still possible for the low part of the D-Band, designing cost-efficient modules to address the THz band remains an open issue. Second, high-gain antennas are required to meet the link budget. While the design of fixed-beam antenna is mastered, the Holy Grail remains the co-integration of RF and antenna to provide an electronically beam-steerable system. This would be significant breakthrough toward the next generation wireless system.

RELATED PUBLICATIONS:

[1] D. Belot, J.L. Gonzalez-Jimenez, E. Mercier, J.B. Doré, "Spectrum Above 90 GHz for Wireless Connectivity: Opportunities and Challenges for 6G", Microwave Journal, vol. 63 Issue 9, p20-34 (2020).

Spectrum sharing for 5G satellite and terrestrial multi-connectivity

RESEARCH TOPIC:

Millimeter wave 5G and 5G+ connectivity everywhere and everytime

AUTHORS:

Gosan Noh, Stephan Jaeckel, Leszek Raschkowski, Jean-Michel Houssin, Laurent Combelles, Marjorie Thary, Junhyeong Kim, Jean-Baptiste Doré, Marc Laugeois, **Nicolas Cassiau**

This work presents the first results of the 5G-ALLSTAR project aiming at providing solutions and enablers for spectrum sharing in a 5G cellular and satellite multi-connectivity context. An exhaustive study of the frequency bands eligible for these systems in the short and medium term has been conducted. A ray-tracing based and a geometry-based stochastic channel models have also been developed. These models can be used to simulate systems involving terrestrial and non-terrestrial networks. Interference management has been investigated in three ways: signal processing (5G New Radio compatible physical layer), beamforming (steering and switching beams) and radio resource management (joint optimization of satellite and terrestrial resource sharing).

Context and Challenges

The integration of Non-Terrestrial Networks (NTN) into 5G is now well underway. More and more researchers are taking an interest in this subject, as evidenced by the recent publications that deal with the impacts on the network architecture as well as with the adaptation of the physical layer. Standardization is also on track. In this perspective, enablers for spectrum sharing between satellite and terrestrial networks must be provided. Many and different avenues of study may be investigated: software and hardware developments, simulation based and analytical findings or link-level and system-level studies. The 5G-ALLSTAR project brings together researchers and industrialists from Europe and South Korea and explores these solutions for satellite and terrestrial spectrum sharing.

Main Results

The first result is the identification of the frequency bands for 5G via satellite that could be simultaneously used by both terrestrial and non-terrestrial 5G systems. Potential frequency ranges were identified for the implementation of the NTN segment of 5G. In each case, incumbent uses were discussed as well as the existing regulatory conditions, which in certain cases may require changes to accommodate 5G NTN.

In order to simulate joint terrestrial/satellite systems, researchers need channel models that are able to simulate both satellites and terrestrial networks at the same time. The 5G-ALLSTAR project has done pioneering work in this area by developing two such models. One model utilizes Ray-Tracing and thus allows simulating specific environments, while the other uses a geometry-based stochastic model approach that is typically used for system-level simulations of terrestrial networks.

5G NR standard makes room for innovative waveform designs. We therefore proposed the use of Block Filtered-Orthogonal Frequency Division Multiplexing (BF-OFDM) for 5G transmitter. The advantages, in the context of spectrum

sharing between satellite and cellular systems are (i) the high out-of-band rejections capability, i.e. the spectrum leakage in adjacent bands is very low; (ii) the ability to create spectrum holes (this paves the way for radio resource management (RRM) algorithms, dynamically allocating sub-bands to cellular and satellite systems in the same bandwidth); and (iii) the inherent support of multiple services with a unique filtering stage.

If a UE has directional antennas with beam selection and switching capabilities, this can be used for avoiding interference between different systems such as terrestrial and non-terrestrial systems. Considering realistic antenna models, we developed beamforming techniques by properly steering and switching the beams in order to avoid interference without sacrificing the spectrum usage.

5G-ALLSTAR also implemented a system-level simulator that allows the simulation of interference scenarios between multiple radio access technologies (cellular and satellite) sharing the same spectrum, in C-band and millimeter bands, at a RRM level. RRM algorithms are being designed for mitigating the interference while maximizing the overall throughput and the user Quality of Service. Optimal implementation approaches in the 5G system of the joint cellular/satellite RRM was studied.

Perspectives

During the 5G-ALLSTAR project, both Korean and EU partners are devoting substantial effort into developing their proof of concept testbeds and giving various demonstrations of their respective 5G services. The wide range of demonstrations will be showcased at a key event to reveal our technological achievements in the field of 5G, thus validating the potential and the feasibility of our new proposed technologies. This will lead to new disruptive business models, stakeholders and opportunities for entrepreneurial innovation.

Assessment of mesh backhaul capabilities using sub-THz wireless link

RESEARCH TOPIC:

Signal processing, sub-THz, 6G

AUTHORS:

S. Bicaïs, **J-B. Doré**, G. Gougeon¹, Y. Corre¹

Spectrum above 90 GHz is a promising investigation domain to offer future wireless networks with enhanced performance with respect to 5G, such as 100+ Gbit/s data rate or sub-ms latency. The huge available bandwidth is envisaged to serve the backhaul transport network in the perspective of future ultra-dense deployments, and massive fronthaul data streams. This work investigates the feasibility and characteristics of sub-THz mesh backhauling systems, either installed in the streets or inside large venues. The study relies on highly realistic simulations of the physical layer based on a new robust polar modulation, RF impairments modelling, detailed geographical representation, and ray-based propagation modelling.

SCIENTIFIC COLLABORATIONS: This work was made jointly with SIRADEL¹ in the framework of ANR-BRAVE project

Context and Challenges

The “sub-THz” spectrum from 90 to 300 GHz is identified as a key enabler for the next generation of wireless systems. An aggregated bandwidth of 58.6 GHz was identified as possibly available for terrestrial radio-communications between 90 and 200 GHz. The aim of this study is to assess the performance of a broadband wireless mesh backhaul network working in the sub-THz spectrum. Based on a digital twin of a given environment in which the wave propagation is predicted as well as the physical layer capturing RF impairments is modelled, realistic throughput coverage maps are drawn. We demonstrate the potential of such a technology to address the requirements of the next generation of wireless technologies.

Main Results

We have characterized the sub-THz propagation channels using ray-based deterministic numerical simulations [1]. Second, the design of robust communications over a phase noise (PN) channel is addressed from both receiver and transmitter perspectives [2]. The optimum symbol detection criterion and the corresponding probabilistic demapper is derived for PN channel upon the maximum likelihood (ML) decision rule. We also proposed a PN robust modulation scheme defined upon an efficient and structured constellation, adaptable to any signal-to-noise ratio (SNR) and PN variance. Third, the results of system level simulations are presented, considering a high-capacity backhaul scenario in a North-American city (downtown area). These simulations are based on ray-tracing channel predictions using accurate LiDAR point cloud and a realistic link budget. The system performance is characterized for an outdoor mesh backhaul situation, which could be exploited to feed an ultra-broadband mobile access network or fixed wireless access network. The sub-THz devices are supposed to be installed on lampposts, located along the streets at 8 meters above the ground, in order to transport the data streams from a fiber Point of Presence to dense local high-speed access points that either provide mobile or fixed wireless access typically at a lower frequency. The antenna beam is

supposed to be perfectly aligned on the dominant propagation path. As depicted in Fig 1 conventional modulation schemes, namely Quadrature Amplitude Modulation (QAM), cannot achieve high data rate communications over sub-THz channels while the proposed dedicated signal processing, based on Polar-QAM, enables to maintain high spectral efficiency. These throughput heat maps demonstrate that optimizing the modulation and demodulation schemes for PN channels results in significant performance gains for future sub-THz systems.

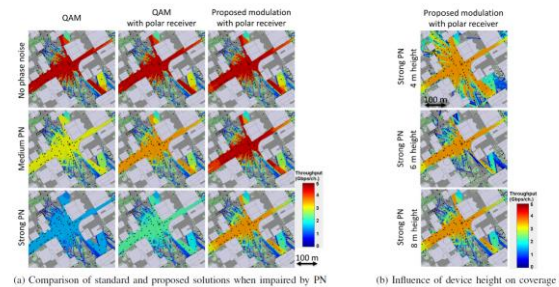


Fig 1: Throughput heat map for a city center

Perspectives

Performance were assessed using a modified QAM modulation on top of a single carrier modulation. The proposition of 5G-NR waveform modifications to support the deployment of beyond 5G system in the sub-THz is currently investigated by our research team.

RELATED PUBLICATIONS:

- [1] G. Gougeon, Y. Corre, M. Aslam, S. Bicaïs, J-B. Doré. "Assessment of sub-THz Mesh Backhaul Capabilities from Realistic Modelling at the PHY Layer". EuCAP 2020, Mar 2020, Copenhagen.
- [2] S. Bicaïs, J.-B. Doré, G. Gougeon, Y. Corre. "Optimized Single Carrier Transceiver for Future Sub-TeraHertz Applications". 2020 45th International Conference on Acoustics, Speech, and Signal Processing (ICASSP), May 2020, Barcelona, Spain.

Design of MIMO systems using energy detectors for Sub-TeraHertz applications

RESEARCH TOPIC:

Signal processing, MIMO detector, Energy detector, THz communications

AUTHORS:

S. Bicaïs, V. Savin, **J-B. Doré**

The significant amount of unused spectrum in sub-TeraHertz frequencies is contemplated to realize high rate wireless communications for beyond 5G networks. Yet, the performance of sub-TeraHertz systems is severely degraded by strong oscillator phase noise. Therefore, we have investigated the use of multiple-input multiple-output (MIMO) systems to achieve high rate communications with a good immunity to phase noise. Our results demonstrate that high rate sub-TeraHertz systems can be implemented on low-complexity and low-power architectures using MIMO systems and energy detection (ED) receivers.

Context and Challenges

With regard to the spectrum shortage in cellular bands, the interest for communications in the TeraHertz (THz) spectrum from 0.1 THz to 1 THz is continuously growing. THz frequencies offer a significant amount of unused bands and represent an opportunity to achieve high data rate wireless communications. We investigate in this work one of the contemplated sub-THz use-cases: a fixed indoor high data rate wireless link. As the carrier frequency increases, the phase noise performance of oscillators largely deteriorates. These strong phase impairments limit the achievable data rate of sub-THz systems, notably by causing detection errors. Therefore, state-of-the-art approaches investigate the use of coherent systems together with channel bonding. This type of architecture needs to be further combined with signal processing optimizations to mitigate the effects of phase impairments leading to complex practical implementations. Conversely, we consider in this study non-coherent detection, for its inherent robustness to phase noise and simple implementation combined with a multiple antenna scheme (MIMO) to increase the spectral efficiency.

Main Results

We have investigated the design of MIMO systems with ED receivers for future applications in sub-THz bands [1]. First, the system model has been described by characterizing the sub-THz channel and the RF architectures of the transmitter and receiver. Fig 1 depicts the studied transmission scheme. Next, we have derived the Maximum Likelihood (ML) decision rule for the studied nonlinear MIMO channel using a Gaussian approximation. Later, a realistic scenario modeling an indoor wireless link has been considered to assess the communications performance. Simulation results have proved that low error rate communications can be achieved on strongly correlated Light of Sight (LoS) channels. In addition, we have shown that polar-coded MIMO systems can take advantage of the strong spatial interference to enhance performance: a gain of up to 4 dB in comparison to the interference-free case for an

8×8 antennas system is obtained. In conclusion, our results demonstrate that spatial multiplexing with non-coherent sub-THz transceivers can be achieved on strongly correlated LoS channels, opening the way to cost-effective high data rate THz systems.

Perspectives

This study is based on a simple antenna model and we are currently investigating the use of a real antenna model to confirm the potential of the proposed technique. Moreover, as the detection problem is nonlinear, the consideration of a neural network in the detector is also envisaged.

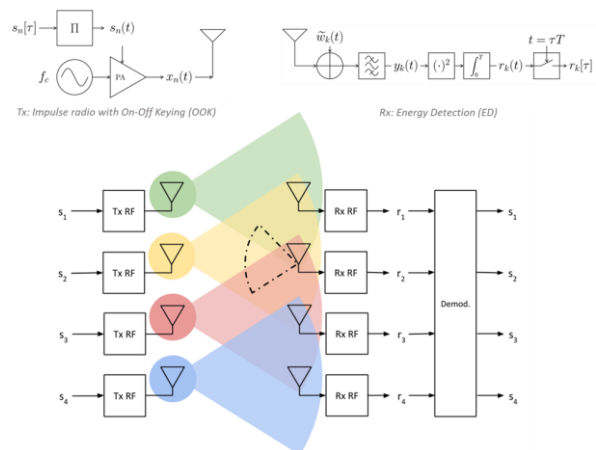


Fig.1: System model for a non – coherent MIMO transmission with spatial interference

RELATED PUBLICATIONS:

[1] S. Bicaïs, J.-B. Doré, V. Savin, "Design of MIMO Systems Using Energy Detectors for Sub-TeraHertz Applications", 2020 International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), August 2020, London, United-Kingdom

Multi-agent deep reinforcement learning in dynamic dense mmWave networks

RESEARCH TOPIC:

Machine Learning. Resource Allocation in Wireless Network. Network Resource Optimization.

AUTHORS:

E. Calvanese Strinati, Y. Lostanlen¹, W. Yu¹, A. De Domenico, M. Sana

Network densification and millimeter-wave technologies are key enablers to fulfill the capacity and data rate requirements of 5G networks. In this context, designing low-complexity policies able to adapt the user association with respect to the network dynamics is a challenge. So far, solutions of the literature require continuous access to global network information and to re-compute the association when the radio environment changes, inducing a complexity unsuitable to dense 5G networks. This work addresses this issue with a scalable and flexible user association algorithm using multi-agent reinforcement learning to optimize the network sum-rate and to adapt to changes of the radio environment, thus providing large sum-rate gain compared to baseline solutions.

SCIENTIFIC COLLABORATIONS: ¹ Department of Electrical and Computer Engineering, University of Toronto, Toronto (CN)

Context and Challenges

To boost the network capacity, 5G relies on millimeter-wave (mmWave) technologies and network densification. Whereas mmWaves suffer from severe path-loss, densification of base stations (BSs) results in co-channel interference requiring efficient resource allocation. In this context, optimally associating user equipment (UEs) to BSs is a fundamental task, particularly challenging when considering environment dynamics viz. interference, fast fading, mobility, or network traffic dynamics (see Fig. 1). So far, current solutions of the literature typically require global information of the network, are computationally expensive, and do not consider the dynamic nature of wireless networks. As a result, the state-of-the-art algorithms are re-computed either periodically or whenever a notable change has occurred in the environment to correct possible drifts from the optimal association, thus, leading to significant computation and signaling overhead. Therefore, there is the need for flexible and adaptive solutions with respect to environment dynamics.

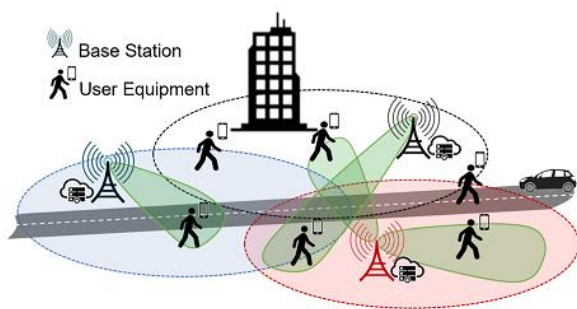


Fig. 1. User association in a dense network

Main Results

To address the aforementioned problem, we propose a distributed and decentralized multi-agent reinforcement learning framework, where each UE acts as an independent agent that operates in a fully distributed manner [1], [2], [3]. UEs learn by experience, based only on their local and partial observations in order to maximize the network sum-rate, as we focus on mmWave technology for enhanced Mobile Broadband services. Specifically, UEs learn to map their observations of the environment to actions corresponding to connection requests to their surrounding BSs. Our proposed framework has the advantage of being able to incorporate the environment dynamics during the learning phase (i.e., the time varying nature of mmWaves channels and network traffic [1],[2] as well as user mobility [3]), so that the user association is self-reorganized towards the optimal association when a relevant change occurs in the environment. Furthermore, we reduce the signaling overhead since agents do not exchange any direct information. Our analysis shows that, in cases of full buffer traffic, the proposed scheme achieves up to 98.7% of the optimal performance obtained through exhaustive search. Also, when we consider dynamic traffic, it provides nearly 40% of performance gain with respect to centralized baseline solutions from the literature [2]. Regarding mobility, we show that our solution can reduce the handover events up to 70% and increase the average network throughput by 18% compared to solution based on maximum received signal strength [3].

Perspectives

Results of this work open new perspectives for applications in scenarios such as multiple access edge computing, where multiple UEs compete for radio resources to offload tasks, as well as for computation resources to process these tasks in distant edge servers.

RELATED PUBLICATIONS:

- [1] M. Sana, A. De Domenico, and E. Calvanese Strinati, "Multi-Agent Deep Reinforcement Learning based User Association for Dense mmWave Networks," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2019, pp. 1-6.
- [2] M. Sana, A. De Domenico, W. Yu, Y. Lostanlen, and E. Calvanese Strinati, "Multi-Agent Reinforcement Learning for Adaptive User Association in Dynamic mmWave Networks," in *IEEE Transactions on Wireless Communications*, June 2020, vol. 19, no. 10, pp. 6520-6534.
- [3] M. Sana, A. De Domenico, and E. Calvanese Strinati, "Multi-agent deep reinforcement learning for distributed handover management in dense mmWave networks," in *Proc IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, May 2020, pp. 8976-8980.

Super high speed optical communication on microleds

RESEARCH TOPIC:

Optical wireless communication, microLED, micro-OLED, multicarrier waveform, link adaptation, digital-to-optical converter

AUTHORS:

A. Lagrange, L. Dupré, T. Maindron, L. N. Dinh, **L. Maret**

This work embraces recent activities on ultra-high speed Optical Wireless Communications using a single blue 10- μm Gallium-Nitride microLED, implemented within an experimental setup with software for direct-current optical OFDM and hardware optical components. A modulation bandwidth of 1.8 GHz with bit and power loading algorithms enabled to reach a data rate of 7.7 Gb/s, to be compared with the previous record of 5.37 Gb/s reached in 2016. Future works will implement arrays of 10 000+ microLEDs, to allow for new digital-to-optical modulations, for integrated system-on-chips. Higher emitted optical power is expected to open such technology to indoor multiple access where light collection and alignment is no more possible.

Context and Challenges

MicroLEDs are one of the most promising OWC optical sources due to their high illumination efficiency and their large modulation bandwidths. CEA-Leti achieved recent activities on ultra-high speed Optical Wireless Communications (OWC) using custom Gallium-Nitride microLEDs.

Main Results

Preliminary work focused on the implementation of a 10- μm single blue micro-LED on sapphire wafer within an experimental OWC setup, mixing software generation of direct-current optical orthogonal frequency division multiplexing (DCO-OFDM) patterns and hardware optical components for light collection, high speed photo-detection and digital acquisitions. Intensity modulation conveys DCO-OFDM waveform and direct detection is used at reception. A high current density of 25.5 kA/cm² provided a modulation bandwidth of 1.8 GHz. Associated to bit and power loading algorithms with up to a 256-QAM subcarrier modulation, it enabled a new data rate world record of 7.7 Gb/s, which broke the previous leading mark of 5.37 Gb/s of the literature.

Perspectives

Next investigations will study the electrical modelling of microLEDs in the high frequency regime. Future works will cover the use of large arrays of 10 000+ microLEDs. The first objective is to open the way to new digital-to-optical modulations by independently driving each pixel and to target highly integrated system-on-chips for ultra-high speed OWC. Secondly, higher emitted optical power is expected to open such technology to indoor applications.

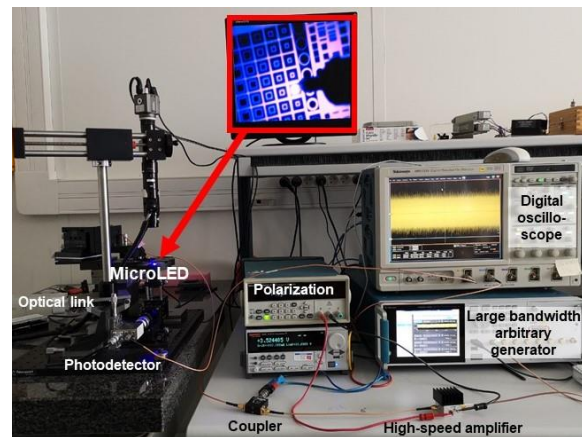


Fig. 1 :Experimental optical transmission setup

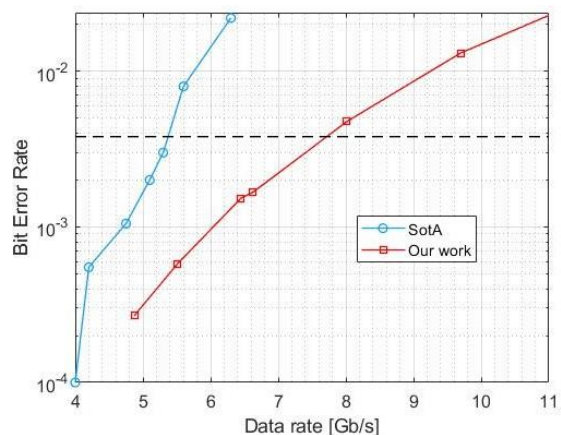


Fig. 2 :Data rate function of Bit Error Rate

RELATED PUBLICATIONS:

- [1] L. Maret, Lam Ngoc Dinh, Alexandre Lagrange, Patrick Demars, Ludovic Dupré et Olivier Lartigue, "Reaching 7.7 Gb/s in VLC with DCO-OFDM on a single GaN Blue Micro-LED", Optical Wireless Communication Conference, October 5th, 2020
- [2] L. Maret, Alexandre Lagrange, Ludovic Dupré, "Ultra-High Speed Optical Wireless Communications with gallium-nitride microLED", Photonic West, SPIE OPTO, Light-Emitting Devices, Materials, and Applications, March 6-11, 2021.

Multi-user interference characterization in antenna arrays: an algebraic angle approach

RESEARCH TOPIC:

Antenna array, beamforming, interference mitigation, multi-user communication

AUTHORS:

Reda Bekkar, Laurent Ros¹, Cyrille Siclet¹, Serge Bories, **Benoit Miscopein**

Antenna arrays are widely used in mobile networks to mitigate interference as well as to enhance the reliability and the capacity of the system. The performance of beamforming algorithms depends on the channel realization and its associated parameters (angle of arrivals, multi-path components, fading) plus the array geometry. The multiplicity of these parameters makes it difficult to establish a tractable characterization of the overall performance. In this study a new parameter, an algebraic angle cosine between the signal subspace and the interference subspace, is introduced to characterize the interference impact. It allows the derivation of a lower bound on the signal-to-interference-plus noise ratio (SINR) of the state-of-the-art beamforming algorithm.

SCIENTIFIC COLLABORATIONS: ¹ Univ. Grenoble Alpes, CNRS, GIPSA-lab, Grenoble (FR)

Context and Challenges

The data-rate provided by 5G networks is expected to follow the exponential trend observed since several decades. One possible way to drastically increase networks capacity is the densification of the deployed base stations, using heterogeneous topologies composed of small cells. As a result, network operators face interference issues associated with this densification, which may limit the user quality of experience. In 5G networks, antenna array systems are viewed as a key enabler to manage this interference and improve the system overall performance. In this context, various interference cancellation algorithms exist, and the Capon beamformer is a well-known and optimal solution from the signal-to-interference-plus-noise ratio (SINR) perspective. Generally speaking, in a multiuser situation, the performance of beamforming algorithms depends on the propagation channel parameters like array geometry, multi-path components, angle of arrival (AoA) statistics and fading. In this work, a new *meta* parameter of the channel has been introduced to characterize the interference between different users and to allow the determination of the expected performance of the system.

Main Results

The SINR resulting from a Capon beamformer is intractable when it comes to multi-users and multipath propagation. To this end, the algebraic angle cosine parameter ($\cos \square$) is introduced as a metric of the interference between signal and interference subspaces. This is not a physical angle but $|\cos \square|$ is, in a single user case, the correlation coefficient between the user and the interferer channel vectors. In a multiuser/multi-interferer situation, it corresponds to the algebraic angle between the desired user and the hyper-plane generated by the other users and the interferers. Using this angle allows, for single interference case, the determination of the SINR attained by the Capon beamformer. In the multi-interferer case, a lower bound on the SINR can be derived. It asymptotically varies between a

floor value (user and interferers quasi aligned) and maximum value (user and interferers quasi orthogonal) defined by the number of antennas and the user SNR value. Between these two zones, the SINR variation in dB is asymptotically linear with a slope of 10dB per decade. Scattered plots of SINR vs. ($\cos \theta$) in different configurations of antenna array and interference situations shows that that lower bound is valid and confirm the existence of the three typical zones of operation (worst case, best case and standard case where the SINR asymptotically linearly varies).

Perspectives

According to the knowledge of author, this formalism is a new way to characterise performance of beamforming algorithms for antenna arrays and it open interesting ways for network planning tools. Perspectives embraces the determination of a close form of the lower bound and an analytical formula for SINR of beamformers.

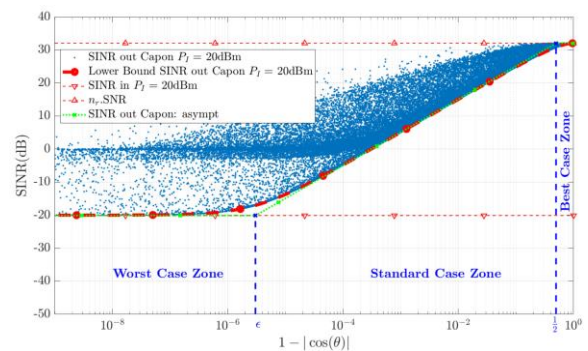


Fig.1: SINR lower bound and typical zones

RELATED PUBLICATIONS:

[1] M. R. Bekkar, L. Ros, C. Siclet, S. Bories et B. Miscopein. "Multi-user interference characterisation in antenna arrays: an algebraic angle approach". IET Electronics Letters 56.5. IET Digital Library, p. 257-260 ; jan 2020.

Indoor mmWave Channel Characterization with large virtual antenna arrays

RESEARCH TOPIC:

mmwave channel, propagation, large array, massive MIMO

AUTHORS:

Alfred Mudonhi, Claude Oestges¹, Raffaele D'Errico

In this work we present an investigation on indoor mmWave channel, using large antenna array. In the measurement campaign massive virtual array of 21×21 elements was considered. Multipath components were extracted by means of a high resolution algorithm. The results obtained with the full massive array are compared with those obtained with a small sub-array, in order to investigate the effect of array size in channel modeling.

SCIENTIFIC COLLABORATIONS: ¹ICTEAM-Université Catholique de Louvain, Belgium

Context and Challenges

Massive MIMO (Multiple Input Multiple Output) systems are based on large number of antennas (from tens to hundreds) in order to simultaneously serve different users is what we call massive MIMO. In the last years these approaches have been first investigated for sub-6GHz systems. Nowadays the advent of millimeter wave (mmWave) technologies in 5G and beyond networks, foresee the use of large arrays combined with hybrid beamforming. In this context radio propagation modelling is a fundamental step order to efficiently develop and evaluate these systems. Here we address the mmWave massive MIMO propagation in an indoor environment by investigating the impact of the array size on the channel characteristics.

This work was partially funded by the 5GmmFlash project and the ANR project MOREOVER.

Main Results

A measurement campaign using virtual antenna arrays has been carried out in indoor scenario by considering an array of 21×21 elements at transmitting side, while at the receiving side, a 3×3 spatial grid emulating a user equipment (UE) was considered (Fig.1). Measurements were performed in the 26-31.5 GHz. High resolution algorithms were employed to estimate multipath components (MPCs), considering the full large array or sub-arrays (Fig.2). Estimation of the Line-of-Sight path is almost unchanged when considering a massive array or a subarray. On the contrary, the size of the array has an impact on the secondary MPCs, which yields to different overall delay and angular spread.

Perspectives

Future works include identification of common multipath components among different sub-arrays and Investigation on non-stationarity over large mmWave array. This would yield to novel propagation model enabling mmWave massive MIMO systems design.



Fig. 1: Indoor mmwave channel measurement campaign employing large array, and repartition in sub-arrays.

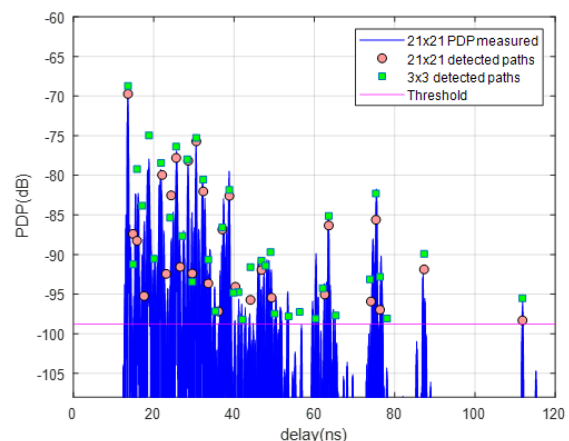


Fig. 2: Example of measured power delay profile and the detected multi-path considering 3×3 subarray vs 21×21 massive array

RELATED PUBLICATIONS:

[1] A. Mudonhi, R. D'Errico and C. Oestges, "Indoor mmWave Channel Characterization with Large Virtual Antenna Arrays," 2020 14th European Conference on Antennas and Propagation (EuCAP), Copenhagen, Denmark, 2020, pp. 1-5, doi: 10.23919/EuCAP48036.2020.9135628.

Lock detector integrated in a high order frequency multiplier operating at 60-GHz-band in 45nm CMOS SOI technology

RESEARCH TOPIC:

High-data rate wireless links for 5G+ and 6G

AUTHORS:

Abdessamad Boulmirat, Alexandre Siligaris, Clément Jany, José L. Gonzalez-Jimenez

This work presents a lock detector integrated in a 60-GHz band frequency multiplier with high multiplication factor. The proposed circuit detects the locking state of an injection locked oscillator. It relies on power integration besides the ILO targeted frequency. The proposed lock detector and the associated frequency multiplier presents a consumption of 61 mW and 5.2 mW respectively. The area occupied by the lock detector is less than 3% of the overall chip area. The locking detector is the cornerstone of injected oscillator calibration, and enables high-N frequency multiplication-based frequency synthesis.

Context and Challenges

This work is part of new high-frequency synthesis technique that is based on injection locked oscillators (ILO) [1]. Such frequency synthesizers present state of the art performances in terms of phase noise and jitter, but need to be calibrated in order to ensure optimum performance. For that purpose, we present a low-area, low-power consumption lock detector integrated into a high-N frequency multiplication-based frequency synthesizer operating at 60GHz. The presented lock detector is based on sub-sampling of the ILO output spectrum and low frequency signal processing [2].

Main Results

The proposed circuit is fabricated in a 45nm CMOS SOI technology (Fig.1). The lock detector output response with respect to the ILO tuning voltage is shown in Fig. 2. For values smaller than 0.8V and higher than 1V, the comparator output is low indicating that the ILO is not locked on the input signal whereas it is locked in between. The figure also shows the internal output of the integrator and the threshold voltage of the comparator. Examples of ILO spectra for both locked and unlocked states are shown in Fig. 2.b-d. It is clear that in the 2 unlocked cases (Fig. 2.b and Fig. 2.d), there is a significant amount of power located in the integration band, which results in a low comparator output voltage. Thanks to these results, the lock-detector has been used, not only for ILO locking calibration, but also for output phase noise and jitter optimization into a state machine loop.

Perspectives

Next steps on this topic will consist on realizing high frequency synthesis systems with automatic frequency calibration and phase noise optimization.

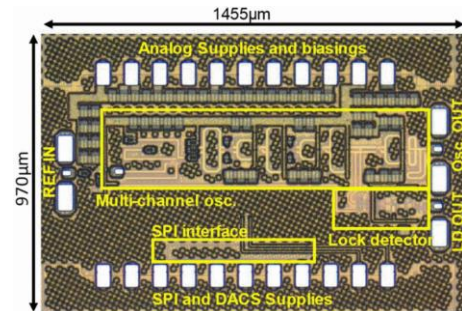


Fig. 1: Frequency synthesis with lock detector IC photograph.

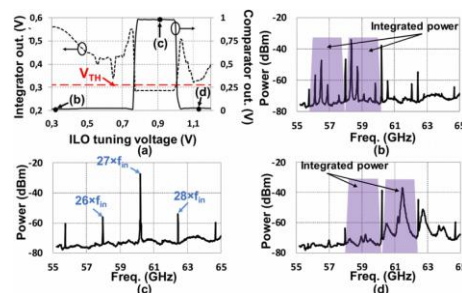


Fig. 2: (a) Lock detector (solid line) and integrator (dotted line) outputs versus ILO tuning voltage. ILO output spectrum in different locking conditions: (c) Locked (b), (d) unlocked.

RELATED PUBLICATIONS:

- [1] A. Siligaris et al., "A Multichannel Programmable High Order Frequency Multiplier for Channel Bonding and Full Duplex Transceivers at 60 GHz Band," 2020 IEEE Radio Frequency Integrated Circuits Symposium (RFIC), Los Angeles, CA, USA, pp. 259-262, 2020.
- [2] A. Boulmirat, A. Siligaris, C. Jany and J. L. Gonzalez-Jimenez, "Lock Detector Integrated in a High Order Frequency Multiplier Operating at 60-GHz-Band in 45nm CMOS SOI Technology," 2020 IEEE/MTT-S International Microwave Symposium (IMS), Los Angeles, CA, USA, pp. 944-947, 2020.

A 84.48 Gb/s 64-QAM CMOS D-Band channel bonding Tx front-end with integrated multi-LO frequency generation

RESEARCH TOPIC:

High-data rate wireless links for 5G+ and 6G

AUTHORS:

A. Siligaris, A. Hamani, C. Dehos, F. Chaix, B. Blampey, N. Cassiau, **J.L. González-Jiménez**

This work presents an ultra-broadband D-band wireless front-end transmitter (TX) in 45-nm CMOS SOI. Based on channel bonding and 64-QAM modulation, it achieves 84.8-Gb/s data rate by combining 8×2.16 GHz baseband channels. The eight baseband channels are aggregated at intermediate frequency (IF) in two sets of four channels and then upconverted to two adjacent sub-bands at D-band. The required millimeter-wave local oscillators (LOs) are generated on-chip. The presented TX integrates two upconverter mixers, two power amplifiers, and an on-chip power combiner in addition to the two LO generators with a total dc power consumption of 420 mW from a 1-V voltage supply, and occupies a compact active area of 2.98 mm².

Context and Challenges

Our research is motivated by the increasing demand of higher data-rates in mobile communications and other wireless links. New bands in the mmW frequencies are currently being proposed by the regulatory bodies and explored by the scientific and technical community, and the D-band around 145 GHz is among them. Realizing low-cost and low-power transceiver able to operate at these frequencies providing 100 Gb/s data rate or more is the main challenge addressed by this work.

Main Results

Starting by the design of the most constraining building blocks (the power amplifier [1] and the low-noise amplifier [2]) a first prototype of emitter (Tx) [3] and receiver (Rx) [4] circuits have been designed and fabricated on 45nm RFSOI CMOS technology. The Tx circuit (see Fig. 1) implements a two-channel up-conversion and power combining (channel bonding) before delivering the D-band signal off-chip. The circuits has been teste in the full link environment. Each Tx channel input signal is composed in its turn by multiple base-band (BB) channels. The spectrum of the Tx output signal and the modulation constellation for each BB channel are shown In Fig.2. A total data rate of 84.48 Gb/s using 64-QAM on all eight channels is achieved with an energy efficiency as low as 4.97 pJ/bit.

Perspectives

The next steps in this research are to design and fabricate a new version of the Tx and Rx circuits with larger number of channels and to integrate them on modules and assemble them to antennas to implement a full wireless point-to-point link.

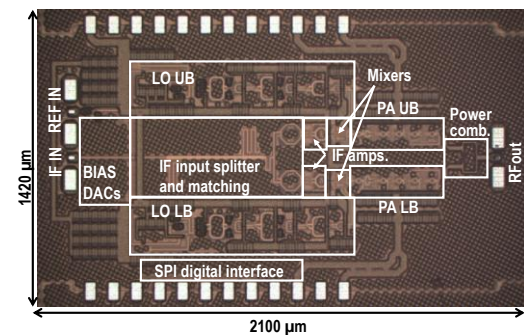


Fig. 1: Tx IC photograph.

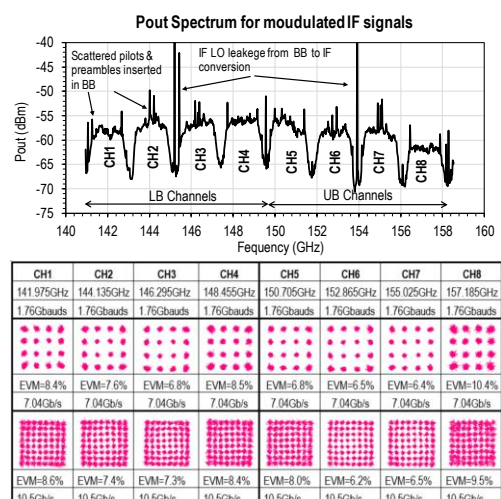


Fig. 2.: Tx output spectrum signal, constellations and main performances.

RELATED PUBLICATIONS:

- [1] A. Hamani, A. Siligaris, B. Blampey and J. L. Gonzalez Jimenez, "167-GHz and 155-GHz High Gain D-band Power Amplifiers in CMOS SOI 45-nm Technology," 2020 15th European Microwave Integrated Circuits Conference (EuMIC), Utrecht, Netherlands, 2021.
- [2] A. Hamani, A. Siligaris, B. Blampey, C. Dehos and J. L. Gonzalez Jimenez, "A 125.5-157 GHz 8 dB NF and 16 dB of Gain D-band Low Noise Amplifier in CMOS SOI 45 nm," 2020 IEEE/MTT-S International Microwave Symposium (IMS), Los Angeles, CA, USA, 2020.
- [3] A. Hamani et al., "A 84.48-Gb/s 64-QAM CMOS D-Band Channel-Bonding Tx Front-End With Integrated Multi-LO Frequency Generation," in *IEEE Solid-State Circuits Letters*, vol. 3, pp. 346-349, 2020.
- [4] A. Hamani et al., "A 108-Gb/s 64-QAM CMOS D-Band Rx With Integrated LO Generation," in *IEEE Solid-State Circuits Letters*, vol. 3, pp. 202-205, 2020.

A 125.5-157 GHz 8 dB NF and 16 dB of gain D-band low noise amplifier in CMOS SOI 45nm

RESEARCH TOPIC:

High-data rate wireless links for 5G+ and 6G

AUTHORS:

A. Hamani, A. Siligaris, C. Dehos, B. Blampey, J.L. González-Jiménez

In this work, a D-band millimeter-wave low noise amplifier circuit in CMOS SOI 45 nm technology is presented. It achieves 8 dB of noise figure and 16 dB of gain with a 3-dB bandwidth of 31.5 GHz (125.5-157 GHz). It is composed of four stages of capacitively neutralized differential common-source cells cascaded using integrated mm-wave transformers to achieve high gain and large bandwidth. It consumes 75 mW from a 1-V voltage supply, and occupies a compact active area of 0.07 mm².

Context and Challenges

To achieve high data rate wireless communications approaching 100 Gbps, a wide bandwidth, in the range of a few tens of GHz. For this reason, D-band frequency range from 110 to 170 GHz has been recently proposed for short-range high speed communication since such large bandwidth is only available for spectral bands beyond 100 GHz. The low noise amplifier (LNA) is a crucial circuit in these systems, since it's the first block in the receiver chain. LNA must achieve simultaneously a low noise figure and wideband operation to allow high data-rate communications at D-band. Most of the previous high performance D-band front-ends have been realized in III-V technologies. Nevertheless, for high volume and lower power applications, lower cost technologies such as CMOS could offer an alternative solution.

Main Results

The die photograph of the fabricated low noise amplifier in 45nm SOI CMOS technology is shown in Fig. 1. Including the pads, the chip size is 0.37 mm² (i.e., 704 μ m x 521 μ m). Its power consumption is 82 mW for a supply voltage of 1 V. The measured and simulated noise Figure versus frequency is shown in Fig. 2 (a). The fabricated amplifier displays a noise figure of 8 dB at 150.5 GHz. Moreover, the NF have a relatively constant behavior over a quite wide frequency range and it's below 10 dB from 127 to 155 GHz. The experimental small-signal gain S_{21} curve of the LNA, in Fig. 2 (b), shows a maximum value of 16.1 dB and exhibits a large -3 dB bandwidth of 31.5 GHz between 125.5 GHz and 157 GHz. A good agreement can be observed between the measurements and simulations, in the term of frequency band.

Perspectives

The next steps consist on the implementation of the designed circuit [1-4] with antennas in the PCB boards to archives high-data rate communication system.

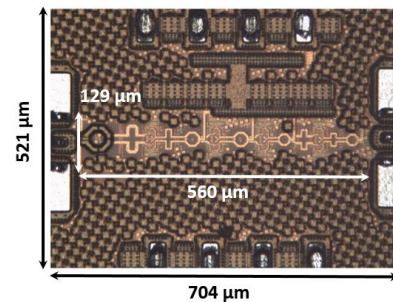


Fig. 1. LNA photograph.

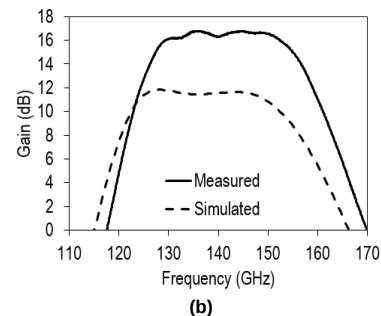
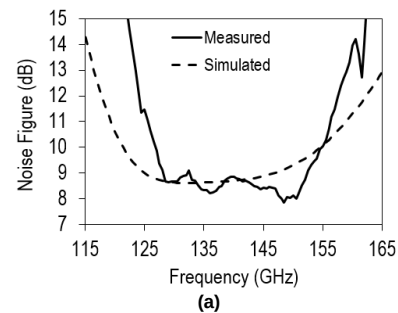


Fig. 2. Noise Figure (a) and gain (b) of the LNA.

RELATED PUBLICATIONS:

- [1] A. Hamani, A. Siligaris, B. Blampey and J. L. Gonzalez Jimenez, "167-GHz and 155-GHz High Gain D-band Power Amplifiers in CMOS SOI 45-nm Technology," 2020 15th European Microwave Integrated Circuits Conference (EuMIC), Utrecht, Netherlands, 2021.
- [2] A. Hamani, A. Siligaris, B. Blampey, C. Dehos and J. L. Gonzalez Jimenez, "A 125.5-157 GHz 8 dB NF and 16 dB of Gain D-band Low Noise Amplifier in CMOS SOI 45 nm," 2020 IEEE/MTT-S International Microwave Symposium (IMS), Los Angeles, CA, USA, 2020.
- [3] A. Hamani et al., "A 84.48-Gb/s 64-QAM CMOS D-Band Channel-Bonding Tx Front-End With Integrated Multi-LO Frequency Generation," in *IEEE Solid-State Circuits Letters*, vol. 3, pp. 346-349, 2020.
- [4] A. Hamani et al., "A 108-Gb/s 64-QAM CMOS D-Band Rx With Integrated LO Generation," in *IEEE Solid-State Circuits Letters*, vol. 3, pp. 202-205, 2020.

Si and SOI CMOS technologies for millimeter wave wireless applications

RESEARCH TOPIC:

This work presents an overview of CMOS-only, partially depleted and fully depleted SOI technologies for mm-wave applications.

AUTHORS:

D. Belot, **B. Martineau**

This paper presents an overview of Si and SOI CMOS technologies for millimeter-wave applications. Implementations of CMOS-only, partially depleted and fully depleted SOI technologies are compared for the different blocks constituting an integrated RF system.

Context and Challenges

The upcoming 5-6G and the densification of the backhauling network will reinforce the need for low cost high performance mm-wave technologies. Due to its cost advantage, and ease of integration of digital and high-speed Analog/RF circuits, the CMOS has emerged as the favorite solution satisfying the needs of the communications market. However, what is the comparative advantage of using CMOS, CMOS Partially depleted (PD) SOI or CMOS Fully Depleted (FD) SOI? This work discuss on devices and specificities of each technologies for mm-wave circuit design.

Main Results

CMOS transistor can be design atop of the surface of a monocrystalline silicon wafer (bulk CMOS) or isolated to the substrate thanks to a buried oxide (SOI CMOS). In SOI CMOS, it can be used as "floating" device or, when a specific contact is designed, as body contacted. If the body thickness is too high to have a full control of the depletion layer then the transistor is called PD-SOI standing for Partially Depleted SOI. At the opposite CMOS FD-SOI, stand for Fully Depleted SOI. For mm-wave designer concern, gain (f_{MAX}), noise figure, phase noise, power-handling capabilities are transistor key performance indicators. Because the mobility of electrons and holes are very similar in deep sub-micron CMOS SOI, f_{MAX} performance of PMOS transistors is very comparable to NMOS. This latter property offering a unique advantage since it open the door at millimeter wave frequency push-pull architecture that offers a better power handling capacity and improved phase noise [1]. A comparison of NF_{min} shows that whatever the node, SOI CMOS has a lower noise figure than the equivalent bulk one. PD-SOI technology takes advantage of a lower substrate parasitic noise source due to the high resistivity substrate used. Moreover, the FD-SOI technology, with no channel and pocket doping, causing lower noise coupling. Another benefit of using FD-SOI technology for noise improvement is the reduction of drain-to-well capacitance and its non-linearity due to PN junction diode. This is important for oscillator phase noise since it reduces the

phase non-linearity (AM-PM distortion) in large voltage swing conditions. This property is also important for phase linearity in power amplifiers when they are used for complex IQ modulation standards [2].

The main weakness of CMOS is the limited voltage levels capability. One approach to overcome the problem is based on stacked FETs. For bulk CMOS, the junction breakdown voltage together with the mm-wave frequency operation limit the maximum number of FETs that can be stacked to two devices. In CMOS-SOI, the isolated floating body for each device eliminates this limitation. Therefore, the number of devices that can be stacked is only limited by the breakdown of the buried oxide (BOX) below each device. Moreover, because CMOS SOI transistors have reduced parasitic to the substrate (especially PD-SOI), they introduce less phase variation and losses from one cell to another offering a better power efficiency for stacked power amplifier design.

The last concern is passives devices performances which are mainly dominated by two criterion: the top metal layer resistance and the substrate resistivity. The first one can be enhanced by a dedicated RF Back End of Line (BEOL) where specific thick copper metal layers are used in order to improve metal conductivity. This improvement is done at a cost of a more expensive process in comparison to standard CMOS. The substrate resistivity is a more complicated equation. Because of the latch-up immunity requirement, the bulk CMOS and CMOS FD-SOI technologies have a low resistivity substrate ($\sim 10\Omega\cdot\text{cm}$). Conversely, thanks to a higher resistivity substrate ($1-3\text{ k}\Omega\cdot\text{cm}$), PD-SOI technologies have a better passive components performances together with an improve isolation to the current injected into the substrate.

Perspectives

SOI CMOS has already demonstrate its viability for 6G D-band [3], the next step will to study new devices and technologies for the sub-THz band.

RELATED PUBLICATIONS:

- [1] B. Martineau, E. Mercier and P. Vincent, "Opportunity of CMOS FD-SOI for RF power amplifier," IEEE S3S, 2017.
- [2] A. Larie et al., "A 60GHz 28nm UTBB FD-SOI CMOS reconfigurable power amplifier with 21% PAE, 18.2dBm P1dB and 74mW PDC," IEEE ISSCC, 2015.
- [3] A. Hamani et al., "A 84.48-Gb/s 64-QAM CMOS D-Band Channel-Bonding Tx Front-End With Integrated Multi-LO Frequency Generation," in IEEE Solid-State Circuits Letters, vol. 3, pp. 346-349, 2020

A broadband SOI-CMOS linear doherty power amplifier module supporting 100MHz 5G signal without predistortion

RESEARCH TOPIC:

RF Front-End Module for 5G user equipment

AUTHORS:

A. Serhan, A. Giry, P. Reynier, D. Parat

The design complexity of 5G power amplifier (PA) has significantly increased due to the ever-increasing modulated signal bandwidth (BW, up to 100MHz), PAPR (peak-to-average-power-ratio, >8dB), number of operating frequency bands, and output power levels (PC2, power class 2) that need to be supported. This research demonstrates a broadband SOI-CMOS Doherty PA module operating in the 1.9GHz to 2.7GHz frequency band and supporting PC2 mode with a peak output power of 4W and a peak PAE of 57%. The PA delivers 29dBm of output power with -34dBc of NR-ACLR and 33.8% of average PAE using a 100MHz 5G signal (7.5dB of PAPR), without using digital predistortion.

Context and Challenges

To meet the linearity specification, the average power of the power amplifier need to be backed-off from its peak power according to the PAPR of the amplified signal. For 5G standard, the PAPR is almost twice that of the LTE standard (Fig. 1). The increase in power back off (BO) drastically degrades the average efficiency of the PA, when using conventional PAs architectures (Class-BJ or F). Hence, PA architectures that use supply modulation (Envelope Tracking, ET) and load modulation (Doherty) are adopted to improve the BO efficiency. This work demonstrates a highly integrated reconfigurable PA Modules combining high-efficiency Doherty architecture, 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.

Main Results

The PA IC is fabricated in a 130nm SOI-CMOS process and assembled, using flip-chip, on a laminate package (Fig. 2). From 1.9GHz to 2.7GHz, the PA provides 28dBm of output power under 3.4V supply voltage, with a PAE higher than 35% and an E-UTRA ACLR lower than -35dBc when using a 10MHz LTE signal, without predistortion (Fig. 2). At 2.3GHz, the PA achieves 43.5% of PAE and -39.6dBc of ACLR at 28dBm.

When operating at Vdd=5V (PC2 mode), the PA reaches a saturated power of 4W with a maximum PAE of 57% and delivers a linear P_{out} of 31dBm with 42.6% of PAE and -36.8dBc of E-UTRA ACLR using a 10MHz LTE signal (Fig. 3).

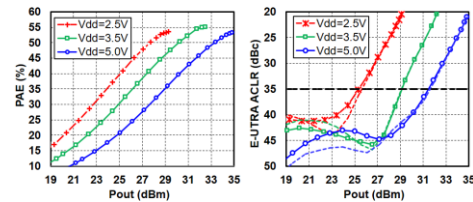
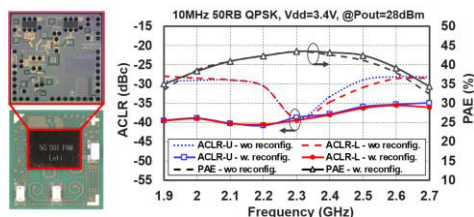


Fig. 1. (top) PA Module photo, E-UTRA ACLR and PAE versus frequency at 28dBm output power. (bottom) PAE and E-UTRA ACLR vs. output power measured for different supply voltage levels at 2.3GHz: 10MHz-50RB and 20MHz-100RB.

Moreover, the PA delivers 29dBm of linear output power with an EVM of 1.86%, a NR-ACLR of -34dBc and a PAE of 33.8% measured under Vdd=5V using a 5G signal with 100MHz of instantaneous bandwidth and a PAPR of 7.5dB, without applying predistortion. The output constellation and spectrum confirms the good linearity of the PA (Fig. 4).

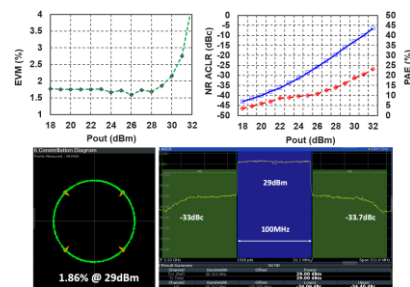


Fig. 2. Measured EVM, NR-ACLR, constellation and output spectrum for a 100-MHz 5G signal at 2.31 GHz under Vdd=5V.

Perspectives

Future LETI's 5G PA solutions associate Doherty architecture and envelope tracking technique using a new integration approach to address wider modulated signal bandwidth with improved efficiency and linearity.

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] P. Reynier et al., "A High-Power SOI-CMOS PA Module with Fan-Out Wafer-Level Packaging for 2.4 GHz Wi-Fi 6 Applications," in IEEE RFIC, 2021.

A multichannel programmable high order frequency multiplier for channel bonding and full duplex transceivers at 60 GHz band

RESEARCH TOPIC:

High-data rate wireless links for 5G+ and 6G

AUTHORS:

A. Siligaris, J. L. Gonzalez-Jimenez, C. Jany, B. Blampey, A. Boulmirat, A. Hamani, C. Dehos

This work describes a high order programmable frequency multiplier in the 60 GHz band. The circuit implements four chains that can address simultaneously four different frequencies of the IEEE 802.11ay standard and aims to channel bonding, full duplex, or MIMO systems. It is fabricated in a 45nm CMOS PDSOI technology. Each chain consumes 32.6mW and achieves lower than 178fs of integrated jitter (in the band 10KHz-1.08GHz) for all synthesized frequencies.

Context and Challenges

This research is motivated by the increasing demand on wireless high-throughput, high-frequency systems that require very low phase noise on the integrated local oscillator. Indeed, complex modulation schemes (16 QAM, 64QAM ...) with high occupied bandwidth (~GHz) require low phase noise and jitter. For that, we propose a new approach in which the frequency synthesis is performed at low frequency and the high frequency signal is obtained by frequency multiplication based on injection locking. A pulsed oscillator and injection locked oscillators are used for this purpose. Injection locking allows to copy the low frequency reference Phase noise close to the carrier but also reject the far from carrier noise floor by filtering it out.

Main Results

The chip is designed and fabricated on a 45nm SOI CMOS technology. Each frequency multiplication chain occupies $750 \times 250 \mu\text{m}^2$ (Fig. 1). High order multiplication is achieved (close to 30) and the resulting signals show state of the art phase noise that enable high order modulation schemes at high frequency. Thanks to these features, four channels of the IEEE 802.11ay standard are synthesized at the 60 GHz frequency band. The total integrated jitter on a >1 GHz band is less than 180 fs for all synthesized frequency channels, which represents the best performance among previous works operating in the same frequency range and opens the door for higher order modulation schemes at mmW than those previously used (Fig. 2). Its potentialities for very high data rate wireless systems using channel bonding techniques have already been demonstrated in [2, 3].

Perspectives

Next steps on this topic will consist on realizing a 60 GHz MIMO system exploiting the programmability and flexibility offered by this frequency synthesis architecture for 5G and beyond 5G infrastructure.

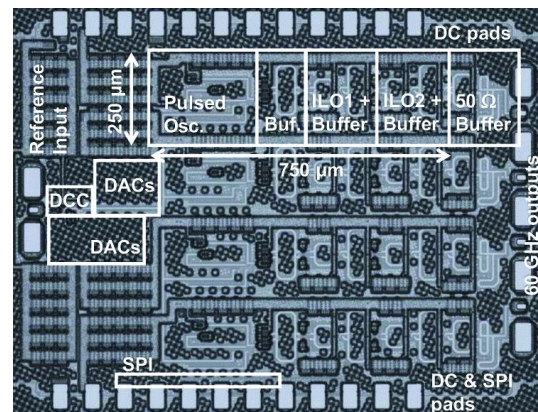


Fig. 1. Frequency multiplication IC photograph.

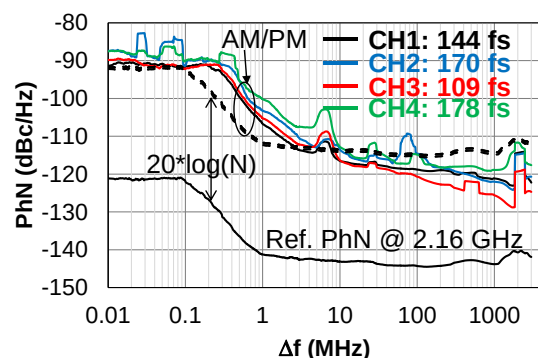
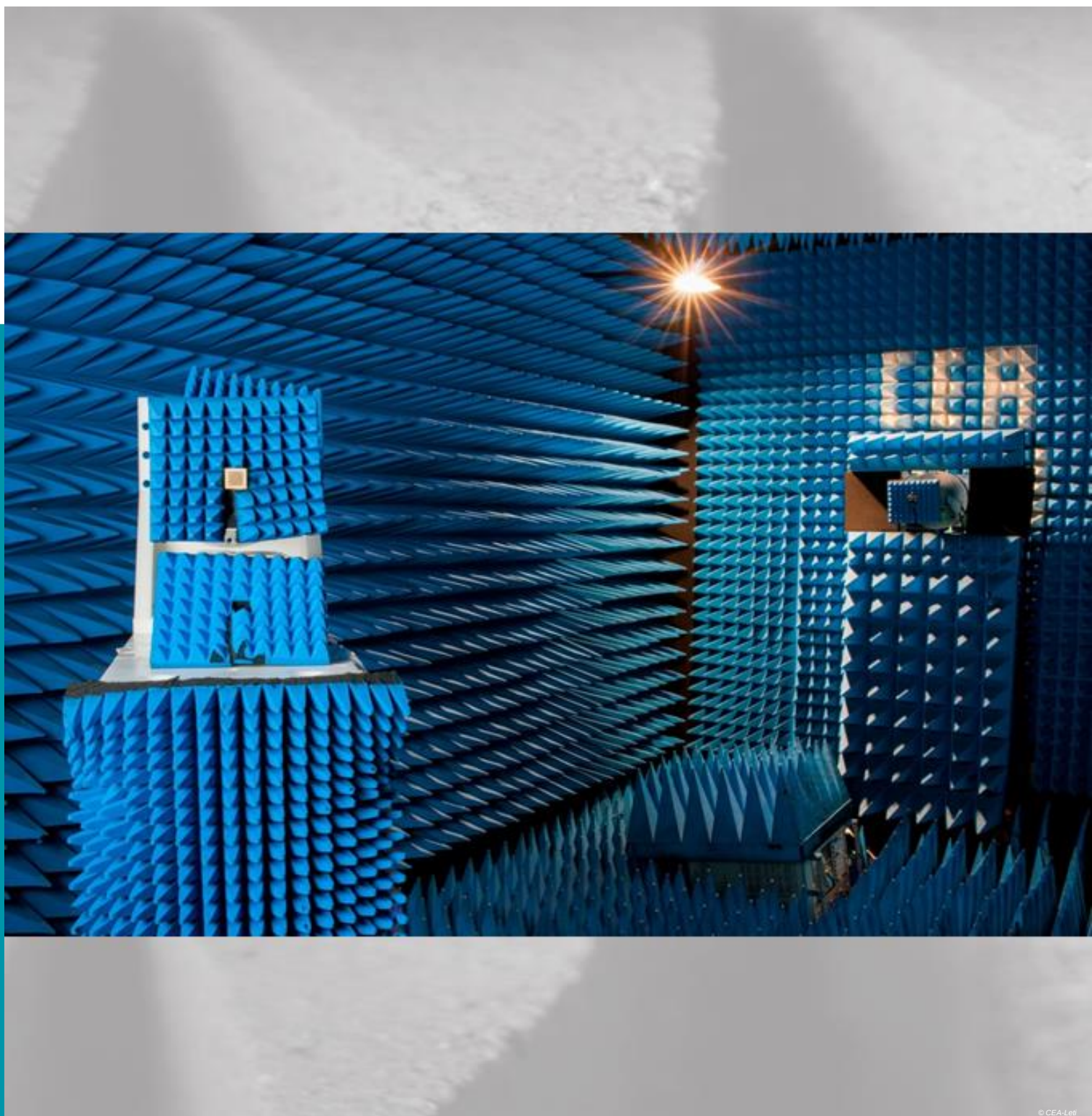


Fig. 2. Phase noise and jitter at the output of the frequency synthesis for the four synthesized channels (58.32GHz, 60.48GHz, 62.64GHz and 64.8GHz).

RELATED PUBLICATIONS:

- [1] A. Siligaris et al., "A Multichannel Programmable High Order Frequency Multiplier for Channel Bonding and Full Duplex Transceivers at 60 GHz Band," 2020 IEEE Radio Frequency Integrated Circuits Symposium (RFIC), Los Angeles, CA, USA, pp. 259-262, 2020.
- [2] A. Hamani et al., "A 84.48-Gb/s 64-QAM CMOS D-Band Channel-Bonding Tx Front-End With Integrated Multi-LO Frequency Generation," in *IEEE Solid-State Circuits Letters*, vol. 3, pp. 346-349, 2020.
- [3] A. Hamani et al., "A 108-Gb/s 64-QAM CMOS D-Band Rx With Integrated LO Generation," in *IEEE Solid-State Circuits Letters*, vol. 3, pp. 202-205, 2020.



02

**ANTENNA SYSTEMS
FOR FUTURE IOE
APPLICATIONS**

- **Communications for the Internet of Everything (IoE)**
- **Novel antenna configurations**
- **High performance antennas**
- **Simulation, specific design and characterization**

Frequency reconfigurable antenna loaded with magneto dielectric materials at VHF frequency band

RESEARCH TOPIC:

Electrically small antennas for airborne systems and IoT applications

AUTHORS:

C. Delaveaud^{1,2}, J-F. Pintos^{1,2}, J-L. Mattei³, V. Laur³, A. Chevalier³, **L. BATEL**^{1,2}

This work describes a frequency agility technique of an electrically small Inverted-F Antenna (IFA) loaded with tunable magneto-dielectric materials (MDM). A specific material developed for VHF applications is used for antenna size reduction and frequency tuning of antenna's frequency response using a low intensity magnetic field control. Using this material to load the antenna leads to a miniaturization factor of 20 % and a potential of frequency agility of 6 % in VHF band close to 50 MHz.

SCIENTIFIC COLLABORATIONS: ¹ CEA-Leti, 38000 Grenoble, France, ² Grenoble Alpes University, 38000 Grenoble, France, ³ LABSTIIC 3Lab-STICC, UMR CNRS 6285, 6 av. Le Gorgeu, 29238 Brest, FRANCE

Context and Challenges

The common use of connected objects these last few years has led to a special need of both electrically small, cost effective and performing antennas. Antenna miniaturization becomes a real challenge at UHF and VHF frequency bands, since the wavelength are large at those frequencies (e.g. 6 m at 50 MHz). Designers of electrically small antennas (ESA) are always facing a tradeoff involving the electrical size of the antenna, its frequency bandwidth and its radiation efficiency, following the fundamental laws of physics. For applications requiring long-range communications, antenna radiation properties are crucial to achieve a correct link budget. This critical issue particularly arises for airborne systems industry, where the need of small antennas at VHF frequencies is also justified by a limitation in weight and aerodynamic drag. In this kind of application, antennas frequency bandwidth is often sacrificed, in order to achieve small antennas with sufficient radiation properties [1]. A possible solution to overcome the limited bandwidth issue is to design a frequency reconfigurable antenna that covers the used communication channels.

Main Results

Classical techniques using active electronic circuits to tune antenna's frequency response are often used to solve the narrow bandwidth issue of ESA. These techniques introduce additional losses in antenna structure leading to a decreasing radiation performances. We propose here an original method for frequency fine tuning using a tunable MDM specifically fabricated for antennas working at VHF frequency band [2]. A DC biasing current generating a magnetic static field in the MDM leads to a variation of its relative permeability, leading to antenna frequency response agility [3]. The fabricated IFA is illustrated in Figure 1. It is composed by a conductive strip of $40 \times 420 \text{ mm}^2$ ($\lambda_0/107 \times \lambda_0/10$) at a height of 120 mm ($\lambda_0/36$) above a circular ground plane with a diameter of 1250 mm ($\sim \lambda_0/4$). λ_0 is the wavelength computed at the resonance frequency of 50 MHz. Ground plane's dimensions

are chosen to meet air craft conditions. One side of the conductor is shorted to the ground plane with three short-circuits loaded by the tunable MDM. Three short-circuits are designed instead of one due to material's shape constraint [1]. An RF block inductor and a bias-tee working below 100 MHz and limited to 5A currents is used for biasing the MDM to ensure antenna's frequency response tuning. A demonstration of the frequency agility of a miniaturized IFA thanks to this particular loading technique is performed using the dedicated tunable MDM (Figure 1). The fabricated IFA has been measured in VHF band achieving a frequency agility of 6 % around 50 MHz, in agreement with simulation results.

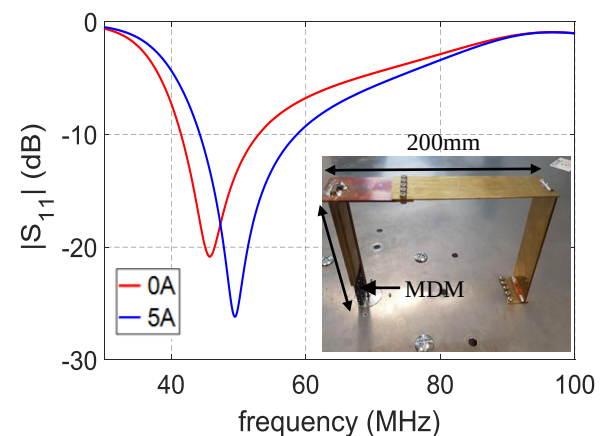


Figure 1: Antenna geometry and frequency response versus current polarization

Perspectives

Improving the biasing circuit and the model of the material will offer a better potential for antenna frequency tunability in VHF band.

RELATED PUBLICATIONS:

- [1] L. Batel, C. Delaveaud, J. Pintos, "Miniaturization strategy of compact antenna using magneto-dielectric material." In : 2019 13th European Conference on Antennas and Propagation (EuCAP). IEEE, 2019. p. 1-5.
- [2] L. Batel, C. Delaveaud, J. Pintos, J. Mattei, V. Laur and A. Chevalier, "Frequency reconfigurable antenna loaded with magneto dielectric materials at VHF band," 2020 14th European Conference on Antennas and Propagation (EuCAP), Copenhagen, Denmark, 2020, pp. 1-5.
- [3] L. Batel et al, "Tunable Magneto-Dielectric Material for Electrically Small and Reconfigurable Antenna Systems at VHF Band" (2020). Ceramics, 3(3), 276-286.

Experimental validation of a 2-bit unit-cell for transmitarrays at Ka-band

RESEARCH TOPIC:

Transmitarray antennas, beam steering, beam forming, Ka-band, discrete lens, electronically steerable antenna

AUTHORS:

F. Diaby, L. Di Palma, L. Dussopt, R. Sauleau¹, and A. Clemente

This paper presents the experimental results of a 2-bit electronically reconfigurable unit-cell for transmitarrays at Ka-band. The proposed unit-cell architecture is based on a six-metal layers design and three dielectric substrates. Two patch antennas are printed respectively on the top and bottom layers of the stack-up to achieve an antenna-filter-antenna structure. To implement the desired 2-bit phase resolution, two p-i-n diodes are bonded on each patch. The unit-cell has been fabricated and characterized in a specific waveguide simulator. The measurement results are compared to the simulated ones and show minimum transmission loss in the range 1.5 – 2.3 dB. The 3-dB fractional bandwidth is in the range 10.1 – 12.1%.

SCIENTIFIC COLLABORATIONS: ¹ Univ Rennes, CNRS, IETR (Institut d'Electronique et de Télécommunications de Rennes) – UMR 6164 Rennes, France

Context and Challenges

Relatively low cost and low power consumption beam-forming architectures are required to develop innovative electronically steerable antennas for the future mass market high-data-rate satellite and terrestrial communications. In this context, spatial feeding techniques combined with Printed Circuit Boards (PCB) technologies represent cost-effective solutions to design innovative electronically reconfigurable antennas based on the reflectarray or transmitarray concepts. On one side, for large antenna apertures, the spatial feeding mechanism drastically reduces the loss and complexity of the power division network compared to classical phased array architectures. On the other side, PCB technologies are compatible with the integration on the array aperture of p-i-n diodes, RF-MEMS switches, varactors, etc., which can be used to easily control the antenna aperture phase distribution without using complex and lossy phase shifters. Furthermore, as they operate in transmission mode, transmitarrays are also compatible with solutions to reduce the overall antenna profile.

Main Results

The proposed unit-cell architecture is based on six-metal layer (M1 – M6, thickness 18 μm) stack-up with three RT/Duroid 6002 Rogers substrates and two bonding films (RO4405F, thickness 100 μm). The substrate between layers M5-M6 has a thickness of 508 μm . Instead, the substrates between layers M1-M2 and M3-M4 have a thickness of 254 μm . The six metal layers are the following: transmitting (Tx) patch antenna (M1), delay line (M2), bias line associated to the Tx patch (M3), ground plane (M4), bias line associated to the receiving (Rx) patch (M5), and the Rx patch (M6). Standard Printed Circuit Board (PCB) process, i.e. with minimum trace width of 80 μm and minimum via-diameter of 120 μm , has been selected to demonstrate the possibility to implement the proposed design by using mature and relatively low cost fabrication technologies. Two p-i-n diodes MACOM MA4AGP907, indicated as D1 – D4, are flip-chipped on each radiating element (O-slotted rectangular patch antennas) to control electronically the

transmission phase of the unit-cell with the required 2-bit phase resolution. Four phase states (UC000, UC090, UC180, and UC270) are generated by opportunely controlling the diode states. The unit-cell has been characterized using a waveguide simulator composed by two coax-to-WR28 adaptors, two WR28 straight waveguide sections, and two tapered transitions between the rectangular section of the waveguide and the square aperture of the unit-cell.

Perspectives

The possibility to generate more phase states and as a consequence increase the phase resolution will be studied in the future.

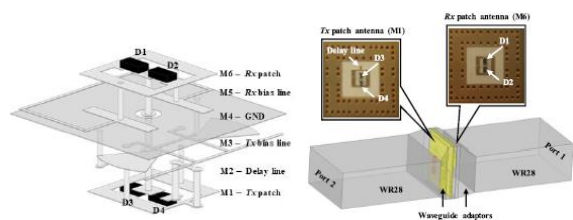


Fig.1: Stack-up of the proposed 2-bit unit-cells with four p-i-n diodes and proposed waveguide measurement system.

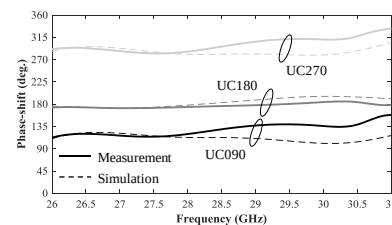


Fig.2: Simulated and measured relative phase-shifts between the UC000 and the other phase states.

RELATED PUBLICATIONS:

- [1] A. Clemente, F. Diaby, L. Di Palma, L. Dussopt, and R. Sauleau, "Experimental validation of a 2-bit reconfigurable unit-cell for transmitarrays at Ka-band," IEEE Access, vol. 8, pp. 114991-114997, 2020.
- [2] A. Clemente, F. Foglia Manzillo, M. Smerczalski, and R. Sauleau, "Electronically-steerable transmitarray antennas for SATCOM terminals: a system perspective," IEEE International Workshop Antenna Technology, (IWAT 2020).
- [3] 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 and Propag., vol. 68, no. 6, pp. 5003-5008, Jun. 2020.

Three-element end-fire linear array (super) directivity and gain optimization

RESEARCH TOPIC:

End-fire arrays, superdirectivity, supergain, array synthesis

AUTHORS:

A. Debard, C. Delaveaud, and A. Clemente

This contribution presents the results of the optimization of two three-element linear arrays based on straight- and bent-electrical dipoles, respectively. To achieve a compact architecture, the inter-element distance is fixed to 0.12λ , with λ the wavelength calculated at the operation frequency (850 MHz). The array excitation coefficients have been optimized to achieve either maximum directivity or gain. The synthesis procedure is based on the optimization of the directivity or gain formulas considering the array factor and the active element patterns. The numerical results have been validated by 3D full-wave simulations. The maximum directivity is equal to 10.0 (gain 2.91 dBi) and 9.83 dBi (gain 3.67 dBi) in the case on the straight- and bent-electrical dipole based arrays, respectively. Instead, the maximum gain is equal to 6.81 (directivity 8.84 dBi) and 7.85 dBi (directivity 9.19 dBi).

Context and Challenges

Electrically Small Antennas (ESAs), where small is meant in the sense of the antenna electrical size compared to the operation wavelength, have been the subject of several researches from the middle of the twentieth century. Nowadays, the development of innovative small or compact antennas with high performance and advanced functionalities such as spatial selectivity, frequency or pattern agility, high directivity and gain, etc. is a topic of increasing interest for the antenna international community. In fact, these antennas technologies are largely required in the development of the future Internet of Thing (IoT), wireless sensor networks, radiofrequency identification (RFID) systems, remote power control or wireless power transfer. Furthermore, the use of small antennas is a fundamental requirement to guarantee the integration of the future wireless systems operating in the frequency bands below 6 GHz in the new generation of connected objects

Main Results

Two compact end-fire linear arrays with three closely-spaced elements (0.12λ), respectively indicated as (1) and (2) in the Figure 1, have been optimized in terms of maximum directivity or gain by using a synthesis procedure based on the array factor theory. The two arrays are based on (1) straight- and (2) bent-electrical dipoles, respectively. The proposed synthesis procedure allows to extract the optimal excitation coefficients associated to each array element required to maximize the directivity or the gain in the end-fire direction. We showed that a maximum superdirectivity around 10.0 dBi can be achieved at the cost of a poor efficiency (i.e. a limited gain of 2.91 dBi or 3.67 dBi in the case of the array (1) or (2), respectively). This directivity value is very close to the theoretical bound (Figure 2). Furthermore, we demonstrated that the array efficiency can be enhanced by relaxing the optimization problem when the efficiency of the individual elements of the arrays is included in the synthesis procedure. Thus a maximum gain of 7.85 dBi was obtained with the bent-dipole array corresponding to a 4.18 dB efficiency improvement compared to the directivity optimization

strategy. Indeed, the gain achieved for the array (1) is equal to 6.81 dBi.

Perspectives

The main technical challenge for the future will be the experimental demonstration of the proposed antenna arrays

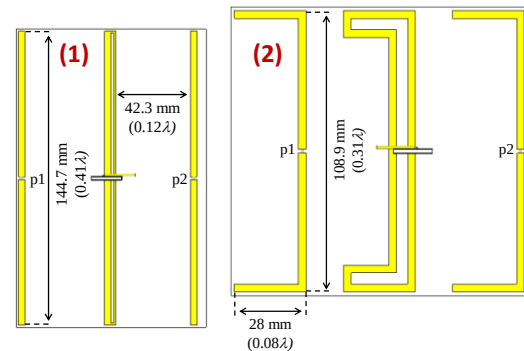


Fig.1: Proposed antenna arrays (1) and (2).

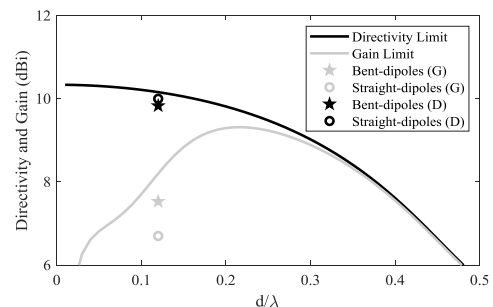


Fig. 2: Proposed results compared to the theory

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 Transaction on Antennas and Propag., vol. 63, no. 11, pp. 4715-4722, Nov. 2015.
- [2] A. Debard, A. Clemente, C. Delaveaud, P. Potier, and P. Pouliguen, "Limitations and optimization of supergain end-fire arrays," 13th European Conf. on Antennas and Propag. (EuCAP 2019).
- [3] A. Debard, A. Clemente, and C. Delaveaud, "Three-element end-fire linear arrays (super) directivity and gain optimization," 14th European Conf. on Antennas and Propag. (EuCAP 2020).

Analysis of the effects of conductivity on small antenna characteristics

RESEARCH TOPIC:

Electrically Small Antenna, Fundamental limits, Inverted F antenna, radiation efficiency, electrical conductivity, Transmission Line model

AUTHORS:

R. Berro, S. Bories and C. Delaveaud

Understanding loss phenomena in miniature antennas is an essential step in the search for more efficient compact radiating structure. In this work, the impact of metallic material conductivity used to build an Inverted F Antenna (IFA) is studied using both an improved antenna model using Transmission Line approach and Full Wave 3D electromagnetism simulation tool. The metal conductivity effect is studied on antenna radiation efficiency and input impedance to evaluate the compliance of the developed IFA antenna model with fundamental limits of Electrically Small Antennas. On the other hand, the antenna model makes it possible to provide an interpretation to the observations made on the properties of the miniature antenna.

This work was rewarded with the special jury prize of the IWAT 2020 conference

Context and Challenges

The notions of physical limitations for Electrically Small Antennas (ESA) were first introduced in the mid of the last century by Wheeler and Chu. Since then, much attention has been drawn to the subject and many research works addressed the study of limitations on bandwidth, gain or efficiency of small antennas of arbitrary shapes. If many antenna miniaturization solutions exist, they lead to drastic limitations in performances and the search for performing miniature antennas is essential for Internet of Thing applications. The shape, topology, size and constitutive materials of these antennas drive their properties. For ESA, the conductivity of the metallic material plays a key role especially as it is actually lower than the classically announced (oxidation, metal tie layers).

Main Results

Firstly, we continued to develop a Transmission Line (TL) model [1]-[3] of a miniature IFA antenna (commonly used in many compact communicating objects) to analyze the impact of the metal conductivity change ranging from copper value to conductive inks on its radiofrequency characteristics (input impedance, radiation efficiency). The improved model takes into account both electric and electromagnetic aspects of the antenna. It is able to estimate the antenna input impedance and to provide the radiation efficiency of the IFA by calculating the radiated far field using analytical expressions. The originality of the developed model is to take into account all kinds of losses in the antenna structure (conductor loss, load and termination losses, radiation loss) and the end effects at the short circuit termination. Consequently, the model is tested to study the impact of conductivity of metal used for the manufacturing of an IFA. As illustration of results presented in [4], Fig. 1 compares the radiation efficiencies given by the model to the simulated ones using full wave 3D electromagnetic tool (CST MWS) for different values of material conductivity σ . The efficiency model shows to be in a good agreement with the simulated results, demonstrating how the model is accurate to retrieves the fundamental physical ESA limitations regarding the impact of

the antenna structure conductivity. The radiation efficiency decreases when conductivity is decreased, due to high resistive loss in the antenna having low conductivity which leads to higher dissipated power.

Perspectives

The electrical and EM model of the IFA and associated equations show how metal conductivity impacts the small antenna behavior. The model is equally valid with fundamental ESA equations and limits, and will help the analysis of small antennas characteristics in order to find ways to improve their performance. Moreover, this model will allow the rapid investigation and optimization of frequency agility technics using a co-designed tunable component that load the antenna structure.

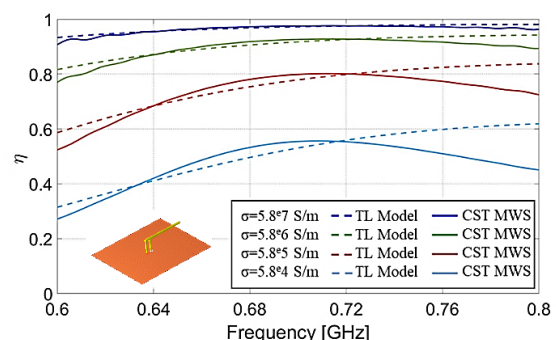


Fig. 1: Comparison of IFA radiation efficiency versus frequency for different values of metal conductivity σ .

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.
- [3] R. Berro, S. Bories and C. Delaveaud, "Radiative Loss In Small Inverted-F Antenna Transmission Line Model," 2020 14th European Conference on Antennas and Propagation (EuCAP), Copenhagen, Denmark, 2020, pp. 1-5.
- [4] R. Berro, S. Bories and C. Delaveaud, "Analysis of the Effects of Conductivity on Small Antenna Characteristics," 2020 International Workshop on Antenna Technology (iWAT), Bucharest, Romania, 2020, pp. 1-4

Antenna perturbation modelling and impact on radio channel

RESEARCH TOPIC:

Propagation, joint antenna-channel modeling, IoT

AUTHORS:

L. Pometcu, R. D'Errico

In this work we investigate a joint antenna-channel model, considering stochastic variability on the radiating element. The perturbed antenna characteristics are described through spherical wave expansion modes coefficient distribution in order to produce a stochastic antenna model. This model is then considered in a classical single cluster and indoor industrial channel, in order to evaluate the impact on delay and angular spread.

Context and Challenges

Radio channel characterization is often performed by using canonical antennas (e.g. omnidirectional in the azimuth plane), arrays, or directive antennas opportunely steered. Channel models generally consider antenna function as an add-on to be considered. However, in most practical applications, the antennas are not ideal and their behaviour strongly depends on the surrounding environments, e.g. the user presence or nearby objects, which can affect their performance and has a consequence on the radio channel characteristics.

Main Results

In this work, we proposed a stochastic channel modeling of antenna perturbation based on spherical wave decomposition (Fig.1). We considered a wide band monopole antenna with a nearby close metallic plate, whose distance and orientation randomly change. We modelled the spherical wave coefficients, with an order up to 10, as correlated Gaussian complex random variables. In order to assess the impact of the antenna model, hence the perturbation on the radio channel, we considered a single cluster scenario and an industrial indoor model, derived from measurements between 2 and 6 GHz. The nearby metallic plate can be considered representative of an antenna perturbation typical in indoor industrial environments. We have shown that the antenna stochastic model combined with the propagation one has an impact on the delay and angular spread. The impact is more important in the Non-Line-of-Sight scenarios when the richness of multipath is more important (Fig.2).

Perspectives

The proposed antenna-channel joint modelling framework will be further extended for different channels and antenna topologies to address diverse deployment conditions and applications.

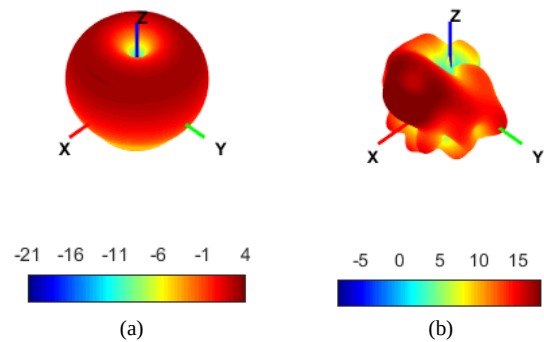


Fig. 1: Antenna directivity [dBi]: (a) isolated, (b) example of perturbed antenna model

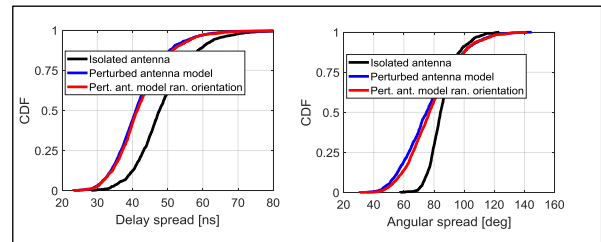


Fig. 2: Cumulative Distribution Function of Delay spread and Angular spread in Non Line of Sight scenarios.

RELATED PUBLICATIONS:

[1] L. Pometcu and R. D'Errico, "Antenna Perturbation Modelling And Impact On Radio Channel," 2020 14th European Conference on Antennas and Propagation (EuCAP), Copenhagen, Denmark, 2020, pp. 1-5, doi: 10.23919/EuCAP48036.2020.9135578.

Synthesis of transmitarrays using iterative convex optimization

RESEARCH TOPIC:

array synthesis, transmitarray antennas, beamforming, pattern shaping, optimization techniques, satellite communications.

AUTHORS:

M. Merluzzi, M. Smierzchalski, N. di Pietro, A. Clemente, **F. Foglia Manzillo**

A mathematical approach for the synthesis of transmitarray antennas using iterative convex optimization has been developed and numerically validated. The proposed procedure leverages on semidefinite relaxation to approximately solve the inherently non-convex phase-only synthesis problem and is suitable for a wide range of beam shaping applications. As an example, the synthesis of a pencil-beam pattern with reduced sidelobe levels and limited gain loss is illustrated. The pattern distortion due to the quantization of the optimal phase distribution is investigated to provide realistic design guidelines.

Context and Challenges

Shaping the radiation pattern of an antenna array is essential for a wide range of communication and imaging systems. Transmitarray antennas (TAs) work as planar lenses and are ideal for manipulating an incident field and shaping the radiated beam. Once the feed is chosen, the pattern of a TA can be shaped only by tailoring its aperture phase distribution. The few works on TA synthesis mainly resort to time-consuming global optimizations, often poorly convergent, or derive analytical solutions for simple cases. Convex optimization offers a good trade-off between efficiency and generality but requires a proper formulation and relaxation of the synthesis problem.

Main Results

The field impinging on each unit cell (UC) of the TA is found using the radiation pattern of the feed and ray tracing [1]. The UCs are modeled as lossless aperture antennas able to introduce any phase shift on the incident wave. The determination of these phase shifts to fit a radiation mask is a non-convex problem. The semidefinite relaxation (SDR) technique in [Fuchs, *IEEE TAP*, Feb. 2014] has been applied, for the first time for TAs, to find an approximate solution by iterative convex optimizations [2]. At each iteration, the optimal solution of a convex problem is efficiently determined using an off-the-shelf routine. The procedure is fast convergent and has been successfully applied to synthesize focused and shaped beams. We present here the results of the synthesis of a 20×20 TA with a half-a-wavelength ($\lambda/2$) period. The feed is a 10-dBi horn at a distance $F = 7.5 \lambda$ from the TA. The synthesis aims at reducing the sidelobe levels (SLLs) in all azimuthal planes with a gain loss < 2 dB with respect to the maximum achievable value. The figure presents the optimized phase distribution, the computed three-dimensional pattern and its cut for $\phi = 90^\circ$. The pattern complies with the mask (in red) in the 1053 points where it is defined. The gain is only 1.4 dB lower than that achieved by the same TA when optimized for gain maximization. The first SLLs are reduced by at least 10 dB. In practical designs, only a few different UCs, and thus phase

values, are used. The impact of a uniform N -bit quantization of the optimal phase distribution has been investigated. The pattern obtained with a 3-bit phase quantization does not satisfy the mask in a narrow angular region. A 4-bit design closely fits the synthesized pattern.

A 300-GHz TA has been designed using the synthesized 3-bit phase distribution and the 8 UCs in [3]. The pattern obtained from full-wave simulations is in-line with numerical results except for large angles, due to the spillover which is neglected by our model.

Perspectives

Several prototypes will be characterized at 300 GHz. The procedure will be enhanced to synthesize large non-symmetric TAs and model the spillover. It will be applied to the design of electronically reconfigurable TAs with a reduced number of controls.

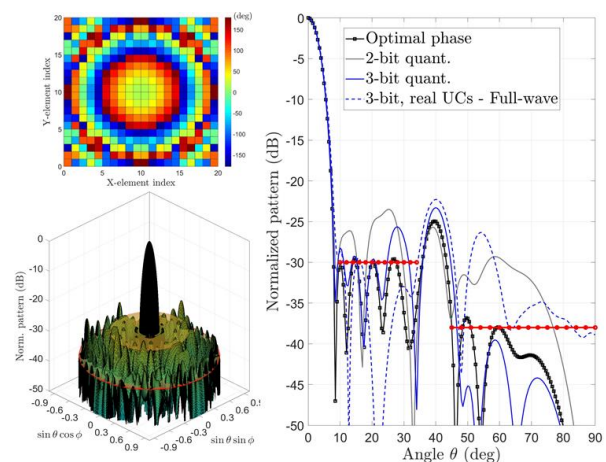


Fig.1: Synthesis results for a focused-beam TA

RELATED PUBLICATIONS:

- [1] H. Kaouach, L. Dussopt, J. Lanteri, T. Koleck, and R. Sauleau, "Wideband low-loss linear and circular polarization transmit-arrays in V-band," *IEEE Trans. Antennas Propag.*, vol. 59, no. 7, pp. 2513–2523, July 2011.
- [2] F. Foglia Manzillo, M. Merluzzi, M. Smierzchalski, N. di Pietro, A. Clemente, "Synthesis of transmitarrays via convex relaxation," in *Proc. IEEE Int. Symp. Antennas Propag. (APS/URSI)*, pp. 2017–2018, Montreal, QC, Canada, 2020.
- [3] O. Koutsos, F. Foglia Manzillo, A. Clemente and R. Sauleau, "Design of a 3-bit transmitarray antenna at 300 GHz using asymmetric linear polarizers," in *Proc. IEEE Int. Symp. Antennas Propag. (APS/URSI)*, pp. 1505–1506, Montreal, QC, Canada, 2020

Linear-to-circular polarization conversion from impedance loading of single-port patch antenna

RESEARCH TOPIC:

Electromagnetic backscattering, clutter, wave depolarization, patch antenna, passive wireless sensor

AUTHORS:

L. F. F. Dias, C. Delaveaud, H. Aubert¹ and C. Jouvaud

Electromagnetic theory of antenna scattering has been previously applied to the minimization/maximization of radar signatures, and has been eventually used for designing antenna sensors for passive wireless sensing systems, in which the antenna backscattering mode is controlled by antenna loading impedances. The reflected signal of interest of an antenna can be damaged by the physical environment between the reader and the antenna, called the clutter. To mitigate the clutter and reduce polarization mismatch in such wireless systems, we investigate the linear-to-circular conversion of electric field from loading single port antennas by passive impedances.

SCIENTIFIC COLLABORATIONS: ¹ LAAS-CNRS, Université de Toulouse, France (Fr)

Context and Challenges

This research focuses on the electromagnetic scattering from antennas intended to be used as sensor. Wireless interrogation of fully passive antenna sensors is based on the modification of the electromagnetic backscattering response, by variation of a physical parameter (i.e. temperature, humidity, pressure, etc.). Challenges are numerous as reading range, sensitivity, antenna miniaturization or signal discrimination from interferences. Focusing on mitigate clutter effects, we work on the control of antenna scattering. This one can be combined as the contribution of a so-called structural and an antenna backscattering modes [R.C. Hansen, doi: 10.1109/5.32056]. The structural mode may be derived from the electric field backscattered by the short-circuited antenna (i.e Fig 1), while impedance loading allows controlling the antenna backscattering mode. For example, the minimization or maximization of the Radar Cross Section of an arbitrary antenna may be achieved from adjusting the load impedance of this antenna. The use of the cross-polarized electric field backscattered by passive (or batteryless) and chipless antennas is rather recent, and is a solution to minimize clutter interferences in electromagnetic reverberant environments.

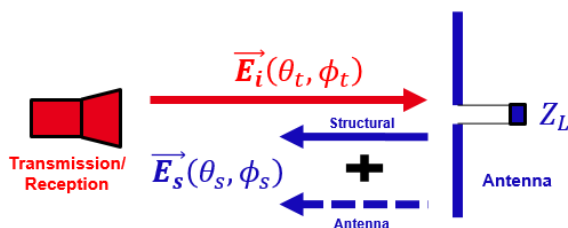


Fig. 1: Sensor antenna backscattering

Main Results

In order to mitigate the clutter and reduce polarization mismatch between an antenna and reader antennas, we propose to load single-port antennas by a passive impedance for converting the linearly polarized incident field transmitted by a radar reader into a circularly polarized field. Thanks to a validated model of the backscattered field of a single port antenna based on Hansen works, values of the loaded impedance to convert antenna field from a linear, elliptic or circular polarization, and to control its RCS amplitude are extracted. A numerical validation of the model is realized with a patch antenna at 915 MHz. By loading the antenna with a control complex impedance, a circular polarisation is built in a desired direction. An axial ratio of 0.3 dB in the direction of a monostatic radar reader has been numerically obtained. With this model, some limitations to achieve a backscattered circular polarization have been alighted: as the choice of the angle of the incident field or as unrealistic or too high complex impedances to be loaded on the antenna.

Perspectives

Experimental validations of the model are in progress. Moreover, an extension of the single port model into a complex two ports model is underway and will also require experimental demonstrations. In addition to reducing clutter effects, such scattering 2-ports model will allow the conception of larger reading range antennas. Another interesting application deals with the simultaneous control of the two polarizations transmission of an antenna in order to design antennas with two independent controlled polarization properties.

RELATED PUBLICATIONS:

- [1] L. F. Fonseca Dias, C. Jouvaud, C. Delaveaud and H. Aubert, "Linear-to-Circular Polarization Conversion from Impedance Loading of Single-Port Patch Antennas," 2020 IEEE International Symposium on Antennas and Propagation and North American Radio Science Meeting, Montreal, QC, Canada, 2020, pp. 1119-1120
- [2] V. Engelhardt, C. Jouvaud, F. Sarrazin, C. Delaveaud and H. Aubert, "Maximization of measurement sensitivity and reading range of passive RF sensors from complex impedance optimization," 2017 IEEE SENSORS, Glasgow, UK, 2017, pp. 1-3,

H-Band substrate-integrated discrete lens antenna for high data rates communication systems

RESEARCH TOPIC:

Integrated antennas, transmitarray antennas, high-gain antennas, millimeter-wave

AUTHORS:

K. Medrar, L. Dussopt, C. Belem-Goncalves¹, G. Ducournau², L. Marnat

A substrate-integrated discrete-lens antenna manufactured in standard printed-circuit-board (PCB) technology is demonstrated in H-band (225-325 GHz). The antenna is composed of the phase-shifting unit-cells and the planar focal source integrated in a monolithic $20 \times 20 \times 4.52$ mm³ module with five metal layers. The linearly-polarized unit-cells are based on resonators placed between two perpendicular polarizing grids. Eight transmission phase states are achieved with 27% 1-dB bandwidth. Two prototypes with radiating apertures of 6.6×6.6 mm² and 10.56×10.56 mm² are designed and fabricated. They demonstrate pencil-beam radiation patterns with low side-lobes, low cross-polarization, a measured gain of 20.6/23.1 dBi at 327/332 GHz and 3-dB gain bandwidth of 26.3/17.2%.

SCIENTIFIC COLLABORATIONS: ¹ STMicroelectronics, Crolles (FR), ² Institute of Electronics, Microelectronics and Nanotechnology (IEMN), Villeneuve d'Ascq (FR)

Context and Challenges

The increasing capabilities of high speed integrated transceivers and the massive expansion of wireless applications boosted the interest for mm-wave systems. The H-band offers wide contiguous bands of unlicensed spectrum enabling extremely high data rate communications up to 100 Gb/s. High-gain antenna-in-package (AiP) solutions are particularly of interest but no solution is available yet. Transmitarrays have been investigated at mm-wave frequencies as a low cost and versatile solution [1-2]. The novel AiP topology proposed in [3-5] (fig. 1) where the discrete lens and the focal source(s) are parts of a monolithic module fill this gap. The main benefit of this approach is to manage the tight alignment and focal distance requirements during manufacturing rather than system assembly.

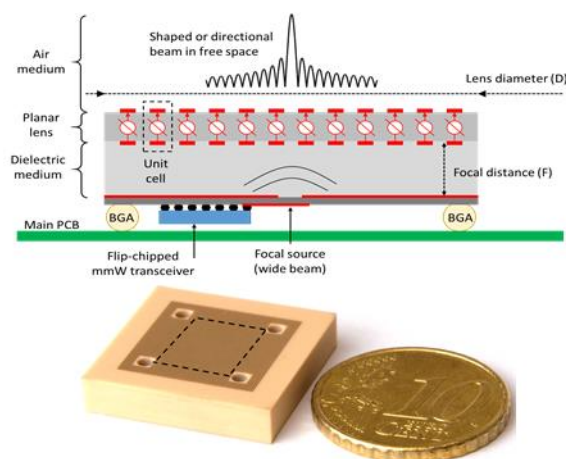


Fig. 1: From antenna concept to 300 GHz prototype

Main Results

Two antenna prototypes were designed and manufactured (fig. 1) with radiating apertures of 6.6×6.6 mm² and 10.56×10.56 mm². The experimental results demonstrate very good performances (fig. 2) with an experimental gain of 20.6/23.1 dBi corresponding to antenna efficiencies of 22.2% and 26.5% for the small and large apertures, respectively. Wide 3-dB gain bandwidths of 26.3 and 17.2% are achieved with focal ratio of 0.55 and 0.34, respectively.

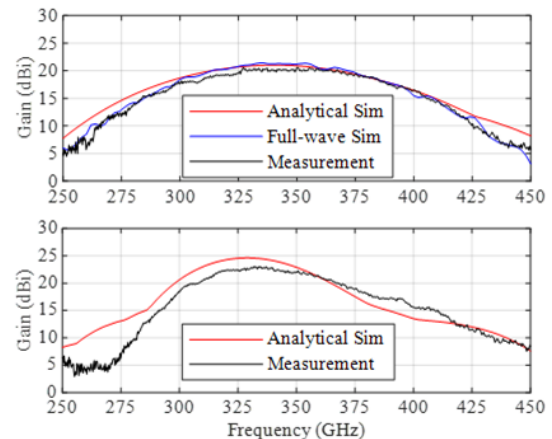


Fig. 2: Antenna gain of both prototypes in H-band

Perspectives

The proposed antenna topology is validated up to 300 GHz with good experimental results. The next steps are to demonstrate a high data rate data link with this highly integrated solution and to reduce further the thickness of the antenna module

RELATED PUBLICATIONS:

- [1] C. Jouanlian et al., "Wideband Linearly Polarized Transmitarray Antenna for 60 GHz Backhauling," in IEEE TAP, vol. 65, no. 3, March 2017.
- [2] F. Foglia Manzillo, A. Clemente and J. L. González-Jiménez, "High-Gain D-Band Transmitarrays in Standard PCB Technology for Beyond-5G Communications," in IEEE TAP, vol. 68, no. 1, Jan. 2020.
- [3] K. Medrar, L. Marnat, et L. Dussopt, « Planar discrete lens antenna integrated on dielectric substrate for millimeter-wave transceiver module », IJMW, dec. 2017.
- [4] K. Medrar, L. Marnat, et L. Dussopt, « Millimeter-wave circularly-polarized substrate-integrated planar discrete lens », in EuCAP 2018.
- [5] L. Marnat, K. Medrar, et L. Dussopt, "Highly Integrable High Gain Substrate-integrated Planar Lens for Wide D-band Applications", in EUCAP 2020.



03

**SENSORS:
INTERACTING WITH
THE ELECTRONIC WORLD**

- Internet of Things (IoT)
- IoT / human interfaces
- Cyber Physical Systems (CPS)
- Artificial intelligence at the edge (Edge IA)
- Learning algorithms
- Sensors and RF sensors
- Biometric sensors
- Magnetic sensors for medical applications
- Sensor data fusion and processing
- Functionalization with sensors
- Functional electronics

Edge AI for sport gesture classification

RESEARCH TOPIC:

Segmentation and classification of boxing strikes by IMU sensors and neural network

AUTHORS:

J. Boutet, PA. Ramahefa-Andry, O. Thomas¹, JP. Gros, V.Cattin

This work proposes a new segmentation method for consecutive gesture analysis, associated with a classification method adapted to real time analysis on a low power consumption platform. The experimental setup consists of a wristband including an IMU, a high G accelerometer and an MCU. A dedicated state machine detects the start and the stop time of each strike during a sequence for slow and fast strikes while ignoring feints, strikes given by the other arm. A set of standard features are extracted from a moving signal window in real time and serves as input for a neural network classifier. The classifier is a fully connected multilayer perceptron. A test was conducted on 9 subjects of various practice levels, showed an accuracy of 96.9% by 10-fold validation

SCIENTIFIC COLLABORATIONS: ¹ MOOVLAB, 119 chemin de Pré Faure, 38420 Revel This work was conducted in collaboration with MOOVLAB, a start-up dedicated to interactive fitness coaching and gamification.

Context and Challenges

Combat sport segmentation is a particularly complex subject as the strikes are aperiodic and involves a wide range of accelerations often exceeding the dynamic range of standard accelerometers (>40G). Secondly, the sequence of strikes generally do not include idle periods, which are often used to segment the signal[1]. Finally, the strikes duration varies highly between beginners learning the technique (several seconds per punch) and experts (250 μ s/punch).

This work aims to propose a new segmentation method for consecutive gesture analysis, associated with a classification method adapted to real time analysis on low resource platform, and without relying on cloud computing, thus respecting user privacy.

Main Results

The system placed on the wrist is based on one IMU sensor (Bosch BNO55) a 3-axis high G accelerometer, an MCU (Nordic NRF52) and a dedicated firmware capable of datalogging all sensors at a frequency of 100Hz on an SD card. The proposed segmentation algorithm relies on a dedicated state machine to detect the start and the stop time of each strike during a sequence for slow and fast strikes while ignoring feints, strikes given by the other arm, hopping and bad form strikes.

The system was tested on 9 subjects of various practice level. Each subject was equipped with two dataloggers placed at the wrist and instructed to perform a sequence 5 strikes of a given type (ex: jab) of increasing speed followed by 5 consecutive strikes at full speed with the right arm, then another sequence with the left arm, and finally, by alternating right and left arm strikes. The protocol includes jabs, hooks, uppercuts, and feints with and without target.

Results showed that the segmentation algorithm was capable of detecting 100% of the strikes, while ignoring all feints.

A standard cross-validation pipeline assessed classification performance. This pipeline includes the following steps: standardization, feature selection and classifier optimization.

The selected criteria was the standard accuracy as the dataset was well balanced.

The Feature Selection step showed that all the features are useful, as removing one of them makes the classification results drops significantly. We also noted an overall accuracy of 96.9% in the case of a cross-validation on a tenth of the samples (10-fold cross validation) and 88.5% in the case of a validation on a new person (not learned in the base).

Perspectives

We proposed a complete embedded system capable of segmenting and classifying boxing strikes in the context of a workout or a match. It may be extended by adding more strike classes, for instance by differentiating cross and straight strikes. The proposed segmentation algorithm may be also applied to other sports involving fast, aperiodic and chained movements (other martial arts, whitewater canoeing...).

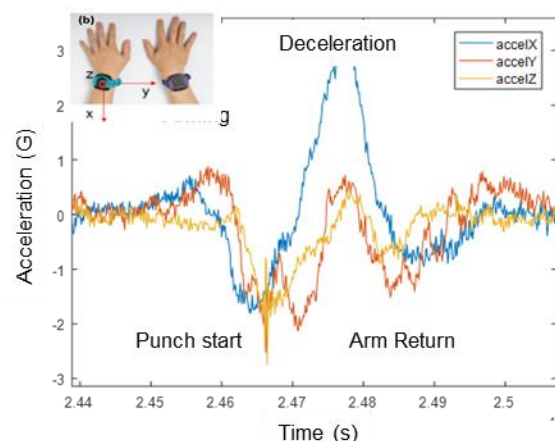


Fig. 1: Accelerometer signal corresponding to a jab

Comparative study of radar architectures for human vital signs measurement

RESEARCH TOPIC:

FMCW, IR-UWB, millimeter-wave radar, radar, ultra-wideband, vital signs extraction

AUTHORS:

Mykhailo ZARUDNIEV, Michael PELISSIER, Olivier MICHEL¹, Etienne ANTIDE

Radars can be used as a non-invasive solution to monitor the vital signs of patients. The heart and respiratory rates are generally extracted by analyzing the phase variations of the radar signal, thus motivating the use of millimeter-waves. While the state-of-the-art considers various radar architectures, they are seldom compared in terms of hardware complexity and power consumption even though these aspects are of utmost importance for autonomous applications. This paper presents a comparative analysis of the state-of-the-art short-range radar solutions and takes into account their respective hardware complexity needed to improve the signal to noise ratio. It aims to select the most relevant low-power architecture for an autonomous application.

SCIENTIFIC COLLABORATIONS: ¹ Université Grenoble Alpes, CNRS, Grenoble INP, GIPSA-lab, FRANCE

Context and Challenges

The use of radars for extraction of human vital signs was the subject of recent developments in the domain of radiofrequency front-ends. Recent works have suggested the use of millimeter-wave radars to offer more phase dynamics. These works, being very promising to show the potential of radar sensors in this application, are lacking of system level approach where the main characteristics of measured signals are analyzed and multiple radar solutions are compared on the same level of abstraction. As a result, there is a need to develop a comparative study starting from application level specifications which includes spatial resolution, minimum range variation due to heart activity, and the SNR levels on the ADC end.

Main Results

We present a comparative scaling of state of the art radar architectures, and compare them in term of hardware complexity, sampling rate, duty-cycle and SNR.

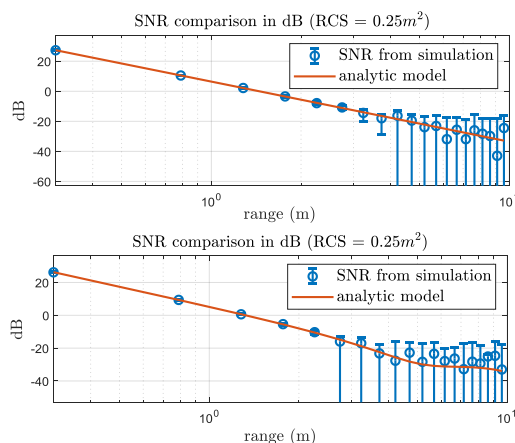


Fig. 1: SNR evaluation (a) FMCW (b) IR-UWB

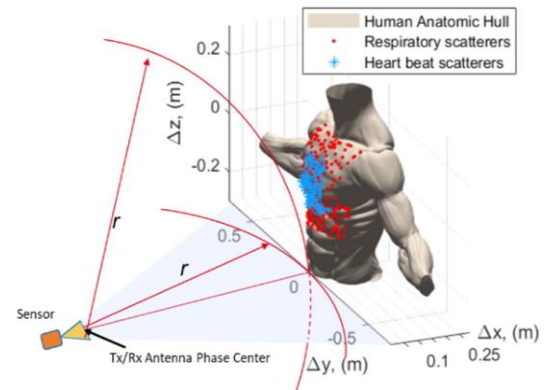


Fig.2: Human Anatomic backscattering model

Perspectives

This study has brought us to consider the Duty-Cycled FMCW solution as being the one that has the best trade-off between power consumption, system complexity and SNR performance. This emphasizes the need to generate very short chirps, which could be leveraged to lower the transmitter power consumption. Based on these results, we believe that a proper signal processing approach should be considered in the future in order to pave the way to a complete all-on-chip solution with low-power consumption.

Space-time-frequency multi-sensor analysis for motor cortex localization using magnetoencephalography

RESEARCH TOPIC:

Magnetoencephalography, cortical mapping, brain-computer interface, neural data analysis

AUTHORS:

V. Auboiron, C. Larzabal, L. Langer¹, V. Rohu, A. Mishchenko, N. Arizumi, E. Labyt, A.-L. Benabid, **T. Aksenova**

Brain activity cortical mapping is a valuable tool, before surgery, to optimize the placement of implanted brain-computer interfaces and more generally of neural interfaces. Brain source imaging and time frequency mapping are commonly used in magneto/electro encephalography (M/EEG) imaging but suffer from important limitations. We developed a regression-based multi-sensor space-time-frequency analysis (MSA) approach, which integrates co-localized sensors and/or multi-frequency information, to overcome these limitations. In a clinical trial including 14 participants, MSA performance was compared to the weighted minimum norm estimate method and showed statistically improved robustness against ill-defined trigger, typical of motor-deficient patients.

SCIENTIFIC COLLABORATIONS: ¹CHU Grenoble Alpes, France

Context and Challenges

Magneto/electro encephalography (M/EEG) is routinely used in non-invasive functional brain imaging. In particular, its ability to provide cortical mapping of mental tasks makes it a valuable tool, as it allows the presurgical localization of areas of interest in the brain. The "Brain-Computer Interface (BCI) and tetraplegia" clinical trial (NCT02550522), held at Clinec, aims at restoring partial motor autonomy to severely motor-impaired patients by the simultaneous use of an implanted brain-computer interface and selected external effectors. Therefore, the capability to localize brain motor activity would allow the optimal positioning of implanted sensors.

Classically, brain activity sources are computed by averaging signals from many trials to increase the signal-to-noise ratio. However, trial averaging is generally sensitive to ill-defined event triggers, which occur for induced response study due to variable subject response time. It is typically the case for BCI studies involving mental tasks and/or patients with motor disabilities, for which precise motor triggers cannot be measured. Another limitation of source imaging approaches concerns high-frequency brain oscillation localization, for which the averaging results in brain signal low-pass filtering. The main goal of this work was to develop a robust brain-mapping method, adapted to tetraplegic patients, which covers the full spectrum of brain activity.

Main Results

To estimate task-specific brain activations, the multi-sensor space-time-frequency analysis (MSA) uses cross-validated, shifted, multiple Pearson correlation, calculated from the time-frequency transformed brain signal and the binary signal of stimuli. The results are then projected from the sensor space onto the cortical surface.

To assess MSA performance, the proposed method was compared to the weighted minimum norm estimate (wMNE) source imaging method, in terms of spatial selectivity and robustness against ill-defined trigger. This first study was performed over a cohort of 14 healthy volunteers, with an

experimental setup usable with tetraplegic patients later on.

Our results show that the MSA approach provides favourable localization performances when compared to wMNE (Figure 1), as well as a statistically-significant improvement of robustness against ill-defined triggers.

These developments are being used to help conduct the "BCI and tetraplegia" clinical trial at Clinec.

Perspectives

This study, based on healthy volunteers, will be completed using MEG and electrocorticography data gathered with tetraplegic patients enrolled in the 'BCI and tetraplegia' clinical trial. On-going developments will also allow us mitigating the need for a Magnetic Resonance Imaging (MRI) acquisition as the anatomical support for brain-mapping projection, thus making the method accessible to patients with MR-unsafe implanted devices.

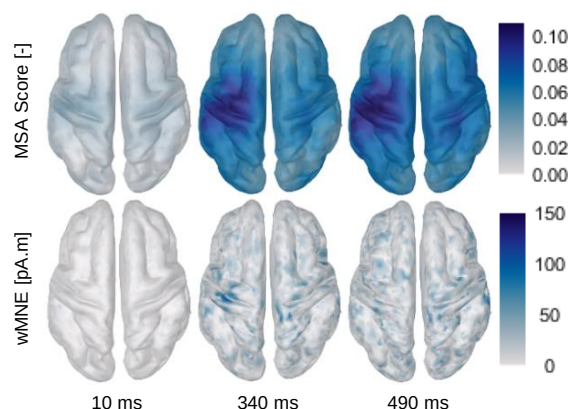


Fig. 1: Group-level brain mapping obtained using MSA and wMNE methods for a motor task (right elbow flexion), based on a visual cue.

RELATED PUBLICATIONS:

- [1] V. Auboiron, C. Larzabal et al., "Space-time-frequency multi-sensor analysis for motor cortex localization using magnetoencephalography", *Sensors*, 2020. doi: 10.3390/s20092706
- [2] A.-L. Benabid et al., "An exoskeleton controlled by an epidural wireless brain-machine interface in a tetraplegic patient: a proof-of-concept demonstration", *Lancet Neurol.*, 2019. doi: 10.1016/S1474-4422(19)30321-7

Second order effect in optically-pumped magnetometers for medical Imaging

RESEARCH TOPIC:

Optically-pumped magnetometers for medical imaging and geophysics

AUTHORS:

F. Beato, A. Palacios-Laloy

Optically-pumped magnetometers (OPM) based on parametric resonance allow real-time vector tri-axial measurement of very small magnetic fields with a single optical access to the gas cell. Most of these magnetometers rely on circularly polarized pumping light. In CEA Leti we focus on the ones relying on linearly polarized light, yielding atomic alignment. For these magnetometers we have investigated three second order effects appearing in the usual regimes of operation, so to clarify if they translate to metrological problems like systematic errors or increased noise. This work should help to clarify the accuracy reachable with OPM, which is an important question notably for medical imaging and geophysical applications.

Context and Challenges

These last years, optically pumped magnetometers (OPM) operating in very low magnetic fields have reached excellent sensitivities. Thereby they have become serious candidates to replace SQUIDS, avoiding cryogeny in applications requiring ultra-low noise magnetic field measurements like magnetoencephalography, magnetocardiography, and magnetorelaxometry. It is important to have an exact picture of the consequences of the breakdown of three usual approximations made for studying these magnetometers (low enough optical power, quick enough rf fields and absence of tensor light-shift) which are hardly respected in real sensors. Indeed, optically pumped magnetometers are often used for applications requiring good accuracy in addition to ultra-low noise. Therefore the presence of offsets in the magnetic field readings, or the emergence of additional sources of noise, could seriously compromise their interest.

Main Results

When optical pumping is made with large enough powers, the system evolution cannot be computed by the very simple three-step approach. In this situation it is usual to calculate the evolution of the whole density matrix, including the excited state, which is cumbersome. We proposed and demonstrated another model, which consists in refining the three-step approach by introducing an anisotropic relaxation resulting from optical pumping. This model, which contains no free parameters, is in good agreement with a set of experimental acquisitions on a broad range of optical powers.

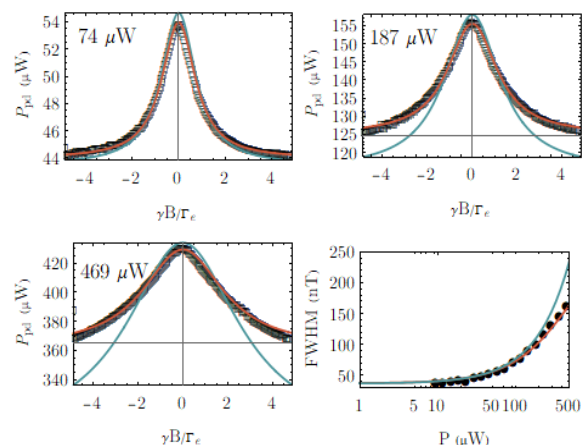
A second aspect we studied is the breakdown of RWA in parametric-resonance magnetometers (PRM). For double-resonance magnetometers it is well known that such breakdown causes a systematic error: the Bloch-Siegert shift. For PRM based on orientation no such systematic errors appear, and these effects are even beneficial, since they provide an additional sensitivity to the third axis of the magnetic field. We have shown that for alignment-based PRM neither systematic errors are expected to result from this

effect.

Finally we studied the tensor light-shifts (TLS) which appear when the linearly-polarized pumping light is not well tuned to the atomic transition. We have shown that these TLS cause a widening of the resonance curves, but no shift of their center, in contrast with vector light-shifts.

Perspectives

A further PhD student found how combining the two first effects within the appropriate optical power range allows a gain on the sensitivity of the worst resolved axis of the OPM. A research program for improving our OPMs and demonstrating their use in imaging applications (both encephalography and cardiology) is ongoing. A startup named Mag4Health aiming to industrialize and commercialize MEG systems based on this sensors is being Incubated by CEA.



Comparison of the experimental data (black dots) with the usual model based on the three-step approach (in blue) and our improved model (in red).

RELATED PUBLICATIONS:

[1] F. Beato and A. Palacios-Laloy, « Second-order effects in parametric-resonance magnetometers based on atomic alignment », EPJ Quantum Technol., vol. 7, n° 1, 1, déc. 2020.

Zero-field magnetometer based on the combination of atomic orientation and alignment

RESEARCH TOPIC:

Optically-pumped magnetometers for medical imaging and geophysics

AUTHORS:

G. Le Gal, L.-L. Rouve, A. Palacios-Laloy

Optically-pumped magnetometers (OPM) allow measurement of very low magnetic fields. Most of them rely on circularly polarized pumping light. In CEA Leti, we focus on the ones relying on linearly polarized light, yielding atomic alignment. Usual OPM configurations yield a worse sensitivity for one component of the magnetic field. Three-axis low-noise measurement with isotropic sensitivity is desirable for medical imaging and geophysics. We developed a new helium-4 magnetometer relying on elliptically polarized light. We show that this configuration can yield isotropic sensitivity. Compared to alignment-based helium-4 OPMs, the sensitivity is degraded by a factor 2 on the well-resolved axes, but improved by a factor 11 on the third axis.

Context and Challenges

These last years, optically pumped magnetometers (OPM) operating in very low magnetic fields have reached excellent sensitivities. Thereby they have become serious candidates to replace SQUIDS, avoiding cryogeny in applications requiring ultra-low noise magnetic field measurements like magnetoencephalography, magnetocardiography, and magnetorelaxometry. Most of the vector OPM configurations are based on atomic orientation, and can measure only two components of the magnetic field. The one we develop at the CEA Leti is based on atomic alignment. It is advantageous because it allows to measure the three components of the magnetic field, but the one parallel to the light polarization suffers from a worse sensitivity. For medical imaging and geophysics applications, it is desirable to measure the three components with the same sensitivity.

Main Results

The vector OPMs usually operate near the null field and rely on either Hanle effect or parametric resonances. The former consists in the resonant variation of the light absorbed by the atoms when the magnetic field surrounding the atoms varies around zero. The latter appears when radio-frequency (RF) fields are applied to the atoms.

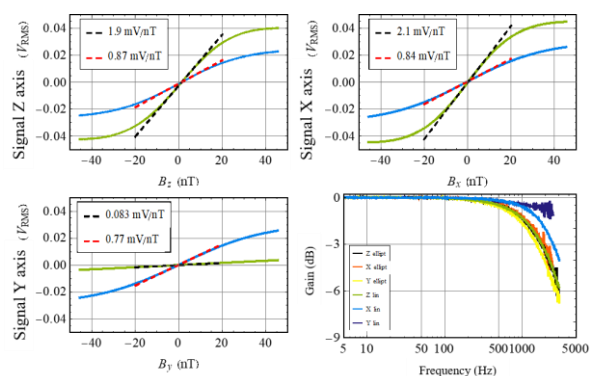
We investigated the behavior of a helium-4 atomic gas –the sensitive species of the OPMs developed at CEA Leti– when the optical pumping light is elliptically polarized. We found that it allows to observe Hanle resonances with the three component of the magnetic field simultaneously. We obtain the best amplitudes of Hanle resonances for the three components of the field simultaneously at an ellipticity of 26°.

Under similar operating conditions of the two magnetometer schemes, we obtain a sensitivity degraded by a factor 2 along the two most resolved axes of the usual helium-4 OPMs based on atomic alignment, and an improvement of a factor

11 for third component. Additionally a 2 kHz bandwidth is achieved for the three components [1].

Perspectives

With the recent improvement of the sensitivity of compact alignment based helium-4 down to 50 fT/√Hz, we expect this new configuration to reach vector three-axial measurements with an isotropic sensitivity of 100 fT/√Hz without loss of compactness. Additionally, three-axis vector sensors are interesting for gradient measurement, because they allow to measure the nine first order magnetic gradients with only three sensors in the same geometric plane. We are currently investigating the insight of building a planar gradiometer based on the presented magnetometer configuration, which is of great interest for sources localization in medical imaging.



Comparison of the obtained sensitivities for the helium-4 alignment-based scheme (green and black dashed lines), and the one based on elliptically-polarized light (blue and red dashed lines). Bottom right corner: measured bandwidth for the three axes in both schemes.

RELATED PUBLICATIONS:

[1] G. Le Gal, L.-L. Rouve and A. Palacios-Laloy, « Parametric resonance magnetometer based on elliptically polarized light yielding three-axis measurement with isotropic sensitivity », Appl. Phys. Lett., to be published.

Flexible large-area multi-fingerprint sensors based on thermal mass detection

RESEARCH TOPIC:

Fingerprint sensors, printed electronics, IGZO TFT, biometrics, pyroelectricity, thermal sensing

AUTHORS:

F. De Roose¹, D. Gallaire², A. Martinet², A. Torchia³, U. Emanuele³, S. Sinopoli³, B. Peeters⁴, H. Akkerman⁴, A. van Breemen⁴, A. J. Kronemeijer⁴, M. Pouet⁵, S. Steudel¹, K. Myny¹, **JF. Mainguet**

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 sensor detects the thermal mass of different materials, e.g. the skin with high heat capacity and air with very low heat capacity. We show the device architecture and readout strategies. The performance of the 500ppi flexible sensor is not influenced by bending within a radius of 5mm.

SCIENTIFIC COLLABORATIONS:¹ imec, Leuven (BE), ² Univ. Grenoble Alpes, CEA-LITEN, Grenoble (FR), ³ Bioage, Lamezia Terme (IT), ⁴ TNO / Holst Center, Eindhoven (NL), ⁵ Idemia, Paris (FR)

Context and Challenges

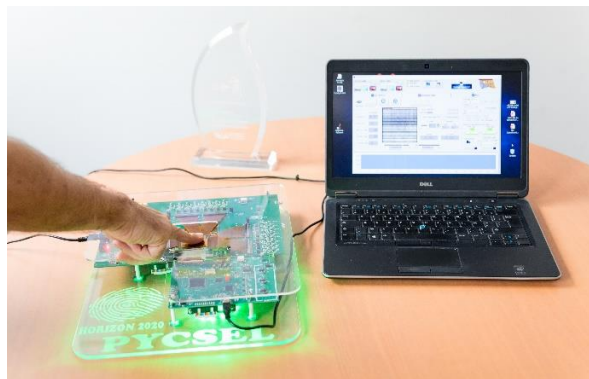
Biometric sensors for personal identification undergo a huge evolution since a few years, being not only reduced to governmental and enterprise markets anymore. Two main technologies can be mostly found: optical devices (robust and mature, but thick & bulky) and silicon devices (mainly capacitive & small size). 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 using TOLAE (Thin and Organic Large Area Electronics) technology, combining an organic sensor with a TFT matrix on a plastic foil. We simulated and developed a manufacturable process, 500 dpi high-resolution, including encapsulation and specific sensor poling methods. We designed a 256x256 pixels sensor ('1 finger') and a 1600x1500 pixels ('4 fingers'), with their associated demo boards. Fingerprint acquisition campaigns showed similar performances compared to regular optical acquisition devices.

Perspectives

Moving flexible and wearable electronics to a next level of applications addressing the growing worldwide biometrics market is the ambition of PYCSEL. 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.



RELATED PUBLICATIONS:

[1] De Roose, F., Mainguet, J., Gallaire, D., Martinet, A., Torchia, A., Emanuele, U., Sinopoli, S., Peeters, B., Akkerman, H., van Breemen, A., Kronemeijer, A.J., Pouet, M., Steudel, S. and Myny, K. (2020), 14-1: Flexible Large-Area Multi-Fingerprint Sensors based on Thermal Mass Detection. SID Symposium Digest of Technical Papers, 51: 176-179. <https://doi.org/10.1002/sdtp.13831>

The role and impact of “Functional Electronics” on energy and the transition towards a circular economy by 2030

RESEARCH TOPIC:

Federating European Electronics Ecosystems: Nanoelectronics, Flexible and wearable Electronics, Electronics smart systems.

AUTHORS:

J.Gavillet, E.Pauliac-Vaujour, B.Stree, P.Weiler¹, N.Gouze¹, S.Brongersma², C.Rentrop³, S.Karmann⁴, S.Zerbinati⁵, **E.Saoutieff**

The European project 5E (2019-2021) is a coordination and support action (CSA) with 7 partners, which aims to federate and identify interfaces between the 3 areas of electronics (Nano-Electronics; Flexible, Organic & Printed Electronics; Electronic Smart Systems) and thus identify R&D priorities for Europe. An inventory of the 3 areas in Europe was first of all carried out. Then a methodology was put in place to identify the points of convergence and new opportunities at the interfaces of these 3 fields. A new concept was thus set and defined: the “**Functional Electronics**”. A common vision was established and 4 Position Papers were written. The CEA coordinated the production of the two position papers on Circular Economy (LITEN) and Energy (LETI).

SCIENTIFIC COLLABORATIONS:¹ VDI/VDE-IT (project coordinator, DE) ² IMEC (NL) ³ TNO (NL) ⁴ Hahn-Schickard (DE) ⁵ MESAP (IT)

Context and Challenges

5E underpins digitisation and supports the electronics industry in seizing opportunities by federating the 3 European electronics areas. We paid special attention to products and manufacturing processes in which unconventional nano-electronics (NE), flexible, organic and printed electronic components (FOPE) and electronic smart systems (ESS) interact. By this convergence, innovative solutions result as “functional electronics” that were not realizable without the interaction of the three individual areas arose.

Main Results

CEA contributed in the supervision of the joint vision of the three electronics areas by describing a unified landscape of the three electronics areas and their interfaces, identifying white spots at these interfaces, developing a joint vision for competitive electronics industries in Europe. “Functional Electronics” (FE) concept was set and defined as acting principle of convergence across electronics ecosystems. The visions are set in 4 key areas with Functional Electronics at their core: Energy (CEA-Leti, fig.1) [1] / Circular economy (CEA-Liten, fig.2) / Automation / Sensing.

Perspectives

Recommendations on new opportunities of Functional Electronics highlighted in the different vision papers are disseminated in the Electronics community [2,3]. (FE) is supported as a topic on electronics inside Horizon Europe programme to open up new collaborations and is potentially relevant to structure upcoming actions in Digital Europe.

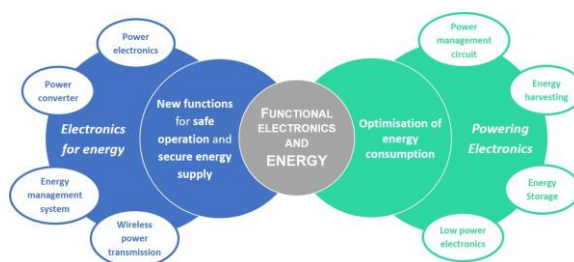


Fig. 1: Energy Position paper

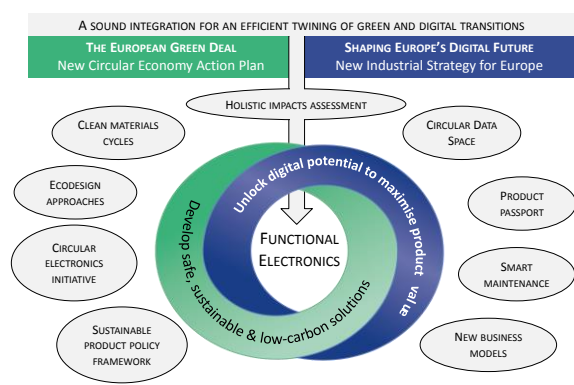


Fig. 2: Circular Economy Position paper

RELATED PUBLICATIONS:

[1] E.Saoutieff et al., Vision paper on the role of functional electronics enabled energy solutions for the digitalisation of European industries and societies “Functional electronics and energy”, Sept. 2020

[2] E.Saoutieff, 5E Transversal Workshop, Vision paper: Functional Electronics and energy, Sept. 2020, EPOSS-EPSI Annual forum 2020

[3] E.Saoutieff, Workshops 5E 2020: Joint Vision and Meta-Roadmap for European Electronics Industries; Vision Paper: The role and impact of “Functional Electronics” on the transition towards a circular economy, Nov.2020, EFECs 2020



O4

ELECTRONICS FOR
ENERGY

- Energy & Power conversion
- Energy & Power management
- Energy harvesting
- Power management systems and circuits
- Battery monitoring systems (BMS)
- Wireless Power Transfer (WPT)

Acoustic power transfer through metal walls

RESEARCH TOPIC:

Transmitting power through metal walls using acoustic waves.

AUTHORS:

F. Frassati, S. Boisseau, N. Garraud, P. Gasnier, G. Despesse, O. Freychet

Acoustic power transfer and communication through metal layers is of great interest in many applications where the integrity of metal boxes, tanks, pipes or walls must be preserved by avoiding through-hole electrical connections. While acoustic power transfer has been widely studied last decades, the optimization of such systems has not been assessed comprehensively, and typically regarding the choice of transducers' dimensions and materials and the impact of the wall's characteristic acoustic impedance.

This work stands at answering these optimization issues and shows that intermediary layers sized with our optimization process can result in important gains in terms of transmitted power.

Context and Challenges

Many industrial applications require the power supply and the communication with sensors placed behind metal walls: boats or submarine hulls, fuel tanks, pipes or boxes. Holes can be made in the metal wall to pass wires but result in reduced sturdiness or fluid leak risks. Electromagnetic techniques commonly used to power and communicate wirelessly, such as RFID are inefficient through metal walls due to the Faraday shielding occurring in conductive media or are limited to very low frequencies (<100 Hz), which is inappropriate for communication purposes. Acoustic waves do not suffer from the same attenuation issues, even at frequencies as high as MHz. Thus, acoustic power transfer and communication using piezoelectric transducers is a promising solution to transmit power and data through metal walls. However, a comprehensive analysis of the optimization of these solutions is missing in the state of the art, and in particular regarding the choice of transducers' dimensions and materials and the impact of the wall's characteristic acoustic impedance. This work aims at addressing these points.

Main Results

A new implementation of the commonly-used analytical model based on the one dimension propagative model (ODPM) has been proposed. This new implementation allows to model piezoelectric stacks, even when all transducers are not supplied by in-phase voltages, which was not possible previously. This model has then been used to determine design rules on transducers' dimensions and a criterion to compare piezoelectric materials has been proposed. In particular, we have analyzed the impact of the piezoelectric and the mechanical coefficients on the transmission efficiency. It has been shown that, contrary to what was expected, having identical acoustic impedances for the wall's and transducers' materials is not optimum and that using properly-designed intermediary layers could increase significantly the transmitted power (multiplied by 40 in our example) [1]. An upper bound of performances for Acoustic Power Transfer systems allowing to

know whether the maximum performances have been reached has also been identified and an advanced study of losses has been conducted. Finally, a new figure of merit, the normalized transmitted power, quantifying the transmitted power for a given excitation voltage has also been proposed. This FoM is of great use to facilitate electronic implementations and practical application supplying matters and paves the way towards APT devices optimized for real-life applications.

Perspectives

An industrial transfer of the technology is in progress. The next works will be focused on optimizations for communication and on multiple-in multiple-out devices to implement beamforming and to control the direction of the power transfer.

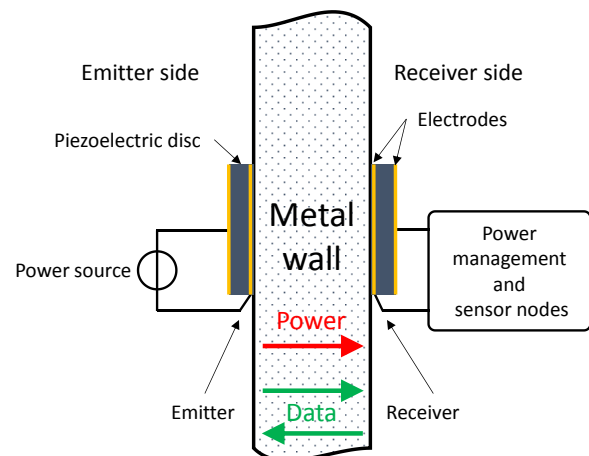


Fig.1: Acoustic Power Transfer system

RELATED PUBLICATIONS:

[1] O. Freychet, F. Frassati, S. Boisseau, N. Garraud, P. Gasnier, et G. Despesse, « Analytical optimization of piezoelectric acoustic power transfer systems », *Eng. Res. Express*, vol. 2, n° 4, p. 045022, nov. 2020, doi: 10.1088/2631-8695/abcb4a.

DC/DC converter based on mechanical storage

RESEARCH TOPIC:

Refund the power electronic by removing inductors in DC/DC converters and by using mechanical energy storage.

AUTHORS:

Mustapha Touhami, François Costa¹, Ghislain Despesse

In classical DC/DC converters, the input energy is stored in an inductor as a magnetic energy before going to the output. These converters are limited because the power density of the inductors are limited. Nevertheless, by increasing the operating frequency, one can increase the number of energy transfer per second and then increase the power density. Unfortunately, the energy density that the inductor can store decreases with the frequency. To overcome that limitation, we propose to use a mechanical storage. To exchange energy between mechanical and electrical domains, we use a piezoelectric material. By comparing the volume of the piezoelectric material with the volume of an inductor at same power level, we show a significant power density increase (up to 10).

SCIENTIFIC COLLABORATIONS: ¹SATIE (Système et Application des Technologies de l'Information et de l'Energie), ENS Paris-Saclay, France

Context and Challenges

Inductors are limited by their saturation magnetic field, which decreases with frequency, reducing the energy density; moreover, magnetic and copper losses increase with frequency, reducing efficiency. To overcome these limitations, the idea is to use a piezoelectric material. The advantage is a higher energy density capability and a higher quality factor (>1000), even at high frequency, increasing at same time the power density and efficiency. The challenges in using mechanical resonator in power electronic is the fact that a piezoelectric material is mainly capacitive compare to an inductor, disrupting at same time the conventional power electronic topologies and their driving. Indeed, the operation principle needs at least 6 steps in place of 2 and these steps have to be synchronized on the mechanical movement.

Main Results

A prototype was designed; it can operate from 100kHz to few MHz thanks to the use of GaN power transistor (fig. 1). Experimental measurements were done with a piezoelectric disk of diameter 2.5cm (fig. 2). A peak output power of 100W was reached for a 200 to 60V step down conversion with an efficiency of 83.5% [1]. A control electronic board using a 300MHz FPGA was also developed to autonomously control the converter and regulate the output voltage [2], it is a world first.

Perspectives

The next step is to go towards miniaturization thanks to MEMS technology and an increase in the operating frequency ($\geq 10\text{MHz}$).

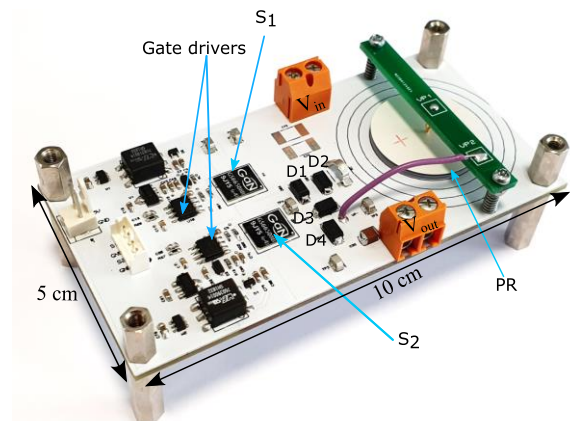


Fig 1: High to low voltage DC/DC prototype

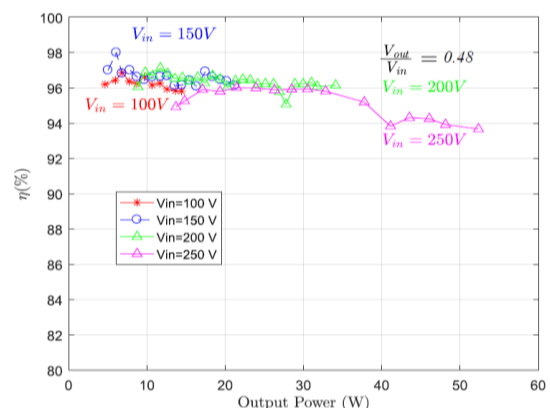


Fig 2: Efficiency versus output power

RELATED PUBLICATIONS:

- [1] M. Touhami, G. Despesse, F. Costa, "A New Topology of DC-DC Converter Based On Piezoelectric Resonator" 2020 IEEE 21st Workshop on Control and Modeling for Power Electronics (COMPEL), 2020, pp. 1-7, doi: 10.1109/COMPEL49091.2020.9265767.
- [2] M. Touhami, G. Despesse, F. Costa and B. Pollet, "Implementation of Control Strategy for Step-down DC-DC Converter Based on Piezoelectric Resonator" 2020 22nd European Conference on Power Electronics and Applications (EPE'20 ECCE Europe), 2020, pp. 1-9, doi: 10.23919/EPE20ECCEurope43536.2020.9215910.

Energy harvesting for batteryless switches

RESEARCH TOPIC:

Energy Harvesting, Small-scale electromagnetic converters, Smart Buildings

AUTHORS:

O.Tosoni, G. Delette, M. Bohnke, G. Despesse, J. Leprince¹, B. Vulcano¹, C. Bossan¹, M. Daccord², **S. Boisseau**

Autonomous switches are among the most promising market for energy harvesting solutions with millions of products per year targeted. Their principle of operation is to convert the mechanical energy provided by the user, when it presses the buttons, into electricity to supply electronic components within (microcontroller, RF chips) that will allow the remote control of lights or roller shutters for example. We report on an innovative electromagnetic energy harvester for autonomous switches relying on a rotating magnet driven by magnetic launchers, and its mechanical integration. The experimental output energy reaches 1.235 mJ ($350\mu\text{J}/\text{cm}^3$) which outperforms the state of the art.

SCIENTIFIC COLLABORATIONS: ¹Legrand, Digital Infrastructures Business Unit, St-Marcellin (FR), ²Legrand, User Interface Business Unit, Limoges (FR)

Context and Challenges

While various solutions of batteryless switches are commercially-available, improvements are still required to increase output energies, to reduce the dimensions, the costs or to enhance the tactile sensation for the users.

Main Results

A new concept of energy harvester for batteryless switches has been developed (Figure 1). This breakthrough system exploits a highly-nonlinear electromagnetic converter made of a rotating central magnet, ferromagnetic elements and magnetic launchers to turn the pressure applied by the user into an oscillation movement of the central magnet, which is finally turned into electricity thanks to the coil.

The energy harvester has been modeled, optimized, manufactured, characterized and integrated into a mechanical actuation system to form a complete autonomous switch. The experimental output energy reaches 1.235 mJ ($350\mu\text{J}/\text{cm}^3$) which are the highest output energy and the highest energy density ever reached in the state of the art. The energy harvester has finally been connected to a power management circuit to supply the RF emission of the commands with a Zigbee Green Power ® transmitter.

Perspectives

The autonomous switch with the energy harvester will be manufactured by Legrand and commercially-available in 2021 (Figure 2). This disruptive concept paves the way towards more efficient and more compact energy harvesting architectures and could be adapted to address new fields such as autonomous presence sensors or for inventory management in warehouses.

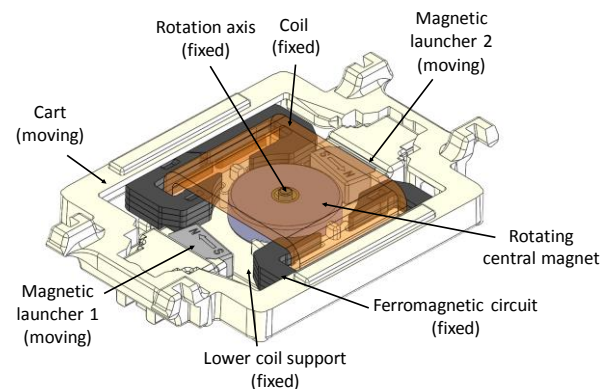


Figure 1: Energy Harvester



Fig. 2 : Batteryless switches (© Legrand)

RELATED PUBLICATIONS:

[1] S. Boisseau et al., An Autonomous Switch based on a Rotating Magnet driven by Magnetic Launchers, Smart Materials and Structures, 2021

Wideband Vibration Energy Harvesting

RESEARCH TOPIC:

Design of strongly coupled piezoelectric harvesters and self-tuning power management circuits for wideband vibration harvesting

AUTHORS:

David Gibus, Adrien Morel, Nicolas Garraud. Sébastien Boisseau, Gaël Pillonnet, Adrien Badel¹, **Pierre Gasnier**

This work reports the experimental evidence of the effectiveness of strongly-coupled generators coupled with nonlinear extraction techniques for vibration energy harvesting to power sensors nodes. We proposed a method to design piezoelectric cantilevers with strong electromechanical coupling coefficients. The fabricated cantilevers, some of which are made of PZT material, exhibit some of the best coupling and the widest frequency bandwidths reported. The self-powered harvesting IC that includes self-tuning capabilities, dynamically maximizes the harvested power when the harvester's characteristics or excitation frequency shift. Together with the PZT-based harvester, the experimental results show a 368% harvested bandwidth enlargement with the highest convergence Figure of Merit.

SCIENTIFIC COLLABORATIONS: ¹ SYMME laboratory, University of Savoie Mont-Blanc (USMB), Annecy (FR)

Context and Challenges

Because a mismatch between the harvesters' resonant frequency and the input vibrations makes them unusable, the frequency selectivity is a major technical barrier. Strongly coupled harvesters are considered as a solution to extend the frequency bandwidth. These harvesters [1] associated with non-linear extraction techniques [2] and dedicated circuits [3] are proposed in the framework of an internal transverse work and an academic collaboration with USMB.

Main Results

Three harvesters, based on strongly coupled single crystals and temperature-tolerant PZT ceramics, have been proposed to show the influence of the beam width on the global electromechanical coupling [1]. The fabricated cantilevers exhibit some of the best coupling reported (11.3-16.6%) and suggest great potential for frequency tuning (7.8-11.3%). Within the framework of this research work, one of the prototypes tested with a dedicated power management circuit allowed an automatic adjustment over a wide frequency band (17% of the resonance frequency).

Perspectives

The mechanical ageing and non-linear behaviors of the harvesters must be investigated in future works. Measurements on both materials have to be compared to consider the influence of mechanical and dielectric losses. In terms of electrical frequency tuning, we have started a thesis to propose new algorithms and microcontroller-based architectures that allow to quickly converge towards the maximum power point in a robust manner.

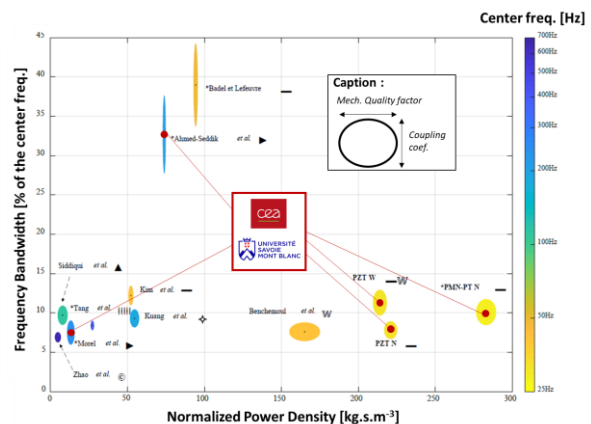


Fig. 1: Harvesters' performances

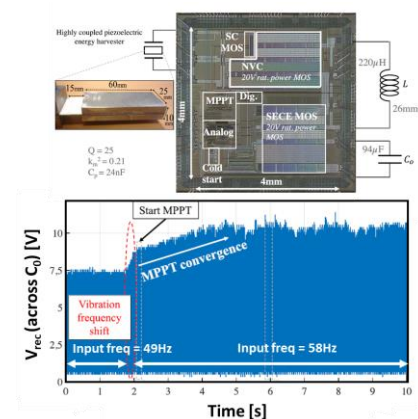


Fig. 2: Complete system and transient response of the IC

RELATED PUBLICATIONS:

- [1] D. Gibus et al., "Strongly coupled piezoelectric cantilevers for broadband vibration energy harvesting," *Applied Energy*, vol. 277, p. 115518, Nov. 2020, doi: 10.1016/j.apenergy.2020.115518.
- [2] A. Morel et al., "Fast-Convergence Self-Adjusting SECE Circuit With Tunable Short-Circuit Duration Exhibiting 368% Bandwidth Improvement," *IEEE Solid-State Circuits Letters*, vol. 3, pp. 222–225, 2020, doi: 10.1109/LSSC.2020.3012340.
- [3] A. Brenes et al., "Large-bandwidth piezoelectric energy harvesting with frequency-tuning synchronized electric charge extraction," *Sensors and Actuators A: Physical*, vol. 302, p. 111759, Feb. 2020, doi: 10.1016/j.sna.2019.111759.

Fault detection and isolation for proton exchange membrane fuel cell

RESEARCH TOPIC:

Proton Exchange Membrane Fuel Cell, fuel cell ageing, fuel cell modelling, Electrochemical Impedance Spectroscopy, Fault Diagnosis, Prognostic and Health Management (PHM)

AUTHORS:

G. Jullian, C. Cadet, S. Rosini, M. Gérard, V. Heiries, C. Béranger

This work proposes a fault detection and isolation tool for proton exchange membrane fuel cell (PEMFC) operating in embedded applications. The considered faults are the abnormal operating conditions that can decrease the fuel cell lifetime. The fault detection approach is based on residual generation using both voltage and high frequency resistance measurements and thus combining the advantages of knowledge-based model and electrochemical impedance spectroscopy (EIS) diagnosis approaches. A multi-physics fuel cell model has been used which computes the stack voltage and the high frequency resistance in dynamic conditions. The results on a new fuel cell stack show a score of 91% for fault isolation. The method has also been adapted to mitigate ageing loss of performance.

SCIENTIFIC COLLABORATIONS: ¹ GIPSA-Lab, Grenoble INP, University Grenoble Alpes (UGA), Grenoble (FR)

Context and Challenges

Fuel cell systems are leading candidates for powering next generation vehicles with a range comparable to thermal vehicles but with no CO₂ emission. But cost and durability remain the main issues of this technology. The diagnosis and management of degradation phenomena of fuel cell systems which lead to performance losses remains very challenging. Their links with operating conditions (humidity, stoichiometry, temperature) have been demonstrated. The purpose of this work is to develop methods for abnormal operating conditions detection and classification, in order to adapt the fuel cell control and in the end, extend its lifetime.

Main Results

The principle of the Fault Detection and Isolation method used is depicted in Figure 1. This method is based on the comparison between the response of a simulated system (physico-chemical model) and the data recorded on the real system. Here, the measurements are limited to voltage and high frequency resistance to fit the online embedded application requirements. For each parameter, stack voltage and high frequency resistance, the difference between the model output and the measurement (residuals) is computed. When one of these residual values becomes higher than a specified threshold value, a fault is detected. Once faults are detected, they still have to be isolated. A machine learning algorithm, namely a k nearest neighbours classifier (k-NN) is implemented to this end, operating in the two-dimensional residual space. Once trained on a representative dataset, the k-NN algorithm can be used to classify the experimental data, and the results are shown in Figure 2 (a). In this figure, the points corresponding to the nominal operating conditions, marked with green asterisks, are as expected in the non-detected area. It can be noticed that there is neither false alarm nor missed detection. As expected, the detection algorithm detects all the faults. Concerning fault isolation, results shows that humidity fault is correctly classified on more than 99% of the data and stoichiometry or temperature fault reaches a 68%

of correct classification. At last, the global isolation average score is 91%, therefore the diagnosis method can be considered reliable. Figure 2 (b) illustrates the results obtained when the method is adapted to mitigate loss of performance of the solution when the fuel cell stack is ageing.

Perspectives

In future works, the fuel cell ageing estimation has to be improved to adapt the fault detection and isolation method at best. Moreover, this diagnosis of abnormal operating conditions has to be included in the complete fuel cell system management. An optimal feedback control on the system ancillaries has to be designed in order to target a significant increase of the fuel cell lifetime.

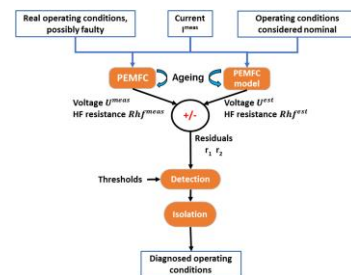


Fig. 1: PEMFC stack Diagnosis method.

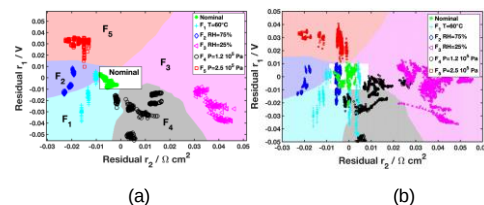


Fig. 2: PEMFC Fault isolation for the stack at the beginning of life (a); and with the method adapted to stack ageing (b)

RELATED PUBLICATIONS:

- [1] Jullian, G., Cadet, C., Rosini, S., Gérard, M., Heiries, V., Béranger, C., "Fault Detection and Isolation for Proton Exchange Membrane Fuel Cell Using Impedance Measurements and Multiphysics Modeling", (2020) Fuel Cells, 20 (5), pp. 558-569, DOI: 10.1002/uce.202000022
- [2] Jullian, G., Rosini, S., Gérard, M., Cadet, C., Béranger, C., Heiries, V., "Model-based fault detection using analytical redundancy for automotive proton exchange membrane fuel cell", (2017) Safety and Reliability - Theory and Applications - Proceedings of the 27th European Safety and Reliability Conference, ESREL 2017, pp. 905-912, DOI: 10.1201/9781315210469-117

High frequency self-reconfigurable battery for arbitrary waveform generation

RESEARCH TOPIC:

Battery Management System (BMS), Self-Reconfigurable Battery (SRB), multilevel converter, active balancing.

AUTHORS:

G. Despesse, S. Bacquet, E. Fernandez, Y. Lopez, P. Ramahefa-andry, L. Cassarino, F. Lehmann, J. Blatter, V. Heiries, **R. Thomas**

This work propose an innovative self-reconfigurable battery (SRB) architecture able to generate directly at its output any waveform signals. Thanks to that characteristic it is even possible to dispense with any AC charger. A real prototype of 128 cells demonstrates a charge on the electrical grid, by generating a sine wave voltage, while perfectly balancing the cells in real time. A simulator was developed for long-term evaluation. The balancing performances obtained on vehicle test cycles showed the cell capacity discrepancy that the HF SRB is capable of handling in a single complete charge or discharge cycle. The magnitude of this gap demonstrated the extent to which the HF SRB is capable of operating with second life cells or even different chemistry mixes.

Context and Challenges

Most of classical Li-Ion electrical storage systems are composed of a certain number of unitary battery cells arranged in series and/or parallel, according to a fixed arrangement. Those systems are limited by the weakest cell of the battery pack whatever is the charge balancing mechanism. Consequently, battery manufacturers must use cells having perfectly homogeneous characteristics and must implement advanced thermal management to maintain this homogeneity as long as possible. This kind of limitation makes it difficult to build a battery mixing different cells characteristics as with reusing second life battery cells because the system will be always limited by the cell having the smallest capacity and/or the highest impedance.

The key idea of Self-Reconfigurable Batteries is to introduce individual control of each cell in the battery pack thanks to dedicated half-bridge chopper switches. With such a management, it becomes possible to disconnect only the weakest or damaged cells and supply the required power with the remaining ones. Moreover, bypassing switches offer the capability to adjust the number N of cells placed in serial and thus to dynamically adjust the output voltage of the battery. This allows to provide AC power supply as well as directly recharge a SRB on the electrical network.

Main Results

This work demonstrates the feasibility of embedding cell-switching strategies in a microcontroller with the use of field buses, low voltage MOSFET and a single current sensor. This lead to a real cost-efficient SRB demonstrator of 128 cells able, on the one hand, to charge itself directly on the power grid while reducing the requirement of passive filtering components, and on the other hand to generate a perfect output waveform signal. All this while allowing the exclusion of defective cells and performing real-time cell balancing.

A complete charge performed at $C/2$ on the electrical grid from an initial SoC imbalance of 60% showed that the 128 cells were perfectly balanced before the end of charge. The voltage THD

of the HF SRB output is less than 0.3% when it discharges with a series inductance of 100 μH . The efficiency of the HF SRB is above 98% up to 2300 WRMS of power delivery, which corresponds to a discharge rate of 4.5 C. These results are among the best of the state of the art.

A behavioral simulator has been developed and validated through a comparison with the real demonstrator. The balancing performances obtained on vehicle test cycles showed the cell capacity discrepancy that the HF SRB is capable of handling in a single complete charge or discharge cycle. The magnitude of this gap demonstrated the extent to which the HF SRB is capable of operating with second life cells or even different chemistries mixes.

Perspectives

Optimal SRB management to minimize loss of capacity during aging and maximize battery autonomy.
Electrical motors driving.

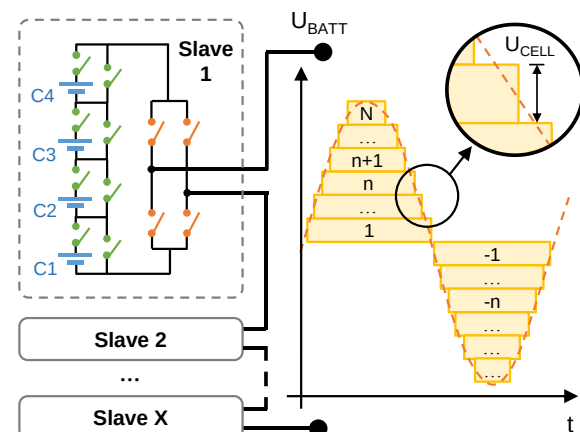
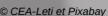


Fig.1: HF SRB hardware architecture

RELATED PUBLICATIONS:

- [1] "A High Frequency Self-Reconfigurable Battery for Arbitrary Waveform Generation" R. Thomas, G. Despesse, S. Bacquet, E. Fernandez, Y. Lopez, P. Ramahefa-andry, L. Cassarino, World Electric Vehicle Journal 2021, <https://doi.org/10.3390/wevj12010008>
- [2] "Performance Analysis of a Novel High Frequency Self-Reconfigurable Battery", R. Thomas, F. Lehmann, J. Blatter, G. Despesse, V. Heiries, World Electric Vehicle Journal 2021, <https://doi.org/10.3390/wevj12010010>



05

**IOT FOR INDUSTRY,
MOBILITY, SPACE AND
DEFENSE**

- Industrial Internet of Things (IIoT)
- Traceability
- Indoor and Outdoor Localisation
- Low-Power Wide-Area (LPWA) communications
- Connectivity in Mobility
- Vehicle-to-X (V2X) communications
- Communication satellites (SATCOM)
- Magnetic sensors in space programs

Accurate ranging in multipath channels with narrowband LPWA systems

RESEARCH TOPIC:

Localization, Ranging, Internet of Things (IoT), Low Power Wide Area (LPWA), Narrowband, Multipath Channels

AUTHORS:

F. Wolf, S. de Rivaz, V. Mannoni, V. Berg, J-P. Cances¹, F. Dehmas

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 waveforms are narrowband and degraded by multipath propagation channels. To improve the temporal resolution, a coherent multi-channel ranging based on the aggregation of sequentially transmitted narrowband signals is proposed. Field trials have been performed in a multipath outdoor environment and strong biases have been observed. Ranging bias estimators are introduced to mitigate these damaging effects: thanks to the new approach, accuracy of 30m in 90% of the cases is obtained. This compares to 250m when legacy Time of Flight (ToF) is considered.

SCIENTIFIC COLLABORATIONS: ¹ Université de Limoges, CNRS, XLIM, UMR 7252, Limoges (FR)

Context and Challenges

The Internet of Things (IoT) connections are rapidly growing and the part dedicated to Low Power Wide Area (LPWA) networks (such as LoRa, SigFox or NB-IoT) has a similar momentum. Accurate geolocalization of these objects is a key enabler of LPWA and provides a significant added-value for many applications including for instance forest fire detection or location of vulnerable elderly people.

But this location feature remains challenging in many contexts or environments. For example, Global Navigation Satellite Systems (GNSS) are inefficient for indoor applications or consume too much energy. LPWA radio based location has the advantage to rely on the same hardware for localization and communication with a limited amount of additional needed energy. However narrowband signals considered for long range communications cannot provide accurate positioning since the accuracy is inversely proportional to the bandwidth.

Main Results

To increase the bandwidth without modifying the waveform and thus keeping the LPWA properties of the signal, we successively transmit packets at different frequencies and estimate the amplitude and phase response of the channel on these frequencies [1][2][3]. This approach provides a sampling of the propagation channel in the frequency domain. To cancel the initial phases of the oscillators, a round trip is used, similarly to classical two-way ranging for Time of Flight (ToF) estimation.

A testbed based on a software defined radio platform has been developed [1][2][3] and field trials have been performed in a semi-urban outdoor environment [1][3]. Ranging estimates have shown large position dependent biases caused by obstructions and reflections by buildings (Non Line of Sight propagation). Using a threshold on the estimate of the delay spread of the channel, we manage to detect the channels causing large biases. Furthermore the threshold value allows a trade-off between the reliability and the availability of the

ranging measurements. Fig. shows the performance obtained during the field trial: with a threshold of 75m, 62% of the measurements are used and the bias is detected in 77% of the cases driving to a ranging error below 30m in 90% of the cases compared to 250m for ToF based range estimation: the accuracy of our solution is improved by a factor close to 10.

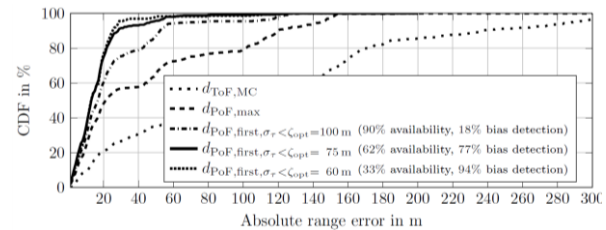


Fig. 1: Ranging errors for PoF and ToF.

Perspectives

First, these results will be reinforced by more extensive field trials comprising outdoor-to-indoor scenarios. Then the study will be extended with a Phase Difference of Arrival (PDoA) approach keeping the fair time resolution while relying on uplink only communications: this provides the benefits to further limit energy consumption and network usage.

RELATED PUBLICATIONS:

- [1] F. Wolf, S. de Rivaz, F. Dehmas, V. Mannoni, V. Berg and J. -P. Cances, "Accurate Narrowband LPWA Ranging: Principles, Performance in AWGN and Multipath Channels," 2020 European Conference on Networks and Communications (EuCNC), Dubrovnik, Croatia, 2020, pp. 149-153
- [2] 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
- [3] F. Wolf, "Multi-channel ranging system for the localization of wireless connected objects in low power wide area networks : From modeling to field trials", PhD dissertation, University of Limoges (FR), 2020, Accessed on: April 9, 2021. [Online]. Available: <http://www.theses.fr/2020LIMO017>

Simultaneous localization and mapping with mmWave multi-link multipath angles of arrival

RESEARCH TOPIC:

Design of estimation algorithms for joint wireless localization and mapping applications at millimeter wave frequencies.

AUTHORS:

R. Koirala, H. Wymeersch¹, B. Uguen², D. Dardari³, **B. Denis**

We propose a simultaneous localization and mapping (SLAM) algorithm that can leverage the angles of arrival/departure of transmitted signals in millimeter wave (mmWave) communication networks. Considering measurements from various base stations (BSs), the previous algorithm estimates the positions of both mobile users and surrounding scatterers through centralized belief propagation (BP), while jointly solving out an underlying data association problem (i.e., between observed measurements and their multiple originating sources). Simulation results show that the proposed approach outperforms more conventional distributed BS-wise BP methods in terms of estimation accuracy.

SCIENTIFIC COLLABORATIONS: ¹ Chalmers University of Technology, Gothenburg (SW), ² Université Rennes 1 - IETR, Rennes (FR), ³ University of Bologna, Cesena (IT)

Context and Challenges

Millimeter wave (mmWave) wireless systems, which rely on directive radio transmissions at high frequency (typically 26-28GHz), are naturally suitable for combining high speed data communications and spatial awareness services (incl. localization and physical mapping) [1]. However, dedicated algorithmic approaches are needed to fully exploit the angular information made available by default over typical mmWave radio links.

Main Results

We propose a Simultaneous Localization And Mapping (SLAM) algorithm based on centralized Belief Propagation (BP), which can jointly localize mobile users and surrounding scatterers, by relying uniquely on multipath Angles of Arrival (AoA) and Angles of Departure (AoD) with respect to multiple Base Stations (BSs) (Fig. 1).

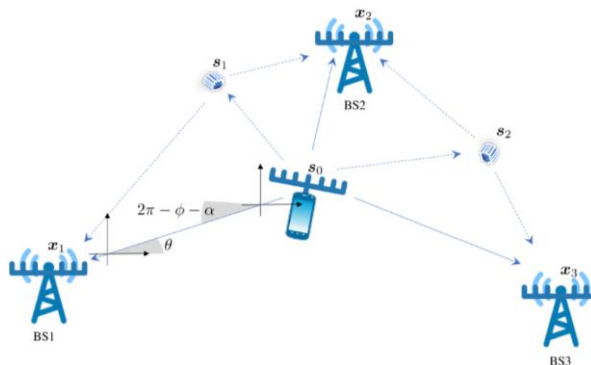


Fig. 1: Multi-BS SLAM with angular information

This algorithm autonomously associates input angular measurements with their corresponding sources over a factor-graph. In contrast to existing distributed BP approaches in similar contexts, another major advantage lies in the lower communication overhead, as particle clouds do not need to be shared among the BSs. Simulation results obtained in a simple canonical scenario show encouraging accuracy mostly in terms of scatterers positioning, despite the lack of a priori location information (Fig. 2).

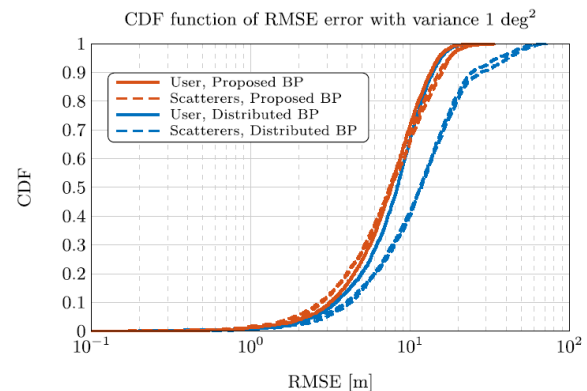


Fig. 2: Positioning accuracy (vs. distributed BP)

Perspectives

Complementary studies, which can advantageously feed the SLAM algorithm described above, aim at fast angle-aided sparse multipath channel estimation, relying on compressed sensing methods [3].

RELATED PUBLICATIONS:

- [1] R. Koirala, et al. "Localization and Communication Resource Budgeting for Multi-user mmWave MIMO", Proc. IEEE Workshop on Positioning, Navigation and Communications 2019, Oct. 2019.
- [2] R. Koirala, et al. "Simultaneous Localization and Mapping in Millimeter Wave Networks with Angle Measurements", Proc. IEEE International Conference on Communications 2020, Workshop on Advances in Network Localization and Navigation, June 2020.
- [3] R. Koirala, et al. "Direction Aided Multipath Channel Estimation for Millimeter Wave Systems", IEEE Vehicular Technology Conference 2021 - Spring, April 2021.

Improved radiolocation coverage and continuity through reconfigurable intelligent surfaces

RESEARCH TOPIC:

Design of control mechanisms for wireless localization based on intelligent surfaces.

AUTHORS:

A. Clemente, H. Wymeersch¹, **B. Denis**

Reconfigurable intelligent surfaces (RIS), which typically rely on (semi-)passive reflect-/transmit-array devices, behave as controllable electromagnetic mirrors, lenses or non-regenerative relays to flexibly shape multipath wireless environments. We herein explore the potential of this transformative beyond-5G technology at system level, with the aim of improving wireless localization performance. While assuming multiple surfaces in the reflection mode, we thus propose a joint RIS selection and phase profile optimization scheme that shows promising gains in terms of both localization coverage and accuracy.

SCIENTIFIC COLLABORATIONS: ¹ Chalmers University of Technology, Gothenburg (SW)

Context and Challenges

High localization accuracy (typically, better than 10cm) will be required in Beyond-5G communication networks, as well as in a variety of other location-based services. Reconfigurable intelligent surfaces (RIS), which typically consist of passive reflect-/transmit-arrays with tunable phase profiles, have thus been considered to assist wireless localization and mapping (e.g., through anomalous reflections, Fig. 1), provided that suitable control strategies at both RIS and system levels are designed [1].

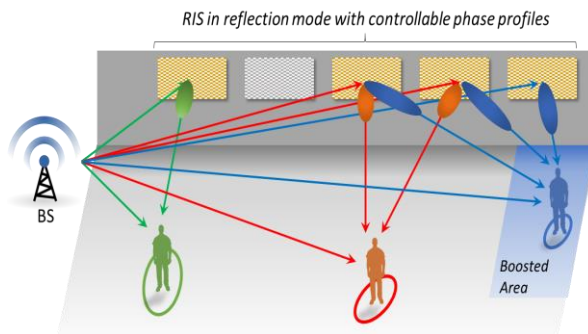


Fig. 1: Ex. of RIS-enabled positioning scenario.

Main Results

Assuming single input single output multi-carrier transmissions between a base station and a mobile user, we have first characterized the theoretical performance bounds of far-field positioning based on the estimated delays of both direct and RIS-reflected paths. Then, using the previous bounds, we have proposed a joint RIS selection and phase profile optimization scheme limiting RIS self-interference and computational complexity [2]. Simulation results show better accuracy in

comparison with usual scatterers and better coverage in comparison with non-intentional reflections (Fig. 2).

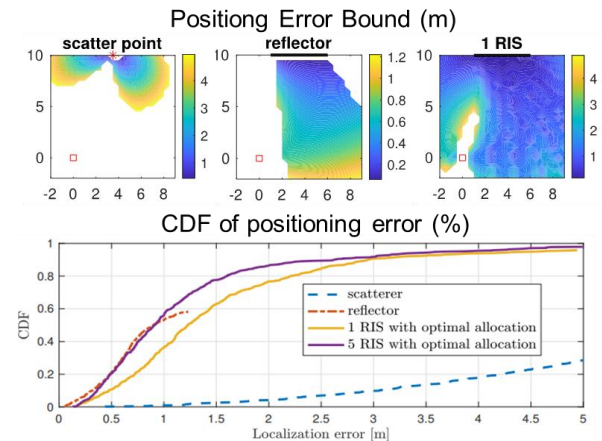


Fig. 2: Performance (vs. scatterer & reflector)

Perspectives

Other works in progress concern the exploitation of signal wavefront curvature for RIS-enabled direct positioning in the near-field regime, the mitigation of radio obstructions, the inclusion of prior user's information for continuous localization refinement or the evaluation of RIS localization footprint (in terms of overhead, latency, consumption...).

RELATED PUBLICATIONS:

- [1] H. Wymeersch, J. He, B. Denis, A. Clemente, M. Juntti, "Radio Localization and Mapping with Reconfigurable Intelligent Surfaces: Challenges, Opportunities and Research Directions", IEEE Vehicular Technology Magazine (IEEE VT Mag.), Vol. 15, No. 4, pp. 52-61, Dec. 2020.
- [2] H. Wymeersch, B. Denis, "Beyond 5G Wireless Localization with Reconfigurable Intelligent Surfaces", IEEE International Conference on Communications 2020 (IEEE ICC'20), Dublin, June 2020.

System-level simulation of cooperative sensor data fusion strategies for improved vulnerable users safety

RESEARCH TOPIC:

Smart connected road infrastructures: cooperative sensor data fusion for improved vulnerable users safety

AUTHORS:

A. Pereira Da Silva, I. H. Brahmi, B. Denis, **S. Leirens**

Cooperation between vehicles and/or with static elements of the road infrastructure enables a wide number of applications and services, such as traffic monitoring and prediction, localization and mapping, or novel safety approaches for vulnerable road users. Through cooperative fusion, vehicles equipped with on-board sensors (e.g, GNSS and LiDAR or RADAR) and connectivity (e.g., ITS-G5 V2X) contribute to elaborate a global view of the physical environment, which can reveal hidden information. We have developed a flexible end-to-end system simulator that can evaluate such cooperative mapping strategies in complex road driving environments.

Context and Challenges

With the foreseen advent of autonomous driving, Cooperative Intelligent Transport Systems (C-ITS) have become an increasingly attractive area to both industrial and research communities in recent years. Among the key enabling techniques, cooperative sensor data fusion and crowdsensing have been regularly put forward, requiring contributions from multiple agents disseminated on the road. This is particularly relevant for road traffic, GNSS continuity and especially Vulnerable Road Users (VRU) safety. Recent studies on VRU safety have focused mostly on local car-centric occupancy maps, whereas our contribution has addressed the problem of V2X-aided cooperative sharing and fusion of local maps, i.e., resulting from multiple and possibly mobile contributors.

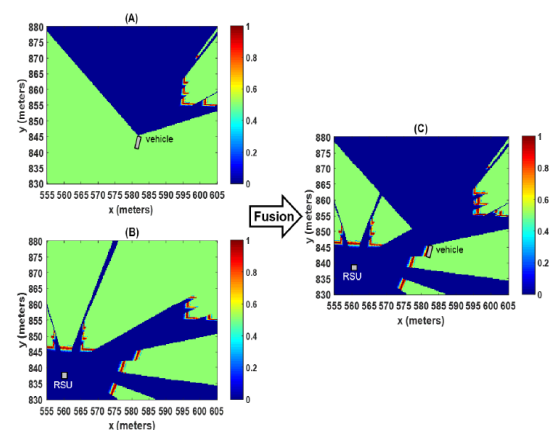
Main Results

To focus specifically on improved VRUs safety in complex road environments such as urban intersections, we have considered a canonical scenario where various vehicles and a few more static elements of infrastructure such as Road Side Units (RSUs) rely on embedded ranging sensors (typically LiDAR) to construct local probabilistic occupancy maps, which are transmitted to a fusion center through V2X connectivity for further processing. The fusion result can be subsequently broadcast back not only to contributing vehicles, but also to any V2X-enabled vehicle in range. In order to assess the performance of this cooperative scheme, we have developed a simulation environment in Matlab®, which has been made deliberately simple but flexible enough to conduct extensive end-to-end system evaluations, spanning from refined sensor and V2X connectivity models up to cooperative fusion algorithms running at the application level. The figure illustrates an example of typical urban intersection, where the fusion is performed at a fusion center collocated with RSU (C) of two probabilistic occupancy maps from an arbitrary vehicle (A) and another RSU (B). The simulation results confirm that quite significant gains are

observable through cooperative fusion, in terms of both obstacles detection rate and detection coverage, as long as one equipped road side unit starts assisting the vehicles. Beyond, the performance gets even better and better, while gradually increasing the number of cooperating vehicles, despite on-board GNSS uncertainty while referencing the local maps.

Perspectives

The result achieved open up new perspectives in the context of V2X-aided cooperative data fusion. Future work will concern (i) more advanced data dissemination and local maps compression strategies under various cooperation levels and distinct fusion partitioning schemes, (ii) the detection/classification of VRU mobility patterns, based on sequences of fused occupancy maps and other complementary sensor measurements (incl. possibly that of VRUs' smartphones) and (iii) trajectory prediction of vehicles (including VRUs) to anticipate and prevent potential collisions.



Fusion of LiDAR-based occupancy maps

RELATED PUBLICATIONS

[1] A. Pereira Da Silva, I. Horiya Brahmi, S. Leirens, B. Denis, "System-level Simulation of Cooperative Sensor Data Fusion Strategies for Improved Vulnerable Road Users Safety", 16th Workshop on Positioning, Navigation and Communication (WPNC), 2019

Impact of the V2X connectivity in a COoperative collision Avoidance (COCA) system

RESEARCH TOPIC:

Vehicular communications, C-V2X, Intelligent Transport System, System level simulation, Cooperative collision avoidance

AUTHORS:

Arturo Guizar, Federico Poli, Benoit Denis, Vincent Berg, Valérian Mannoni

The interest for communications between vehicles and the infrastructure or other vehicles (V2X) has recently increased towards connected vehicle applications and particularly COoperative Collision Avoidance (COCA). In this study, the performance of Cellular V2X (C-V2X) networks is evaluated in the context of Intelligent Transportation Systems for collision avoidance applications based on sharing occupancy maps between the infrastructure and the vehicles. We compare different C-V2X configurations under realistic conditions in an intersection scenario. Then, we evaluate every type of communication link as a function of the density of vehicles. The results show the potential of the concept for V2X COCA and the trade-offs in terms of reliability, capacity and latency.

Context and Challenges

Recent advances in vehicle communications have confirmed the gains in considering real-time exchange of information between vehicles to improve road safety and reduce traffic. It has been showed that C-V2X communication system outperforms the ITS-G5 protocol [2] in terms of reliability and latency, two indicators for traffic collision avoidance investigated in this study. Moreover C-V2X is flexible and can adapt according to the network density and coverage conditions. In this study, we evaluate the performance of a COCA system based on the calculation of occupancy maps using C-V2X communication for an urban intersection scenario. The aim of this service is to provide network-assisted safety information to connected vehicles via the available infrastructure to ensure efficient navigation through intersections, lane changing, overtaking. We then evaluated in [1] the impact of the communication on the COCA application using different C-V2X configurations in terms of reliability, scalability and latency.

Main Results

In the proposed COCA system, the vehicles calculate a Local Dynamic Map (LDM) using the measurements coming from their sensors in their on-board LDM application. Then, the connected vehicles broadcast the LDM through dedicated messages in the network. Finally, the Road Side Unit (RSU) can merge the information from every vehicle to build the global occupancy map and recreate a reliable picture of the whole scene.

To evaluate the large-scale performance of V2X networks, we implemented several models in the discrete-event NS3 simulator. To do so, we followed a cross-layer simulation approach between the physical and higher layers to exploit the mobility traces from Simulation of Urban Mobility. Based on this simulator, we evaluated different C-V2X configurations using realistic mobility and channel models. The results show the trade-offs in terms of capacity, range, reliability and latency for each type of link (Vehicle-to-Infrastructure V2I or Vehicle-to-

Vehicle V2V) depending on the density of vehicles (Fig. 1). Thus, we showed that it is better to send the local occupancy maps in uplink at 5.6 Mb/s via a channel of 10 MHz (resp. a channel of 5 MHz allowing to 2 users) when the network presents a low (resp. high) vehicles density. However, it is preferable that the RSU sends the global occupancy map in DL using a 10 MHz channel at 5.6 Mb/s to reach the UEs in all the intersection. If the connection between UEs and RSU is limited, UEs can still cooperate by sharing their LDM using the configuration at 5.6 Mb/s on 10 MHz.

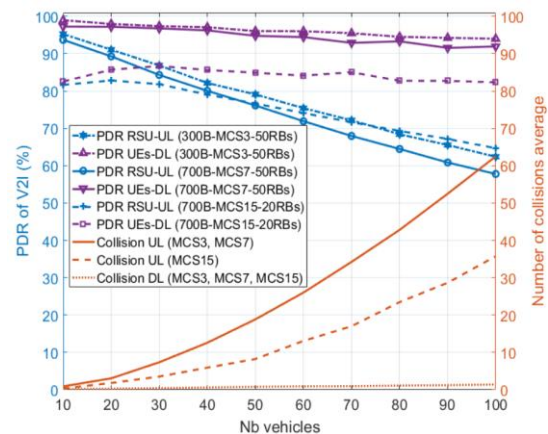


Fig. 1: V2I performance in UL/DL

Perspectives

Future work will consist in evaluating the LDM COCA application in terms of obstacle positioning accuracy and traffic collision detection. We will also investigate the impact of using standardized messages (CPM) on the global performance. Finally, we will integrate more realistic errors in local maps (GNSS error).

RELATED PUBLICATIONS:

- [1] A. Guizar, V. Mannoni, F. Poli, B. Denis and V. Berg, "LTE-V2X performance evaluation for cooperative collision avoidance (CoCA) systems," 2020 IEEE 92nd Vehicular Technology Conference (VTC2020-Fall), Victoria, BC, Canada, 2020.
- [2] V. Mannoni, V. Berg, S. Sesia and E. Perraud, "A Comparison of the V2X Communication Systems: ITS-G5 and C-V2X," 2019 IEEE 89th Vehicular Technology Conference (VTC2019-Spring), Kuala Lumpur, Malaysia, 2019.

Evaluation of V2X standards (C-V2X / ITS-G5) and study of their coexistence

RESEARCH TOPIC:

Vehicle communications, V2X, C-V2X, ITS-G5, Coexistence, mobility, Large Scale Simulations

AUTHORS:

Pierre Roux, Stefania Sesia¹, Eric Perraud², Valérien Mannoni

Vehicular communications are expected to grow rapidly in the coming years, bringing safer driving conditions and optimized traffic management. Two technologies consider the use of the 5.9 GHz ITS band: ITS-G5 (ETSI) and C-V2X (3GPP). This study evaluates the lower layers and protocol stack with a system level simulation in order to compare the performances of both technologies. It is also anticipated that both standards may coexist in the deployment phase. Some scenarios consider to share the radio channel among both technologies under the same geographical area. New mechanisms are explored that assume some modifications of the standards aimed at minimizing the performance losses.

SCIENTIFIC COLLABORATIONS: ¹ Renault Software Labs, Sophia Antipolis (FR), ² Renault Software Labs, Toulouse (FR)

Context and Challenges

Vehicular communications have been identified as a key component in improving vehicle safety, traffic and energy consumption. Vehicle to Everything (V2X), are wireless systems to address several Intelligent Transport Systems standardization and regulatory initiatives worldwide. Two standards are emerging as candidates for V2X operations (device-to-device mode) in the 5.9 GHz frequency band, namely ITS-G5 developed by ETSI and C-V2X derived from 3GPP LTE.

This study proposes a fair comparison of both standards by evaluating both the lower layers and protocol stack performance and in realistic scenarios in terms of vehicle density and mobility.

During the deployment phase, it is likely that ITS-G5 and C-V2X will coexist in the 5.9 GHz band in some geographical areas. It is even possible that both technologies will share the same 10 MHz radio channel, which is referred to as co-channel coexistence. Of course, the simultaneous usage of the same channel by both technologies will result in mutual influence, which might affect the performance. In anticipation of loss of performance, several mechanisms have been proposed and assessed with the aim to reduce performance losses.

Main Results

In [1], we developed a V2X system level simulator including connectivity (ITS-G5 and C-V2X) and mobility modules. Based on this simulator, the results comparison between ITS-G5 and C-V2X (PC5 mode 4) shows that C-V2X is outperforming ITS-G5 in all studied scenarios. If we consider a target packet delivery ratio equal to 0.9 and the urban scenario at 60 km/h, the maximum coverage is of around 25 meters for ITS-G5 and 32 meters for C-V2X (Fig. 1). Furthermore if we consider latency maximum tolerance, the performance gap may only grow because only ITS-G5 may introduce latency when the traffic is high, while C-V2X is not introducing latency by design. In the coexistence scenario in [2], we have investigated the performance losses due to co-channel coexistence. To limit this

loss, we have proposed a coexistence mechanism. This mechanism requires to modify C-V2X radio systems to send an ITS-G5 preamble while ITS-G5 radios are unchanged. Since ITS-G5 devices perform clear channel assessment before transmission, this evolution makes both radios more sensitive to detect activity from surrounding modified C-V2X devices. The benefit of coexistence mechanism have then been confirmed by system simulations. We have also observed C-V2X performance improvements, when C-V2X vehicles face ITS-G5 interference, rather than interference from other C-V2X vehicles.

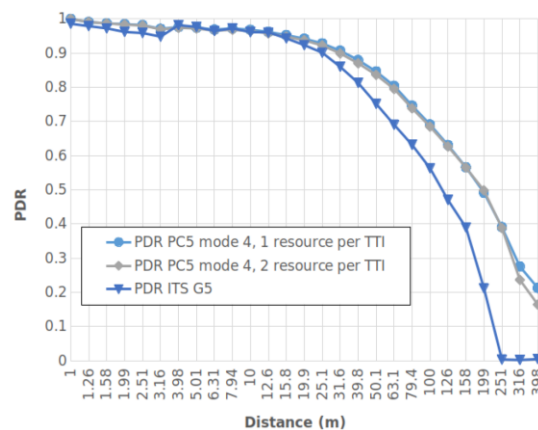


Fig. 1: Performance comparison at 60km/h

Perspectives

In future work, we plan to assess 5G NR cellular communication systems and its sidelink mode. Concerning the coexistence issue, future work should consider more spectrally efficient modes for C-V2X and new coexistence mechanisms to further improve the performance.

RELATED PUBLICATIONS:

- [1] P. Roux, S. Sesia, V. Mannoni and E. Perraud, "System Level Analysis for ITS-G5 and LTE-V2X Performance Comparison," 2019 IEEE 16th International Conference on Mobile Ad Hoc and Sensor Systems (MASS), Monterey, CA, USA, 2019.
- [2] P. Roux and V. Mannoni, "Performance evaluation for co-channel coexistence between ITS-G5 and LTE-V2X," 2020 IEEE 92nd Vehicular Technology Conference (VTC2020-Fall), Victoria, BC, Canada, 2020.

Ultra low power wireless sensors dedicated to machine tools' predictive maintenance

RESEARCH TOPIC:

Autonomous sensors for predictive maintenance

AUTHORS:

S. Brulais, A. Faucon, A. Boness, A.Sanz Arrizabalaga¹, J. Ellinger², **T. Caroff**

Performing predictive maintenance on highly moving parts of machine tools requires wireless and autonomous sensors. Commercial wireless sensors are too restrictive regarding industrial machine tools' requirements. A dedicated standalone wireless sensor platform has thus been designed and developed to fit all the machine tools' requirements. Those wireless sensor nodes are based on ultra-low power electronic devices and communication protocols to minimize their power consumption during all phases: sensing, communication and sleeping mode. Those sensor nodes have been successfully developed and tested in representative environments in laboratory, and then deployed on pilot machine tools in the frame of the H2020 PreCoM project.

SCIENTIFIC COLLABORATIONS: ¹ Centro Tecnológico IDEKO, Gipuzkoa (ES), ² Technical University of Munich - IWB, Munich (DE)

Context and Challenges

The PreCoM project aims to deploy and test a cognitive predictive maintenance system able to identify and localize damage, predict damage evolution, assess remaining asset lifetime and increase in-service efficiency of machines [1]. In this PreCoM system, additional sensors are needed to gather measurements close to critical parts/tools in order to improve failure detection.

Commercial wireless sensor nodes are too restrictive regarding requirements for condition monitoring on industrial machine tools (50 g acceleration, 50 m long wireless range, several months lifetime, presence of cooling fluid and hot metal chips projection). Therefore, a dedicated wireless multi-sensor platform has been designed and developed in the frame of this project to provide additional measurements on highly moving parts, such as spindle heads.

Main Results

The specification for the wireless sensor system has been validated with machine tool manufacturers and maintenance experts for 3 different use cases: low volume manufacturing (General machining), high volume manufacturing (precision reduction gears) and continuous manufacturing (pulp and paper).

The PreCoM wireless sensor platform integrates accelerometers and a temperature sensor as those two sensors are the most suitable for condition monitoring of machine tools. The selected communication protocol is Bluetooth Low Energy. The sensor nodes have been designed to have a lifetime of around 1 year. The key components of the wireless sensor node are: the low power *nRF52840* System on Chip, a 3-axis accelerometer *MEAS 832M1* (50 g - 10 kHz) and a 3D antenna *SRW009* adapted to 2.4 GHz long distance communication. The battery charging is allowed through either USB or Qi type inductive charger.

Tests have been set up to evaluate communication quality, sensor node power consumption, in representative environment in collaboration with DANOBTGROUP and IDEKO. The

power consumption in sleep mode is below 10 μ W and the data processing and communication mode is in the range of 10 to 15 mW. The wireless data transfer speed rate reached 180 kbits/s for up to 30 m distance in a shop floor environment. The full operation of the sensor nodes has been tested and validated at the IWB of the Technical University of Munich shop floor [2].

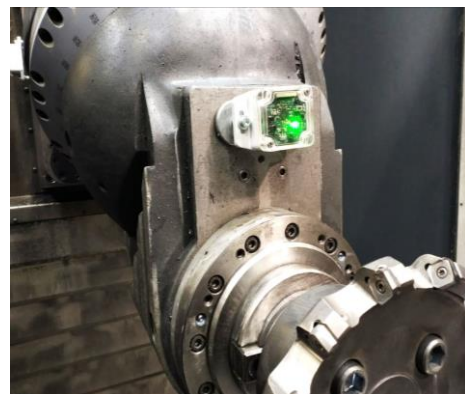


Fig. 1: Wireless communication during validation test at SORALUCE/IDEKO

Perspectives

The PreCoM System and its associated sensor system has successfully been deployed in the 3 different use cases: low volume manufacturing (SAKANA), high volume manufacturing (SPINEA) and continuous manufacturing (GOMACAMPS). Such standalone wireless sensor node shown its added value for the monitoring of highly moving critical parts, and further projects for predictive maintenance are under discussion.

RELATED PUBLICATIONS:

[1] B. Al-Najjar, H. Algabroun, and M. Jonsson, "Smart Maintenance Model using Cyber Physical System" - International Conference on 'Role of Industrial Engineering in Industry 4.0 Paradigm' (ICIEIND), Bhubaneswar, India, September 27-30, 2018

[2] T. Caroff, S. Brulais, A. Faucon, A. Boness, A.S. Arrizabalaga, J. Ellinger, « Ultra low power wireless multi-sensor platform dedicated to machine tool condition monitoring », *Procedia Manufacturing* 51 (2020) 296–301

Spreading Factor Allocation for Multi-Gateway LoRa Adaptive Networks

RESEARCH TOPIC:

Low Power Wide Area, LoRa, Internet of Things, Adaptive Networks, Media Access Control, Large Scale Simulations.

AUTHORS:

Moises Nunez Ochoa¹, Andrzej Duda¹, **Mickael Maman**

In this study, we investigate how to optimise transmission quality in massive deployments of LoRa networks by considering device heterogeneity, network topology, and deployment density. We propose an algorithm to improve network performance by effectively allocating a spreading factor (SF) to end-devices in realistic multi-gateway deployments when nodes progressively join the network. In particular, new nodes are configured based on measured metrics and without modifying the configuration of nodes that already joined the network. The allocation decision is based on different metrics: link packet delivery ratio (PDR), network PDR, and network distribution of SF per gateway. The algorithm enhances LoRa deployments and outperforms Adaptive Data Rate (ADR) of LoRaWAN.

SCIENTIFIC COLLABORATIONS: ¹ Université. Grenoble Alpes, CNRS, Grenoble INP, Grenoble (FR)

Context and Challenges

LoRa has received a lot of interest for the Internet of Things thanks to its long-range and low power capabilities. It presents many degrees of freedom in its configuration parameters that allow to adapt the operation of nodes to the actual conditions of operation of the network. Despite many advantages, LoRa raises some issues on scalability and optimized configuration in large-scale deployments require deeper investigation.

In [1], we investigate how to improve the performance of LoRa networks by considering device heterogeneity, network topology, and deployment density. The objective is to propose a distributed algorithm that effectively allocates the Spreading Factor (SF) to joining devices under realistic multi-gateway (GW) network deployments. The main deployment constraints are: (i) as LoRa is a global open network, it is hard to change the configuration of all the nodes in the network after their joining procedure, (ii) all LoRa devices do not join the network at the same instant, and (iii) each device can choose its initial configuration according to some available metrics at a gateway (i.e., estimated in the topology composed of already joined devices).

Main Results

In [1], we present a strategy to self-deploy LoRa networks by adapting the SF when nodes progressively join the network over time: Nodes select their configuration according to the current state of the network and exploit the current network statistics, easily estimated from GW measurements. We propose a distributed allocation algorithm adapted to multi-gateway deployments. The proposed *Enhanced Link Network Distribution* (ELNDA) algorithm takes into account the link budget with the selected gateway (i.e. the closest, the most reliable, or the least congested one), the multi-connectivity through the GWs in multi-GW deployment and the network distribution to exploit all SFs effectively giving fair use of each SF per GW. The algorithm takes advantage of estimated metrics based on the link quality, network connectivity, and the network distribution of nodes per SF. We refine the proposed

algorithm by adding a dynamic metric that changes with the network size.

To evaluate the performance of the proposed algorithm, we have developed an accurate model of LoRa PHY/MAC layers in the Wsnet simulator [2]. It takes into account spectrum usage, co-channel rejection due to quasi-orthogonality of the LoRa modulation, and the GW capture effect.

Figure 1 shows the reliability in dense deployment scenarios of 9 GWs for classical ADR, ELNDA favoring the SF distribution of the closest GW ($\beta=0$), ELNDA exploiting the network infrastructure ($\alpha=0.8$ and $\beta=1$) and dynamic ELNDA dynamically adapting β to the network size.

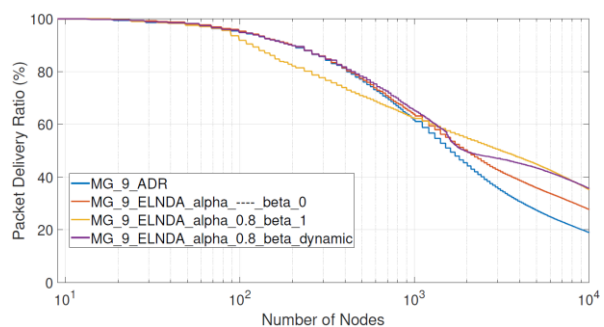


Fig. 1: PDR of classical ADR, ELNDA, and dynamic ELNDA

Perspectives

In future works, we plan to enhance our proposal with machine learning techniques for link coordination and SF allocation to adapt the network and investigate the optimal placement of gateways.

RELATED PUBLICATIONS:

- [1] M. N. Ochoa, M. Maman and A. Duda, "Spreading Factor Allocation for LoRa Nodes Progressively Joining a Multi-Gateway Adaptive Network," *GLOBECOM 2020 - 2020 IEEE Global Communications Conference*, Taipei, Taiwan, 2020, pp. 1-6, doi: 10.1109/GLOBECOM42002.2020.9322637.
[2] CEA-LETI, "Wsnet simulator v4.0." <https://github.com/CEA-Leti/wsnet/>, 2018.

Wake-up radios

RESEARCH TOPIC:

Ultra Low Power Transceivers for IoT

AUTHORS:

B.Martineau, D.Morche, M.Maman P.Courouve, G.Waltener, J.GulfoMonsalve

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.

Context and Challenges

With the massive deployment of IoT applications, long lifetime networks are mandatory. To optimize the network lifetime, several technologies are competing for low power uplink communications (e.g., LoRa, Bluetooth, Zigbee and WiFi). But when interaction with IoT devices is mandatory, ultra-low power as well as predictable latency Downlink communications are missing. 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.

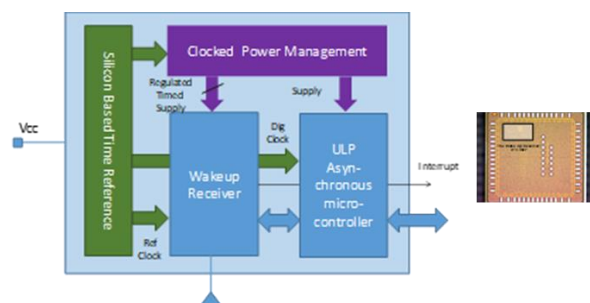


Fig. 1: Description of the Wake Up Module & IC microphotograph

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. All building blocks are tunable and adapt themselves to the selected protocol and wake-up period to reduce the power, as described in the figure 2. It shows that that WuR offers a better latency while consuming negligible power.

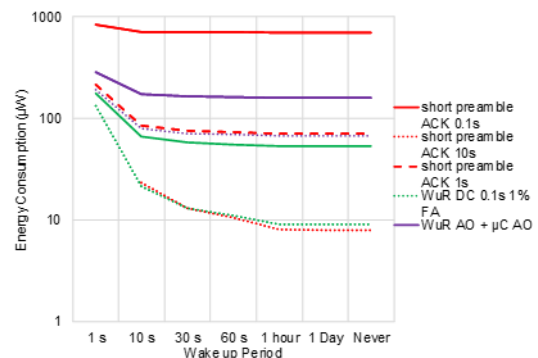


Fig. 2: Energy as a function of the wake-up period for different protocols

Perspectives

Today, 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. Tsvividis, "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
- [4] I. Miro-Panades et al., "Samurai: A 1.7MOPS-36GOPS Adaptive Versatile IoT Node with 15,000× Peak-to-Idle Power Reduction, 207ns Wake-Up Time and 1.3TOPS/W ML Efficiency," 2020 IEEE Symposium on VLSI Circuits, Honolulu, HI, USA, 2020, pp. 1-2, doi: 10.1109/VLSICircuits

Device-to-device radio channel characteristics with dual mobility

RESEARCH TOPIC:

Doppler, correlation, delay, dual mobility, propagation, non-stationary

AUTHORS:

R. D'Errico, C. Oestges¹, G. Makhoul

This paper characterizes the device-to-device (D2D) radio propagation channels based on measurement taken at 3.8 GHz in suburban environment where both terminals were moving simultaneously. The Doppler and delay spreads of pedestrian-to-pedestrian (P2P) communications were studied for multiple mobility patterns considering in Line-of-sight (LoS) and partial-LoS propagation conditions. It was found that the delay spread does not only depend on the propagation environment but also on the mutual body orientations while the presence of moving vehicle in the vicinity of P2P links can have an impact on the Doppler spread. In addition, the correlation properties of vehicle-to-pedestrian (V2P) channels were analyzed for different mobility patterns in LoS and partial LoS.

SCIENTIFIC COLLABORATIONS: ¹ Université catholique de Louvain (Belgium)

Context and Challenges

Device-to-Device (D2D) communication is an emerging short-range 5G and beyond technology envisioned for the direct exchange of information between users. Particular subsets of these networks are the vehicle-to-pedestrian (V2P) and pedestrian-to-pedestrian (P2P) links. Characterizing the D2D propagation is a challenge task and it differs from traditional mobile radio links in two main aspects: dual mobility inducing channel non-stationarity and propagation around human body resulting in body shadowing.

Main Results

D2D measurements were performed in a suburban environment at 3.8 GHz and 200 MHz bandwidth. In the P2P scenarios, Tx and Rx dipole antennas were carried by pedestrians while in the V2P scenarios, Tx antenna was mounted on the car roof. Several mobility patterns were considered under LoS and partial LoS conditions. Partial LoS is considered when the Rx subject was walking behind parked vehicles (cf. Fig. 1).

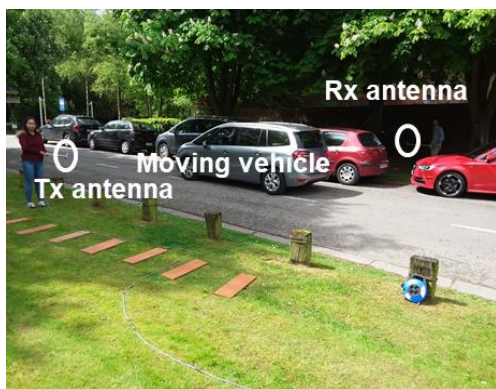


Fig. 1: Example of P2P partial LoS Measurements

For P2P links, a large variation in delay spread was found in partial LoS scenarios, while body shadowing effects, in the LoS condition, cause the delay spread to increase linearly with increase of Tx-Rx distance. The presence of a moving vehicle also induce an increase in P2P Doppler spread. The correlation properties of V2P channel show in Fig.2 that the scatterers are correlated in delay domain and decorrelated rapidly over time, showing the channel non-stationarity in time and delay domains.

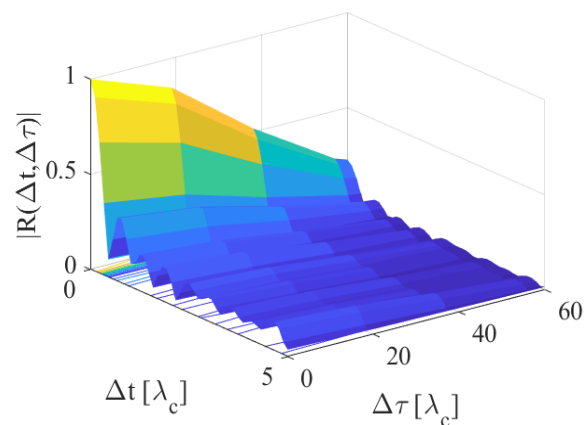


Fig. 2: Example of V2P correlation properties

Perspectives

In future work, the non-stationary dynamic channels of D2D will be modeled.

RELATED PUBLICATIONS:

- [1] G. Makhoul, R. D'Errico and C. Oestges, "Characterization of Vehicle to Pedestrian Correlation Properties," 2020 IEEE International Symposium on Antennas and Propagation and North American Radio Science Meeting, Montreal, QC, Canada, 2020, pp. 1113-1114.
- [2] G. Makhoul, R. D'Errico and C. Oestges, "Delay and Doppler Variations in Device to Device Communications with Pedestrian Mobility," 2020 IEEE International Symposium on Antennas and Propagation and North American Radio Science Meeting, Montreal, QC, Canada, 2020, pp. 1267-1268.

Contribution to 3GPP standard channel model for indoor factory scenarios

RESEARCH TOPIC:

5G, IoT, propagation, radio channel, industrial scenario

AUTHORS:

R. D'Errico

The 3rd Generation Partnership Project (3GPP) unites [Seven] telecommunications standard development organizations (ARIB, ATIS, CCSA, ETSI, TSDSI, TTA, TTC), known as “Organizational Partners” and provides their members with a stable environment to produce the Reports and Specifications that define 3GPP technologies. This paper reports a Contribution to 3GPP standard channel model for indoor factory scenarios.

SCIENTIFIC COLLABORATIONS: 3GPP participants <https://www.3gpp.org/about-3gpp/membership>

Context and Challenges

Industrial internet of things (IIoT) is an emerging area for the deployment of fifth-generation (5G) wireless communication networks. The indoor factory is a challenging scenario in terms of radio propagation, due to the presence of metal machine tools and scatterers which make the corresponding channel models significantly different from those of the indoor office and hotspots.

Main Results

Extensive radio channel measurements were carried out in a machinery room in the sub-6GHz bands, and the results were exploited to extract multipath components and large scale parameters.

This work was promoted to COST IRACON action, 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 definition of a new standard channel model for these applications. The model parametrization is defined for different Indoor Factory scenarios, depending on clutter density and base station height (Fig.1), for which path loss model and Line of Sight probability are defined. The delay spread model is frequency and volume -dependent in order to catch the impact of factories size on radio channel characteristics.

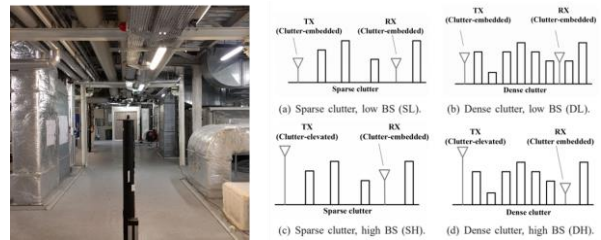


Fig. 1: IIoT channel measurement campaign (left) and scenario classification (right) [1].

Perspectives

The radio model introduced will be exploited for design and testing 5G solutions for Industrial IoT applications.

RELATED PUBLICATIONS:

[1] T. Jiang, J. Zhang, P. Tang, L. Tian, Y. Zheng, J. Dou, H. Asplund, L. Raschkowski, R. D'Errico, T. Jamsa, "3GPP Standardized 5G Channel Model for IIoT Scenarios: A Survey," in IEEE Internet of Things Journal, doi: 10.1109/JIOT.2020.3048992.

Electronically-steerable transmitarray antennas for SATCOM terminals: a system perspective

RESEARCH TOPIC:

Electronically-steerable antenna for satellite and high data rate communications, reconfigurable intelligent surfaces, beam-steering, discrete lens, SATCOM antennas, Ka-band

AUTHORS:

F. Foglia Manzillo, M. Śmierzchalski, R. Sauleau¹, and A. Clemente

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Sed non risus. Suspendisse lectus tortor, dignissim sit The possibility of using electronically-steerable transmitarrays for future SATCOM-on-the-Move ground terminals operating at K-/Ka-bands is investigated here. Starting from realistic antenna specifications, the trade-offs between antenna architecture complexity, phase-control resolution over the radiating aperture, aperture efficiency, side lobe levels, and beam scanning performance are discussed at the antenna system level and evaluated through numerical simulations. Two designs of linearly-polarized 2-bit reconfigurable unit-cells controlled by four p-i-n diodes are proposed for downlink and uplink bands. By opportunely combining orthogonally-polarized designs based on the proposed cells, two transmitarrays achieving switchable circular polarization and fulfilling the targeted specifications are presented.

SCIENTIFIC COLLABORATIONS: ¹ Univ Rennes, CNRS, IETR (Institut d'Electronique et de Télécommunications de Rennes) – UMR 6164 Rennes, France

Context and Challenges

Satellite communication (SATCOM) systems operating at K-/Ka-bands will boost the performance of next-generation terrestrial mobile networks and eventually ensure global space-based connectivity. Novel beam-steering antennas are required for future ground terminals. This need is even more urgent to support the development of SATCOM-on-the-Move (SOTM), for both military and civil applications. A SOTM antenna has to continuously track the satellite over field of views often exceeding 120 deg. In the near future, the constraints on the size, weight and cost of the antenna will become even more stringent to allow SOTM terminals to be mounted on the broadest range of vehicles and to push use in diverse application scenarios. Phased arrays [2] are among the most compact and mature antenna technologies. However, their lossy feed networks, power consumption and complexity hinder their use for commercial applications. Reconfigurable metasurface antennas based on liquid crystal (LC) technology minimize the height of the terminal but are currently limited by costs as well as by the complexity of the bias network featuring sub-wavelength pitches. On the other hand, hybrid electromechanical solutions are typically bulky and require expensive and heavy gimballs.

Main Results

Beam-steering transmitarray antennas (TAs) may represent an attractive and low-cost alternative attaining a good trade-off among the size of the antenna, loss and scanning capabilities. In general, a TA comprises a primary source illuminating an array of different unit cells (UCs), each modifying in a specific way the properties of the incident wave, such as its phase. The array of UCs is typically realized in standard printed circuit board (PCB) technology and acts as a flat lens to radiate directive beams. Electronic beam-steering is achieved by reconfiguring the phase shifts introduced by the UCs. This contribution analyzed the possibility of integrating p-i-n diodes based transmitarrays in the future SOTM ground terminals. Two square transmitarrays operating respectively in downlink

and uplink bands have been designed considering realistic specifications. They are based on 2-bit linearly-polarized reconfigurable unit-cells optimized to work in the two bands. Switchable circular polarization has been achieved by opportunely combining two orthogonally polarized designs. Both polarization switching and electronically beam-steering functions can be implemented by controlling four p-i-n diodes integrated on each unit-cell. In the case of the downlink antenna (38×38 unit-cells), a peak gain of 28.7 dBi is achieved at 20.5 GHz. Instead, a peak broadside gain of 31.8 dBi is achieved at 30.25 GHz by the uplink antenna (50×50 unit-cells). The possibility to steer the beam up to 60° has been demonstrated

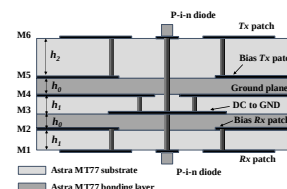


Fig.1: Stack-up of the proposed 2-bit unit-cells.

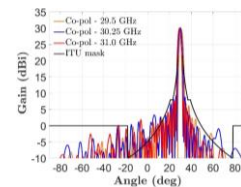


Fig.2: Gain of the uplink 50x50 UCs transmitantenna

Perspectives

The main technical challenge for the future will be the development of an innovative architecture to drastically reduce the total profile of the antenna system, which is strongly impacted by the distance between the array aperture and the focal system required for an efficient illumination taper.

RELATED PUBLICATIONS:

- [1] A. Clemente, F. Diaby, L. Di Palma, L. Dussopt, and R. Sauleau, "Experimental validation of a 2-bit reconfigurable unit-cell for transmitarrays at Ka-band," IEEE Access, vol. 8, pp. 114991-114997, 2020.
- [2] A. Clemente, F. Foglia Manzillo, M. Śmierzchalski, and R. Sauleau, "Electronically-steerable transmitarray antennas for SATCOM terminals: a system perspective," IEEE International Workshop Antenna Technology, (IWAT 2020).
- [3] F. Foglia Manzillo, M. Śmierzchalski, A. Clemente, and R. Sauleau, "P-i-n Diodes Based Electronically Steerable Transmitarray for SOTM at Ka-Band," 14th European Conf. on Antennas and Propag. (EuCAP 2020).

Trimming decoding of color codes over the quantum erasure channel

RESEARCH TOPIC:

Quantum error correction, quantum color codes, quantum erasure channel

AUTHORS:

S. Lee, M. Mhalla¹, V. Savin

We propose a decoding algorithm for color codes over the quantum erasure channel, which is linear-time maximum likelihood (ML) when the set of erased qubits satisfies a certain condition called trimmability. Two methods are proposed for general erasure sets, either by extending the erasure set to make it trimmable, or by inactivating some vertices. The former is linear time but not ML, while the latter is ML but not linear time. Numerical results are provided to assess the error correction performance and the complexity of both methods.

SCIENTIFIC COLLABORATIONS: ¹ Université Grenoble Alpes, CNRS, Grenoble INP, LIG (FR)

Context and Challenges

Quantum error correction is a crucial step for the construction of a fault-tolerant quantum computer. Topological codes, among which surface and color codes, are considered as the most promising approaches to quantum error correction, due to their high thresholds and locality. However, current decoding methods of these codes suffer from high complexity, which may prevent their use in practical applications, especially for large scale systems.

Main Results

The quantum erasure channel is a simple error model, in which arbitrary quantum errors occur at known positions, thus replacing the corresponding qubits by totally mixed states. From a decoding perspective, it turns out that the quantum erasure channel may serve as a proxy for more general quantum channels. The idea is to first devise an efficient decoding algorithm for the quantum erasure channel, and then to reduce the decoding problem for more general quantum channels to the quantum erasure model. Such an approach has been recently successfully exploited for surface codes in [arXiv:1709.06218].

In [1], we addressed the problem of decoding quantum color codes over the quantum erasure channel. We showed that linear-time maximum-likelihood decoding is possible, when the set of erased qubits satisfies a certain trimmability condition, which ensures that its connected components are well separated. Hence, we proposed a decoding algorithm for trimmable erasure sets, called trimming decoding. We also provided two decoding methods for general erasure sets, not obeying the trimmability condition, either by extending the erasure set to make it trimmable, or by inactivating some qubits. The first method is linear-time and almost maximum-likelihood, while the second method is maximum-likelihood and almost linear-time. Fig. 1 illustrates the error correction performance of the trimming decoding with inactivation, for color codes defined by the hexagonal lattice on the torus, with

several minimum distances d . The logical error rate is plotted against the erasure probability of the quantum erasure channel. It can be observed that the proposed decoding achieves an erasure threshold of 50%, corresponding to the theoretical limit of the quantum erasure channel.

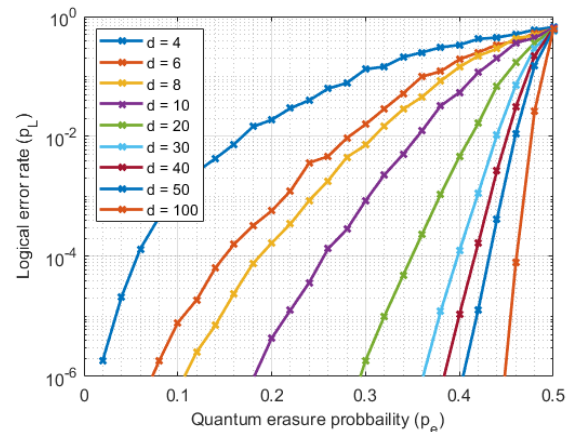


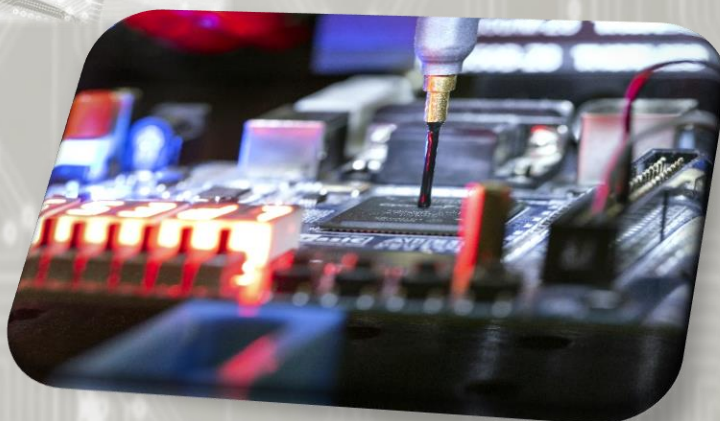
Fig. 1: Trimming decoding with inactivation

Perspectives

The proposed decoding provides an efficient solution to the decoding problem over the quantum erasure channel. It also opens new perspectives for the general decoding problem, by reducing the general problem to the erasure case, similar to the union-find decoding approach used for surface codes. A related perspective is related to the construction and decoding of color codes for biased error models, which have been experimentally demonstrated in many quantum architectures.

RELATED PUBLICATIONS:

[1] S. Lee, M. Mhalla, and V. Savin, "Trimming decoding of color codes over the quantum erasure channel", in *IEEE International Symposium on Information Theory (ISIT)*, Los Angeles, USA, June 2020.



06

**SECURITY OF
EMBEDDED SYSTEMS:
THE HARDWARE ROUTE**

- Security and deployment technologies for the Internet of Things (IoT)
- Security of microarchitectures
- Secured embedded artificial intelligence
- Data security management

Decentralized root-of-trust for device attestation in the industry 4.0

RESEARCH TOPIC:

Smart devices, Trust, PKI, blockchain, Smart contracts

AUTHORS:

Christine Hennebert

For use-cases in Industry 4.0 involving several stakeholders of a value chain around connected and autonomous smart robots, the blockchain Ethereum appears as a high potential technology. However, the use of digital certificates from a PKI also allows to meet the requirements with a more mature technology. This paper explores, through the implementation of two proofs of concept, the advantages of each of the technologies and shows that they could complement each other advantageously. The blockchain reinforces trust between independent stakeholders, involved around cybersecured embedded smart robots distributed in a factory, enabling business development and traceability of the activities in a transparent way.

Context and Challenges

Industry 3.0 appeared in the middle of the 20th century, with the automation of production made possible by electronics and then computer processing. The 21st century is marked by the emergence of Industry 4.0 based on the interconnection of intelligent industrial devices. The new possibilities opened by networking and communication between devices will enhance quality and compliance by assisting operators. The paper [1] proposes a contribution to the security of connected devices by analyzing a use case involving autonomous smart robots, similar to Cyber Physical Systems (CPS), and operating according to a distributed topology. Industrial companies that work in the same field and may not trust each other, regulate the blockchain, by their participation to the consortium agreement to exchange and validate transactions. The use-case is depicted in the fig.1

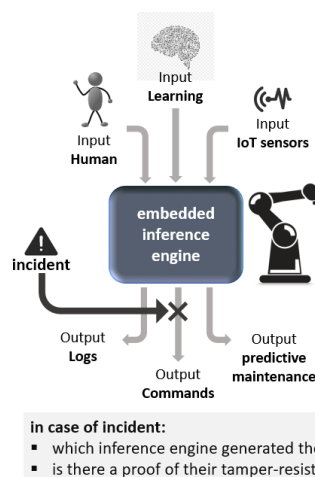


Fig. 1: presentation of the use-case

Main Results

Two solutions are implemented to address the issue of data exchange between smart robots operating in a distributed way: one based on a PKI and the other based on an Ethereum blockchain. In order to protect the business of the stakeholders engaged in the horizontal integration of a product, both approaches should fulfill the following requirements:

- 1) stakeholders and smart robots generating data must be authenticated,
- 2) the integrity, time-stamping, ordering and tamper-resistance of generated data must be ensured,
- 3) the privacy of the operators must be respected,
- 4) all the stakeholders involved must trust the solution,
- 5) the solution must be flexible enough in order to manage new entrances and revocations during the life cycle.

The two solutions are evaluated according to security, privacy and performance criteria. These results show that the security level of both solutions, PKI and blockchain, is comparable. The strong point of the blockchain technology lies in the tamper-resistance of the content of the ledger enabling traceability, as well as in the ability to offer each stakeholder a greater independence in the governance of its data and therefore of its business. In contrast, the PKI solution has proven itself and stands out with a greater maturity. It can be more efficient to offer large bandwidth or responsiveness.

Perspectives

The follow-up to this work consists in anchoring the root-of-trust in a secure hardware component such as TPM2.0.

RELATED PUBLICATIONS:

[1] Christine Hennebert and Florian Barrois, "Is the blockchain a relevant technology for the industry 4.0?," 2020 2nd Conference on Blockchain Research & Applications for Innovative Networks and Services (BRAINS), Paris, France, 2020, pp. 212-216, doi: 10.1109/BRAINS49436.2020.9223290

Design of Protection Profile bricks to secure physical devices

RESEARCH TOPIC:

Security, Common Criteria, Protection Profile, Target of Evaluation, Physical Device, Peer Node, IoT

AUTHORS:

Antonio De La Piedra, Christine Hennebert, **Raphaël Collado**

Evaluating the security of a physical target in a complex information system requires a rigorous methodology. As no experiment can exhaustively test a given mechanism in all scenarios, the Common Criteria (CC) methodology appears relevant to evaluate the security level of a Target of Evaluation (TOE) through the requirements described in a Security Target (ST) derived from a Protection Profile (PP). At the best of our knowledge, the CC methodology is the most powerful formalism to assess the security of a complex information system. Two studies are presented on this theme. The first one aims at building generic bricks of a PP for securing IoT targets. The second one introduces the main elements to build the PP of a peer node device acting in a distributed consensus mechanism.

Context and Challenges

The CC consists of a methodology defined by the ISO 15408 standard to establish an internationally recognized evaluation benchmark of information system security. The methodology to design a PP is based on a prior security analysis (fig. 1). As it aims to be reusable, its design should be as generic as possible.

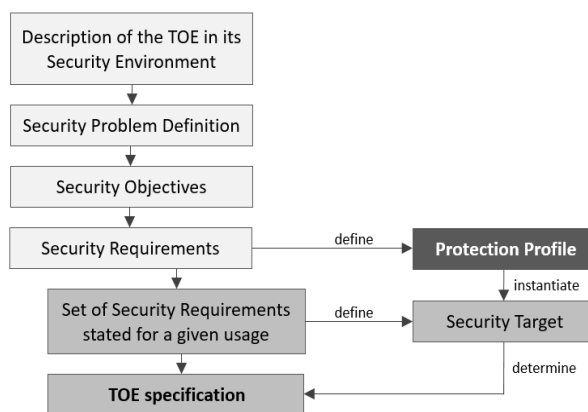


Fig. 1: Methodology to design PP bricks

Main Results

In paper [1], we identify, propose and build bricks of PPs as defined by CC that are applicable to secure IoT architectures. In particular we analyze the mechanisms of composition for complex devices hosting a trusted execution environment (TEE) and embedding a trusted platform module (TPM). We give some guiding rules and introduce some components that can be reused for the future certifications of similar device architectures as shown in fig. 2.

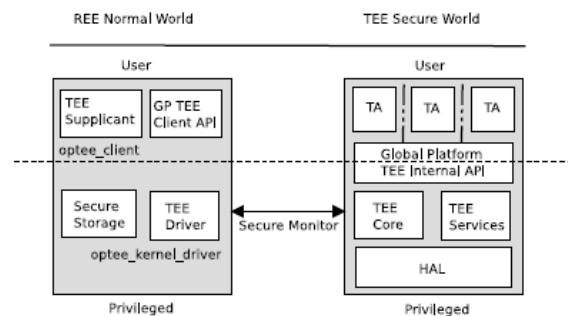


Fig. 2: secure IoT architecture

In the paper [2], we study the elements to be considered to build a PP for the security evaluation of a peer node acting in a distributed consensus mechanism. A classification of requirements is introduced as a table satisfying the security objectives.

Two major conclusions emerge. First, the elapsed time provides a guarantee of security with regards to the protection of a data history. Then, means to prove and measure the elapsed time will have to be implemented in physical objects. Second, a governance body should be able to authorize the peer nodes.

Perspectives

Now that those bricks have been defined, we need to define & implement metrics needed to evaluate those connected devices based on such PPs.

RELATED PUBLICATIONS:

- [1] Antonio De La Piedra and Raphaël Collado "Protection Profile Bricks for Secure IoT Devices" 2020 IEEE International Conference on Internet of Things and Intelligence System (IoT&IS)
- [2] Christine Hennebert, "A first Step towards a Protection Profile for the Security Evaluation of Consensus Mechanisms", 3rd IEEE International Symposium on Future Cyber Security Technologies (FCST 2020), 14-15 december 2020, Paris, France.

Methods and tools for testing and protecting IoT-based critical infrastructures

RESEARCH TOPIC:

Cybersecurity, IoT, SCADA, Honey Pots, Evaluation

AUTHORS:

P-H. Thevenon, M. Gallissot, J-P. Krimm, R. Collado, **M. Puys**

As consumer Internet of Things (IoT) devices become increasingly pervasive, there is a need to assess their security. This challenge is twofolds: first, IoT devices are used to control critical aspects of our lives (e.g., medical devices, door locks, etc); second, they may become open doors for attackers. As part of a collaboration with Bureau Veritas, we studied the state-of-the-art of existing certification schemes for consumer IoT and designed a unified evaluation scheme based on existing ones. In parallel, we propose a solution to emulate IoT devices based only on their firmware, removing the need for the physical device itself and allows running multiple batch of automated tests, with possibly destructive analyses or as part of honeypots.

Context and Challenges

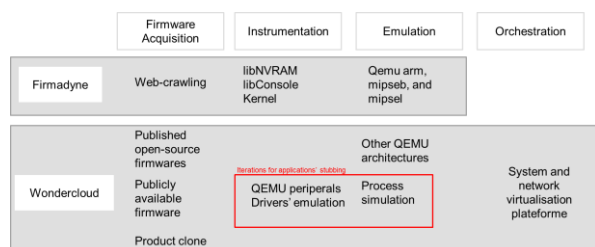
Consumer Internet of Things (IoT) is becoming increasingly pervasive in our society. At first composed of gadget devices such as connected coffee makers or cleaning robots, they now connect critical devices to Internet such as medical devices, key locks or fire alarms. All these devices were designed with commercial and time-to-market constraints in mind, leading to critical misconceptions regarding cybersecurity. In the context of the Cybersecurity Act, a mutually recognized European cybersecurity certification framework is being defined and will condition the access to the European market for consumer goods to proper cybersecurity design and validation. However, testing such products is a difficult task as proper penetration testing of connected objects may result in physical failures. Independent vulnerability researchers might not even have access to the product

Main Results

We tackle the subject in two ways. First, CEA-LETI and Bureau Veritas studied the state of the art of existing evaluation schemes for consumer IoT. Such frameworks are currently being reviewed in the context of the Cybersecurity Act in order to either choose an existing scheme or to design a unified scheme based on existing ones. We assembled a survey on existing evaluation and certification schemes for consumer IoT and compared them based on various criteria. Then, we proposed a unified evaluation scheme for the basic level of the Cybersecurity Act (for consumer goods), based on existing schemes.

In parallel, we proposed an emulation based platform named WonderCloud, allowing to emulate IoT devices only based on their firmware. This removes the need for the physical device itself and allows to run possibly destructive analyses or as part of honeypots. This emulation solution is based on the Firmadyne framework that we have extended to support various peripherals and architectures. It faithfully reproduces the software contained in the object, its real behavior and its interfaces. It is thus possible on one hand to analyze the

security of the object without damaging it and on the other hand to create realistic honeypots. Based on the Software Defined Networking technologies in order to connect several emulated objects, it is then possible to reproduce a large-scale network such as an office building.



Composition of WonderCloud platform

Perspectives

Future works on the evaluation framework are tightly bound to discussions with ENISA regarding the Cybersecurity Act as the main goal was to help select an existing scheme and prepare vendors to whichever is chosen. Thus, technical talks with ENISA and advertisement would be required alongside some case study. Works on the emulation platform are still being carried. We are mainly looking for existing tools to help analyze firmwares before and after emulation and are targeting to make the scheme scalable.

RELATED PUBLICATIONS:

- [1] M. Gallissot, M. Puys, P-H. Thevenon, WonderCloud, une plateforme pour l'analyse et l'émulation de micrologiciels ainsi que la composition de pots de miels. Journées C&ESAR 2020, December 14-15, 2020, Rennes, France.
- [2] M. Puys, J-P. Krimm, R. Collado, Towards Cybersecurity Act: A Survey on IoT Evaluation Frameworks. SECURWARE 2020 - The Fourteenth International Conference on Emerging Security Information, Systems and Technologies, Nov 2020, Valence, Spain.

Towards a new paradigm for secure processors

RESEARCH TOPIC:

Processors and microarchitectural security

AUTHORS:

Thomas Hiscock, Mustapha El Majihi, Jacques Fournier, Mathieu Escouteloup¹, Ronan Lashermes², Jean-Louis Lanet², **Olivier Savry**

The rising number of attacks targeting processors at micro-architecture level encourages more research on hardware level solutions. The paper "Recommendations for a radically secure ISA"[2] proposes modifications in the ISA to prevent timing side-channels, strengthen control flow integrity and ensure micro-architectural state isolation. Those recommendations will provide the foundation for a new hardware/software contract to ensure a secure use of processors. A second paper "CONFIDAENT: CONTROL FLOW protection with Instruction and Data Authenticated ENcryption"[1] provides an example of such a protection based on a control flow integrity enforced by memory encryption and authentication implemented in a RISC V processor on FPGA and the compiler support needed in the LLVM framework

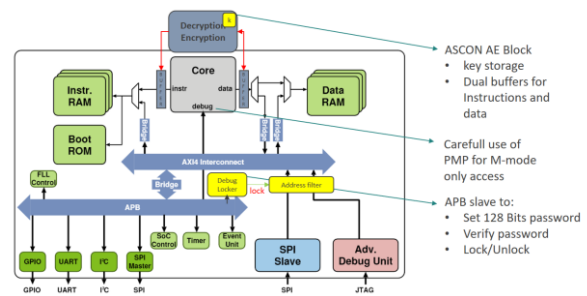
SCIENTIFIC COLLABORATIONS: ¹INRIA, Univ Rennes, CNRS, IRISA, ²INRIA LHS

Context and Challenges

In 2018, the Spectre and Meltdown attacks received a wide attention by showing that most of the performance improvements of the last 10 years had significant security flaws. As of today, these vulnerabilities remain unresolved and still do not allow developers to consider processors as a trusted base. The security of the latter needs to be rethought from a blank page by ensuring a secure transition to software.

Main Results

The paper "Recommendations for a radically secure ISA" proposes modifications to design an ISA for CPUs supporting critical systems which are centred around 4 themes. First, some principles are given to achieve security: simplicity, principle of least privilege, transparency, self proofed and defence in depth. Secondly, processors shall ensure immunity against side channel leakage like timing dependency on a secret value. The confidentiality of registers are then discussed based on memory encryption. Thirdly, new instructions are given to deal with cache memory leakage and transient execution flaws. Finally, requirements of a stricter control flows of the programs are considered. Those last issues are the object of the second paper "CONFIDAENT: CONTROL FLOW protection with Instruction and Data Authenticated ENcryption" where solutions against the corruption of the control flow of a program are proposed. It is based on an authenticated encryption of data and instructions (powered by the ASCON cipher) which are experimented on a 4-stage RISC V processor implemented on FPGA. We show that by adding instructions in the ISA, it is possible to, additionally to confidentiality and authenticity, guarantee protection against fault injection and code reuse attack like ROP (Return Oriented Programming). This CFI (Control Flow Integrity) required a codesign between the hardware and software with the modification of LLVM compilation toolchain. Putting aside the encryption, those countermeasures induce an overhead of 7% to 34% in the required number of cycles and in the code size.



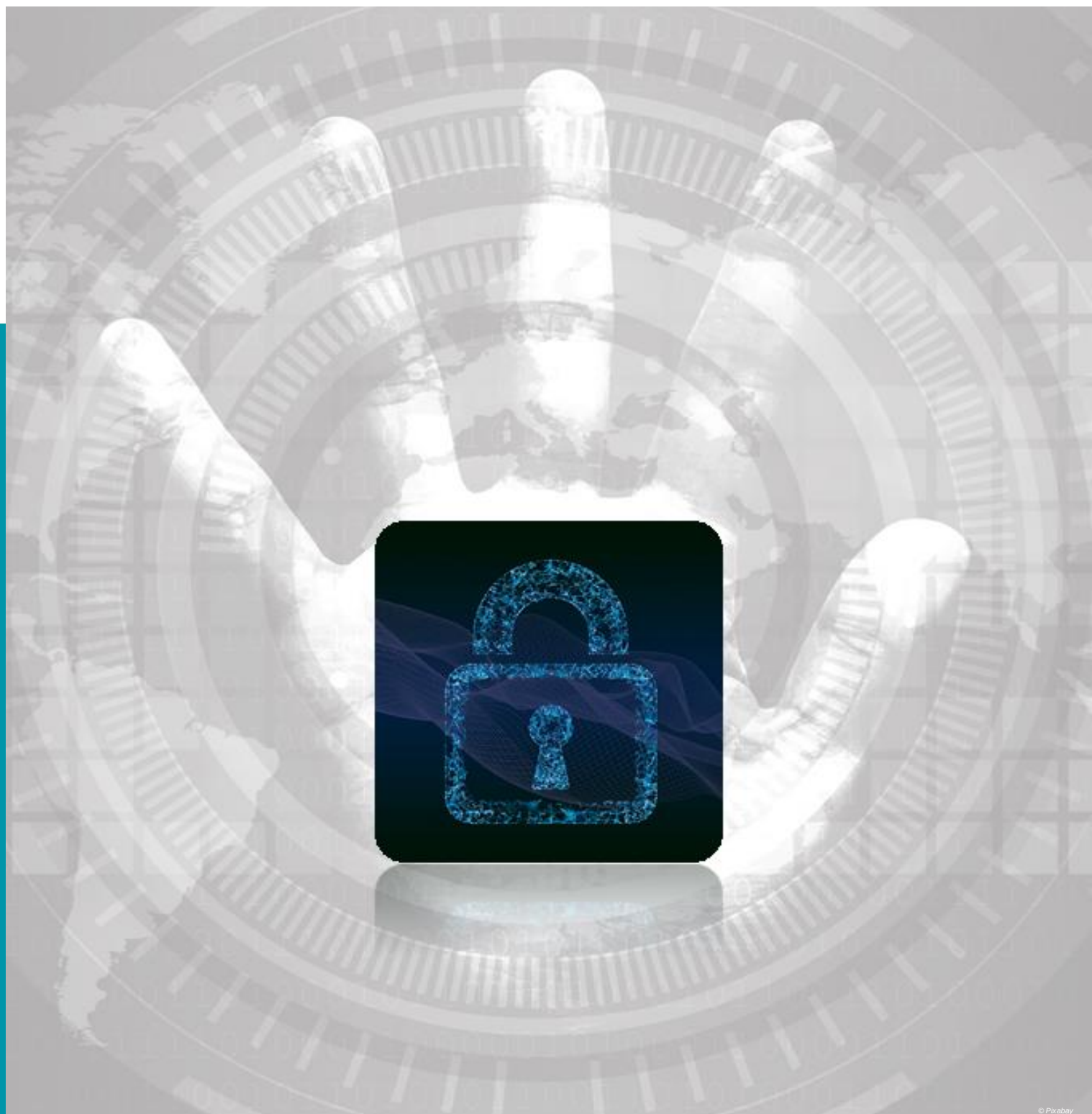
RISC V R5CY Core In its SOC with the ASCON encryption engine

Perspectives

Unfortunately, this CFI does not protect against all attacks. In particular, it does not prevent the exploitation of temporal and spatial memory leaks such as simple buffer overflows. It is now question of extending these hardware/software codesign solutions based on authenticated encryption to guarantee immunity against most of the vulnerabilities left in the code by the developers. Finally, the rest of the recommendations must now be put into practice with functional solutions whose security must be evaluated.

RELATED PUBLICATIONS:

- [1] SAVRY, Olivier, EL-MAJHI, Mustapha, et HISCOCK, Thomas. Confidaent: Control FLOW protection with Instruction and Data Authenticated Encryption. In: 2020 23rd Euromicro Conference on Digital System Design (DSD). IEEE, 2020. p. 246-253.
- [2] Mathieu Escouteloup, Ronan Lashermes, Jean-Louis Lanet, Jacques Jean-Alain Fournier. Recommendations for a radically secure ISA. CARRV 2020 - Workshop on Computer Architecture Research with RISC-V, May 2020, Valence (virtual), Spain. pp.1-22. fhal-03128242f



07

NEW ATTACKS ON
ELECTRONIC SYSTEMS

- Tools for analyzing and preventing security
- Security and cryptographic primitives
- Post quantic cryptography (PQC)
- Learning and deep neural networks (DNN) for security

Physical attacks as forensic tools

RESEARCH TOPIC:

Electromagnetic Fault Injection; SoC; Forensic; Smartphones;

AUTHORS:

Clement Gaine¹, Driss Aboukassimi¹, Simon Pontie¹, Jean-Pierre Nikolovski¹, Jean-Max Dutertre²

Smartphones have a complex hardware and software architecture. Having access to their full memory space can help solve judicial investigations. We propose a new privilege escalation technique in order to access hidden contents and execute sensitive operations [3]. While classical forensic tools mostly exploit software vulnerabilities, it is based on a hardware security evaluation technique. Electromagnetic fault injection is such a technique usually used for microcontrollers or FPGA security characterization. A security function running at 1.2 GHz on a 64-bit SoC with a Linux-based OS was successfully attacked. The Linux authentication module uses this function to verify the password correctness by comparing two hash values. Hence, this work constitutes a step towards smartphones privilege escalation through electromagnetic fault injection. This approach is interesting for addressing forensic issues on smartphones.

SCIENTIFIC COLLABORATIONS: ¹ CEA Tech, Centre CMP, Equipe Commune CEA Tech - Mines Saint-Etienne, F-13541 Gardanne (FR), ¹ Univ. Grenoble Alpes, CEA Leti, MINATEC Campus, F-38054, Grenoble (FR), ² Mines Saint-Etienne, CEA-Tech, Centre CMP, Département SAS, F - 13541 Gardanne (FR)

Context and Challenges

The first time that physical attacks have been introduced as a potential forensic application was by Aboukassimi et al. [1] in which the authors showed how to use side channel analysis for recovering data from a mobile device. In this context, this work proposes a new approach for forensic application based on EMFI (Electro-Magnetic Fault Injection). However, faults into a SoC is more difficult than into a microcontroller due to many factors. This is due first, to a small technological node. Thus we have to make a very precise location scan using an EM probe with a small diameter. Moreover, the target size (55 mm² for the targeted SoC) is larger than that of general-purpose microcontrollers (about ten mm²). This enlarges the area to be explored. Due to the higher operating speed, the cycle time is also shorter, which implies increasing the time resolution and accuracy of the scans. Besides, there are many uncontrollable desynchronization sources. Finally, this requires a higher EM field and therefore more powerful equipment. On another aspect, the multiple reboots and the loading time of the OS on a SoC is long, which lengthens the time needed to perform the data acquisition campaigns.

Main Results

We proposed a successfully attack scenario on SoC running an OS on a critical command, allowing Super User privilege escalation on Linux (su) [2]. This is the first study on a 64-bit chip with a complete software architecture, usable in a smartphone of its SoC. We focus on an A53-Cortex core, but it is a 64-bit multi-core SoC used in many smartphones, mainly at entry and mid-range price levels. A preliminary work has been performed on a test code in order to identify some required parameters for a successfully EMFI, such as the delay (figure 1) or to localize an EMFI-sensitive areas (figure 2).

Although the real scenario would require a synchronization tool, in addition to in uncontrolled environment, this approach can be used for forensic purposes to access protected or hidden data or to execute code.

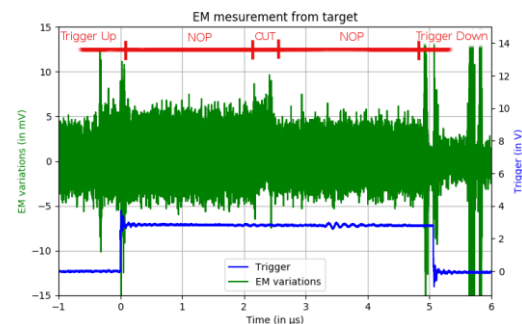


Fig. 1: Delay identification using SEMA, without EM fire

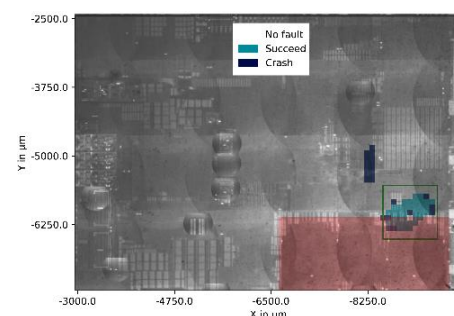


Fig. 2: EMFI-sensitive areas on an IR image of the target

Perspectives

The reported exploitation case consists in bypassing the root privilege protection of the target. As the objective of this study is to present a new approach for forensics, future works will focus on bypassing a secure boot on a Smartphone using the EMFI approach.

RELATED PUBLICATIONS:

- [1] D. Aboukassimi, M. Agoyan, L. Freund, J. Fournier, B. Robisson, and A. Tria, "ElectroMagnetic analysis (EMA) of software AES on Java mobile phones," in 2011 IEEE International Workshop on Information Forensics and Security, 2011.
- [2] N. Timmers and C. Mune, "Escalating Privileges in Linux Using Voltage Fault Injection," Fault Diagnosis and Tolerance in Cryptography, FDTC,
- [3] C. Gaine, D. Aboukassimi, S. Pontie, J. P. Nikolovski & J. M. Dutertre, "EMFI as a new Forens[j]ic Approach", in the proceedings of IEEEWIFS'2020 :

Wavelet scattering transform and ensemble methods for side-channel analysis

RESEARCH TOPIC:

Side-Channels, Wavelets, Time-Frequency Analysis

AUTHORS:

G. Destouet, C. Dumas, A. Frassati, V. Perrier¹

Recent works in side-channel analysis have been fully relying on training classification models to recover sensitive information from traces. However, the knowledge of an attacker or an evaluator is not taken into account and poorly captured by solely training a classifier on signals. This paper proposes to inject prior information in preprocessing and classification in order to increase the performance of side-channel attacks (SCA). First we propose to use the Wavelet Scattering Transform, recently proposed by Mallat, for mapping traces into a time-frequency space which is stable under small translation and diffeomorphism. That way, we address the issues of desynchronization and deformation generally present in signals for SCA. The second part of our paper extends the canonical attacks over byte and Hamming weight by introducing a more general attack. Classifiers are trained on different labelings of the sensitive variable and combined by minimizing a cross-entropy criterion so as to find the best labeling strategy. With these two key ideas, we successfully increase the performance of Template Attacks on artificially desynchronized traces and signals from a jitter-protected implementation

SCIENTIFIC COLLABORATIONS: ¹Université Grenoble Alpes, Grenoble INP, LJK

Context and Challenges

The signal analysis of current consumption and electromagnetic radiations (EM) from electronic components can leak compromising information. Countermeasures and conversely the attacks have been constantly improved in order to cut the leak of sensitive information to potential eavesdropper. In the community of side-channel analysis (SCA), profiled-attacks are critical when cryptographic algorithms are involved. It has been shown with the first Template Attacks, that cryptographic keys can be recovered by training statistical models on traces acquired during an algorithm execution. Given a classification model, we are interested in ways of increasing the performance of attacks by injecting prior information either during preprocessing with time-frequency analyses or during classification. The main motivation for pushing time-frequency preprocessing is to consider bases of analysis in which traces are represented in terms of elementary signals whose characteristics are closer to emanations from physical phenomena. Also it is not clear how a sensitive variable from a cryptographic algorithm leaks into traces and if the classifier is able to recover it. Most works in SCA usually consider only one specific leakage model, historically the Hamming weight of sensitive variables or the variable itself. But generally the leakage is an unknown function of the manipulated sensitive variables. Consequently, the second idea is to act on the goal we fixed for the classifier: we propose to target partitions of the sensitive information in order to find the best strategy of attack.

Main Results

First, we propose to use the Wavelet Scattering Transform as preprocessing so as to provide a stable representation for analyzing misaligned and deformed signals, to the best of our knowledge this transform has not been used before in SCA. Then we develop a combination procedure of classifiers trained on partitions of the sensitive variable's values so as to compare and find efficient strategies of attacks. These two approaches can be used with any type of classifiers, whose relations with

traces can be arbitrary complex. We demonstrate that these steps successfully increase the performance of Template Attacks on the ASCAD database and on a jitter-protected SoC.

Perspectives

Both proposed approaches can be used with other classifications models such as convolutional neural networks, SVM, k-NN, etc... to further increase the performance of attacks.

RELATED PUBLICATIONS:

[1] Destouet G., Dumas C., Frassati A., Perrier V. (2021) Wavelet Scattering Transform and Ensemble Methods for Side-Channel Analysis. In: Bertoni G.M., Regazzoni F. (eds) Constructive Side-Channel Analysis and Secure Design. COSADE 2020. Lecture Notes in Computer Science, vol 12244. Springer, Cham. https://doi.org/10.1007/978-3-030-68773-1_4

Leakage assessment methods and tools for design time security

RESEARCH TOPIC:

Security of embedded systems, side channel analysis, deep learning, mutual information

AUTHORS:

V. Cristiani, P. Maurine¹, M. Lecomte

A large variety of side-channel attacks have been developed to extract secrets from electronic devices through their physical leakages. Whatever the utilized strategy, the amount of information one could gain from a side-channel trace is always bounded by the Mutual Information (MI) between the secret and the trace. This makes it, all punning aside, a key quantity for leakage evaluation. Unfortunately, traces usually have a too high dimension for existing statistical estimators to stay sound when computing the MI over full traces. However, recent works from the machine learning community have shown that it is possible to evaluate the MI in high dimensional spaces thanks to newest deep learning techniques. We explored how such a tool can be used to assess the leakage of any device.

SCIENTIFIC COLLABORATIONS: ¹ Laboratoire d'informatique, de robotique et de microélectronique de Montpellier (LIRMM), Montpellier (FR)

Context and Challenges

Side Channel Analysis (SCA) could be defined as the process of gaining information on a device holding a secret through its physical leakage such as power consumption or Electromagnetic (EM) emanations. The basic assumption is that the secret and the side-channel data are statistically dependent on each other. Many techniques have been developed to extract part of these dependencies such as DPA, CPA, MIA, and profiling attacks. This diversity makes it hard for designers and evaluators to draw an objective metric in order to assess leakage. Testing all the existing attacks is a possible strategy but the incentives to develop a leakage assessment protocol remains strong.

From an information theory point of view, the maximum amount of information one could extract from a side-channel trace is bounded by the mutual information, $I(S, X)$ between the secret S and the trace X , seen as random variables. This quantity is, indeed, central in the side-channel domain. The main problem for designers and evaluators is that $I(S, X)$ is known to be hard to estimate from drawn samples when the variables live in a high dimensional space, which is generally the case with side channel leakages. This explains why conventional leakage assessment tools (Signal to Noise Ratio (SNR), T-tests) focus on one (or a few) samples at a time in the trace. As a result these tools can underestimate the leakages.

In a completely unrelated context, A Mutual Information Neural Estimator (MINE) which uses the power of deep learning to compute mutual information in high dimensions have been recently introduced. It has been proposed in a pure machine learning context but we argue that this tool might be of great interest in the side-channel domain, in particular for a leakage assessment tool.

Main Results

We proposed ways in which MINE could constitute a new tool for side-channel analysis. The main advantage is its ability to estimate MI between high dimensional variables. Indeed, being able to consider full (or large part of) traces as a variable,

allows to quantify all potential leakage sources with no *a priori* neither on the leakage model nor on the implementation. We performed a theoretical and practical analysis of MINE in a side-channel context. MINE's overfitting problem has been deeply investigated as well as the way input representations may have a huge impact on performances.

Based on the prior analysis, we adapted MINE to the side channel context. We showed that MINE can correctly estimate MI between a secret key and full traces (several thousand of samples) when usual estimators failed. An analysis has been performed on an algorithm embedding a countermeasure (second order masking). It results that the measured information is larger than that previously estimated in the state of the art, which asserts the efficiency of the tool as it cannot overestimate the information.

We showed that MINE could be used as a very simple tool to obtain an objective leakage evaluation from traces. Thus, it may be employed for massive and quick evaluations for designers during their development process as well as for evaluators as a first leakage metric.

Perspectives

Future works aim at exploring how to use MINE as a development tool to support the design of countermeasures. Our goal is to quantify a countermeasure's efficiency through its leaked information.

On the other hand, several MI based attacks have been published in the state of the art. MINE could represent a new threat as it can improve them. An objective is now to evaluate the developed technique in an attack context: how to optimally exploit the available information? An upcoming work will aim at investigating possible usages of MINE for extracting secrets in an unsupervised way i.e. in an attack context and quantify the threat posed by this tool.

RELATED PUBLICATIONS:

[1] Valence Cristiani, Maxime Lecomte, Philippe Maurine. Leakage Assessment through Neural Estimation of the Mutual Information. International Conference on Applied Cryptography and Network Security (ACNS), Oct 2020, Rome, Italy. pp.144-162, (10.1007/978-3-030-61638-0_9)

Protecting cryptographic implementations against side channel attacks

RESEARCH TOPIC:

Template Attacks, Side Channel Attacks, PCA, LDA, Curve25519, Elliptic Curve, mbedTLS, Cryptography

AUTHORS:

Maxime Lecomte¹, Jacques J. A. Fournier¹, **Antoine Loiseau^{1,2}**

This work presents a new profiling attack that targets elliptic curves-based cryptographic implementations. This attack exploits leakages from the conditional swap operation used in implementations of the Montgomery Ladder used as a scalar multiplication method for calculating kP in constant time. Our attack requires only one attack trace. The attack is performed on the mbedTLS Curve25519 function embedding the coordinates-randomization countermeasure and which, as shown, does not prevent this type of attack. We introduce a new countermeasure that is efficient against the presented attack.

SCIENTIFIC COLLABORATIONS: ¹ Univ. Grenoble Alpes, CEA Leti, MINATEC Campus, F-38054, Grenoble (FR), ² Mines Saint-Etienne, Gardanne (FR)

Context and Challenges

This work studies the security of the implementation of Curve25519 elliptic curve cryptography against side channel attacks. This curve is mainly used for key exchange and signature protocols. We focus on the implementation provided by the widely used mbedTLS. This library is open source and can be easily used on general purpose microcontrollers. The idea of this attack is to challenge the function which uses the secret key, the conditional swap (CSWAP), and build a new countermeasure to secure this function.

Main Results

We performed a template attack to recover the secret key. It is a two phases attack: a profiling phase where we model the leakage with profiling traces and an attack phase where only one side channel trace is used to recover the secret key. To build a model of the leakage we considered three statistical methods: t-test, Principal Component analysis (PCA) and Linear Discriminant Analysis (LDA). We use electromagnetic emanation to perform the attack. Fig. 1 shows the result of the attack as a function of the modeling method. We reach a success rate of 95% with the LDA method for guessing a secret bit. We propose a new countermeasure to protect the CSWAP operation from leakages by adding random masks. We challenged our countermeasure against the same attack. Fig. 2 shows the results of the attack against the countermeasure: we only have a 50% success which is equivalent to a random guess. Details of this work are given in [1].

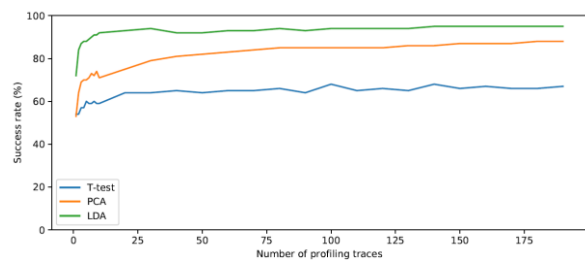


Fig. 1: Attack success rate without countermeasure.

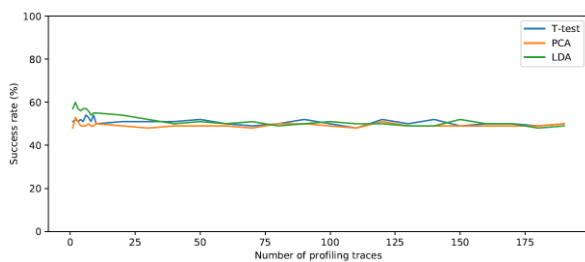


Fig. 2: Attack success rate with countermeasure

Perspectives

This work will be continued through the study of the impact of machine learning for side channel analysis against elliptic curve implementations and how to efficiently protect currently used cryptography against those new attacks.

RELATED PUBLICATIONS:

[1] Antoine Loiseau, Maxime Lecomte, Jacques J. A. Fournier, "Template Attacks against ECC: practical implementation against Curve25519", IEEE International Symposium on Hardware Oriented Security and Trust (HOST), 2020

Application of deep learning methods in side-channel attacks

RESEARCH TOPIC:

Deep Learning; Side-channel Analysis

AUTHORS:

Loïc Masure^{1,3}, Nicolas Belleville², Eleonora Cagli¹, Marie-Angela Cornélie¹, Damien Couroussé², Cécile Dumas¹, Laurent Maingault¹

Code polymorphism allows to automatically protect cryptographic primitives against side-channel attacks (SCA) involving layman adversaries. Yet, it has never been tested in view of the recent improvements in SCA, involving deep learning (DL). To this end, we evaluate two polymorphic implementations of AES. We show how to efficiently adapt DL models used in SCA to scale on traces 32 folds larger than what has been done in the literature. Our results show that the targeted implementations are broken within 20 queries with DL, whereas 100,000 queries would not be sufficient to succeed the attacks previously investigated. Hence, this work pushes towards the search of new polymorphic implementations secured against state-of-the-art attacks.

SCIENTIFIC COLLABORATIONS: ¹ Univ. Grenoble Alpes, CEA, LETI, CESTI, Grenoble, France, ² Univ. Grenoble Alpes, CEA, LIST, Grenoble, France, ³ Sorbonne Université, UPMC Univ Paris 06, POLSYS, UMR 7606, LIP6, Paris, France

Context and Challenges

Side-channel analysis (SCA) is a class of attacks against cryptographic primitives exploiting weaknesses of their physical implementation. During the execution, some sensitive computations are processed that depend on some chunk of a secret value. Hence, combining information about the latter one enables an attacker to (partially) retrieve the secret. Thus, implementations of secure cryptographic algorithms such as the Advanced Encryption Standard (AES) can then be inefficiently. The information on sensitive computations is usually gathered by acquiring time series of physical measurements such as the power consumption or the electromagnetic emanations measured on the target device (e.g. a smart card, micro-controller, CPU).

To protect against SCA, and due to the skyrocketing production of IoT, there is a need for the automated application of protections to improve products' resistance while keeping the performance overhead sufficiently low. In this context, the List-LIALP proposed a compiler toolchain to automatically apply a counter-measure called *code polymorphism* [1]. The working principle relies on the execution of many variants of the machine code of the protected software component, produced by a runtime code generator. Several works have shown the ability of code polymorphism to be effective in practice against standard attacker models in SCA.

Yet, other threat scenarios have not been investigated, especially regarding the recent emergence of deep learning (DL) in SCA evaluations. Such techniques can circumvent some counter-measures, somehow similar to code polymorphism. It is therefore of great interest to assess the security provided by some code polymorphism configurations against such more elaborated attackers.

On the other hand, until now the literature has only demonstrated the relevance of DL on *restricted* signals whose size does not exceed 5,000; which is small, e.g., regarding the size of the raw time series in the public datasets of software AES implementations. This requires to restrict the acquired traces to a tight window where the attacker is confident that the

relevant leakage occurs, which is not possible with code polymorphism.

Therefore, attacking a polymorphic implementation necessarily requires to deal with large-scale traces. This generally spans serious issues for machine learning problems known under the name of *curse of dimensionality*. That is why it currently remains an open question whether DL attacks can scale on larger traces, or whether it represents a technical issue that code polymorphism might leverage. Hence, both problems, namely evaluating code polymorphism and addressing large-scale traces SCA, are closely connected.

Main Results

We tackle the two problems presented so far by extending the security evaluation initially provided by the List-LIALP team on two polymorphic implementations of AES. We assess the security of the highest code polymorphism configuration they used, on same implementations.

We consider a wide spectrum of threat models, ranging from layman attacker to state-of-the-art techniques including DL. In particular, we propose to adapt the architectures used in the literature of DL attacks, in order to handle the technical challenge of large scale traces.

Our results show that simple attacks indeed fail due to the code polymorphism counter-measure, but that more elaborated scenarios lead to successful attacks. In a worst case scenario, our models are able to recover every secret key byte using less than 20 signal traces of dimensionality 160,000, which is 32 times higher than the traces used so far in the literature. This therefore illustrates that large scale traces are not necessarily a technical challenge for deep-learning based SCA.

Perspectives

Following our results, the List-LIALP team has developed an improved version of the code-polymorphism based implementation that is nowadays achieving better security requirements against our attacker models investigated through this work.

RELATED PUBLICATIONS:

[1] Nicolas Belleville, Damien Couroussé, Karine Heydemann, Henri-Pierre Charles: Automated Software Protection for the Masses Against Side-Channel Attacks. ACM Trans. Archit. Code Optim. 15(4): 47:1-47:27 (2019)

[2] Masure L. et al. (2020) Deep Learning Side-Channel Analysis on Large-Scale Traces. In: Chen L., Li N., Liang K., Schneider S. (eds) Computer Security – ESORICS 2020. ESORICS 2020. Lecture Notes in Computer Science, vol 12308. Springer, Cham. https://doi.org/10.1007/978-3-030-58951-6_22

Luring transferable adversarial perturbations for deep neural networks

RESEARCH TOPIC:

Artificial Intelligence, Neural Network, Security, Adversarial Machine Learning.

AUTHORS:

Rémi Bernhard, Pierre-Alain Moëllic

The integrity of deep neural network models is threatened by maliciously modified input samples, called *adversarial examples*, which fool a classifier. With this work, we pave the way towards a new approach to improve the robustness of a model against a specific threat: black-box transfer attacks. The main idea is to deceive an adversary into crafting a successful transferable adversarial perturbation by pasting a neural network to the target model that induces the *luring effect*.

SCIENTIFIC COLLABORATIONS: Ecole des Mines de Saint-Etienne, ISMIN, Gardanne (FR)

Context and Challenges

The massive development of Machine Learning-based systems and the deployment of models (more particularly neural networks) is restrained by major security issues that target the overall Machine Learning pipeline [1]. More particularly, integrity-based attacks at inference time, known as *adversarial examples*, are growing concerns with numerous attacks in both white-box and black-box paradigms. Black-box attacks are realistic threats that concern an adversary with no knowledge about the target model but with the ability to query it. Among the different strategies an attacker can exploit, one is related to the transferability property that explains why an adversarial example crafted from a model can also fool another model with a different architecture or characteristics (such as its bitwidth [2]). For this threat, the attacker trains or uses a model at his disposal that performs the same task as the target model. His goal is to craft adversarial examples on this *substitute* model and transfer them to the target one. An important challenge affects the deployment of a model in multiple systems with heterogeneous security contexts (e.g., an embedded model in several devices), since an attacker can leverage a model from a flawed system to target a critical one.

Main Results

The main result concerns the characterization of the *luring effect* that thwarts transferability between two models. This phenomenon, as conceptually novel, opens a new direction for adversarial research with deceiving approaches. We propose an implementation of the luring effect which fits any pre-trained model and does not require a label data set. An additional neural network is pasted to the target model and trained with a specific loss function that acts on the logits sequence order. We experimentally characterize the luring effect with classical public benchmarks to isolate it from potentially other effects and discuss its potentiality for black-box defense strategies and analyze the scalability on Ima-geNet (ILSVRC2012).

Perspectives

Our first results [3] show that the luring effect is a promising approach, even for adversarial examples detection purpose, that can be jointly used with other defense schemes. In order to better cover a wider attack surface (query-based black-box attacks and white-box settings with adversarial training).

RELATED PUBLICATIONS:

- [1] Moëllic, Pierre-Alain. "The dark side of neural networks: an advocacy for security in machine learning." J1-05. CESAR (2018).
- [2] Bernhard, Rémi; Pierre-Alain Moëllic, and Jean-Max Dutertre. "Impact of low-bitwidth quantization on the adversarial robustness for embedded neural networks." 2019 International Conference on Cyberworlds (CW). IEEE, 2019.
- [3] Bernhard, Rémi; Moëllic, Pierre-Alain; Dutertre, Jean-Max. "Luring Transferable Adversarial Perturbations for Deep Neural Networks". 2021 International Joint Conference on Neural Networks, IEEE IJCNN'21

On the extraction of randomness for PUFs and TRNGs

RESEARCH TOPIC:

Cybersecurity, hardware security, True Random Number Generators (TRNG), Physical Unclonable Function (PUF), resistive memory.

AUTHORS:

J. Marconot, D. Hély¹, T. Dalgaty, L. Grenouillet, **F. Pebay Peyroula**

In this work we investigate the static and dynamic entropy sources, for PUF and TRNG applications, in emerging memories and microelectronic processes. Our first main contribution is the demonstration of PUF and TRNG with enhanced robustness and lower integration cost. Secondly, we prove that more robust primitives require less post processing (in terms of challenge-response for PUF and unbiasing for TRNG). We also propose a small footprint architecture for a PUF challenge-response algorithm.

SCIENTIFIC COLLABORATIONS: ¹ Université Grenoble Alpes, G-INP ESISAR/LCIS, Valence (FR)

Context and Challenges

True Random Number Generators (TRNG) and Physical Unclonable Functions (PUF) are the cornerstone for the security of electronic devices; they are required for running cryptographic algorithms and are full part of encryption schemes. The security level of the system directly depends on the randomness of the bits generated by the TRNG or provided by the PUF. Furthermore, IoT chips are facing harsh constraints in terms of cost and power consumption. In order to be integrated into such chips, PUFs and TRNGs must offer an efficient tradeoff between cost and security. In this perspective, PUFs and TRNGs based on intrinsic chip features or components which have already been integrated into, such as emerging memories. While a static entropy source (each random number is unique to a chip and constant over time) is required for PUFs, a dynamic entropy source is needed for TRNGs. In this work we investigate both sources and we propose a PUF challenge-response mechanism

Main Results

We investigate several entropy sources (either static or dynamic) closely linked to the physics and processing of microelectronic devices. First we focus on OxRAM which is a class of storage memory, categorized as a resistive memory. In the paper [1] we analyze the effect of the memory supply voltage variations on the memory's characteristics. Based on the stochastic behavior of OxRAM bit cells, we demonstrate a random distribution of the bit set probability against the supply voltage. Random bit streams (up to 10^7 bits) were validated with the standardized statistical test suite. We demonstrate that the sub-voltage set probability is compliant with a dynamic entropy source for TRNG applications. Then we describe how the memory initialization mechanism (forming) can be stopped at the intermediate level and generates a static matrix of random bits. This random state is fixed at memory initialization and has been demonstrated to be stable over time and stable against read disturbs. This static entropy source is revealed as a good candidate for robust PUF applications. We also focus

on the SecureBall process [2] which basically creates random VIA at a given metal level. These VIA can be used as a static entropy source and interrogated by a subsequent digital circuit to provide a full PUF feature. The "forming PUF" and SecureBall are static entropy sources that provide robust digital randomness. However, before being used as a PUF, a subsequent digital circuitry is required to build a challenge-response mechanism. In the paper [3] we propose the SPN-DPUF architecture that relies on a digital static source of randomness (such as SecureBall or "forming PUF") and that involves cryptographic operation such as substitution and permutation networks (SPN). The input challenge is mixed with the static random number and, thanks to the SPN cryptography, generates a unique PUF response. This work presents different architectures which optimize the robustness-to-cost ratio.

Perspectives

We proposed an investigation of new entropy sources for PUF and TRNG applications. In order to enhance the robustness and lower the cost, we focused on intrinsic physical and process mechanisms of microelectronics. We also proposed a subsequent architecture in order to use the entropy sources in real world PUF applications. The perspectives are either to investigate other emerging memories to qualify new entropy sources and to further enhance the entropy sources we proposed in this work. More specifically for TRNG we will also work on the stochastic models and its physical parameters which is required by entropy sources certification standards. To reach the Technology Readiness Level 4, we will integrate the entropy sources with the digital circuitry required for PUF challenge-response and for TRNG post-processing in a dedicated ASIC design.

RELATED PUBLICATIONS:

[1] "Entropy source characterization in HfO2 RRAM for TRNG applications" F. Pebay, T. Dalgaty, presented at IEEE-DTIS 2020/04

[2] "Method of securing an integrated circuit during manufacturing", M. May, F. Pebay, US20180358310, 2018/12

[3] Journal: "Conception and Evaluation of Secure Circuits for Strong Digital PUF", J. Marconot, D. Hely, F. Pebay-Peyroula, SN Computer Science, 2020/09

An end-to-end approach to identify and exploit multi-fault injection vulnerabilities on microcontrollers

RESEARCH TOPIC:

Multiple fault injection, Fault Injection Simulation

AUTHORS:

Laurent Maingault, Marie-Laure Potet¹, **Vincent Werner**

Although multi-fault attacks are powerful in defeating sophisticated hardware and software countermeasures, detecting and exploiting multi-fault injection vulnerabilities remains a difficult problem, especially without any prior knowledge of the target. We propose a new end-to-end approach to identify and exploit multi-fault injection vulnerabilities. This tool-assisted methodology lets us configure a given fault injection equipment according to realistic multi-fault injection simulations based on target specific fault models. In addition, we show that we experimentally achieve with our method successful multi-fault attacks, up to 30 times faster than the characterization-based approach, on different microcontrollers and with various fault injection techniques.

SCIENTIFIC COLLABORATIONS: ¹ Univ. Grenoble Alpes, CNRS, VERIMAG, F-38000, Grenoble

Context and Challenges

With the evolution of fault attacks over the last decade, and especially multi-fault attacks, a state-of-the-art security evaluation must now consider multi-fault injection vulnerabilities. However, it is more difficult to detect and exploit multi-fault injection vulnerabilities as the fault injection parameter space increases exponentially with the number of fault injected. So as it is not possible to explore all the fault injection parameter space during time-constrained security evaluations, 1) the evaluator must identify the most promising attack paths that can compromise the target during the fault analysis, and 2) the evaluator must select the smallest subset of optimal fault injection parameters that maximize the number of effective faults.

Main Results

To this end, we propose a new end-to-end approach to identify and exploit multi-fault injection vulnerabilities on different microcontrollers, applications and fault injection techniques. This methodology is a first step in helping evaluators adapt to various situations and achieve multi-fault attacks without any prior knowledge of the target. With target specific fault models, we can successfully exploit multiple fault injection vulnerabilities 10 times faster than a characterization-based approach. Our methodology is a general framework that can be applied to different targets and fault injection techniques. Target specific fault models are generated using a characterization and a fault injection simulation performed simultaneously, and they can be reused to evaluate different security mechanisms of the target of evaluation, thereby reducing the initial time investment. In addition, the other original feature of this approach is that we can simulate multi-fault injections based on different fault models in order to explore even more attack paths. Regardless of the methodology, we also have successfully performed double laser fault injection through the same lens at different chip positions, to induce different instruction jumps with different lengths. The possibility to elaborate complex multi-fault attacks based on different fault models, opening up a new way

to find attack paths and question the dependability of generic software countermeasures alone to protect a device against increasingly powerful faults attacks.

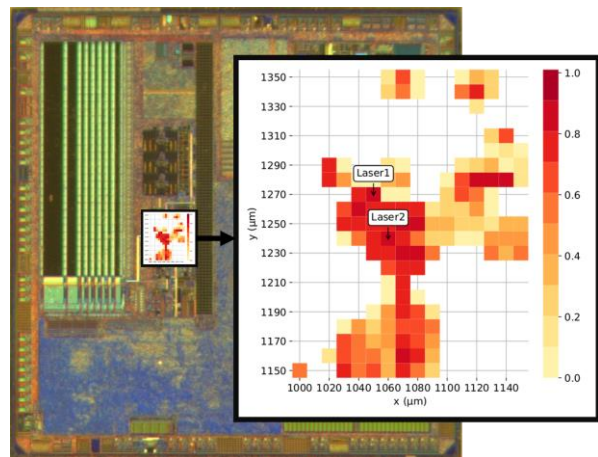


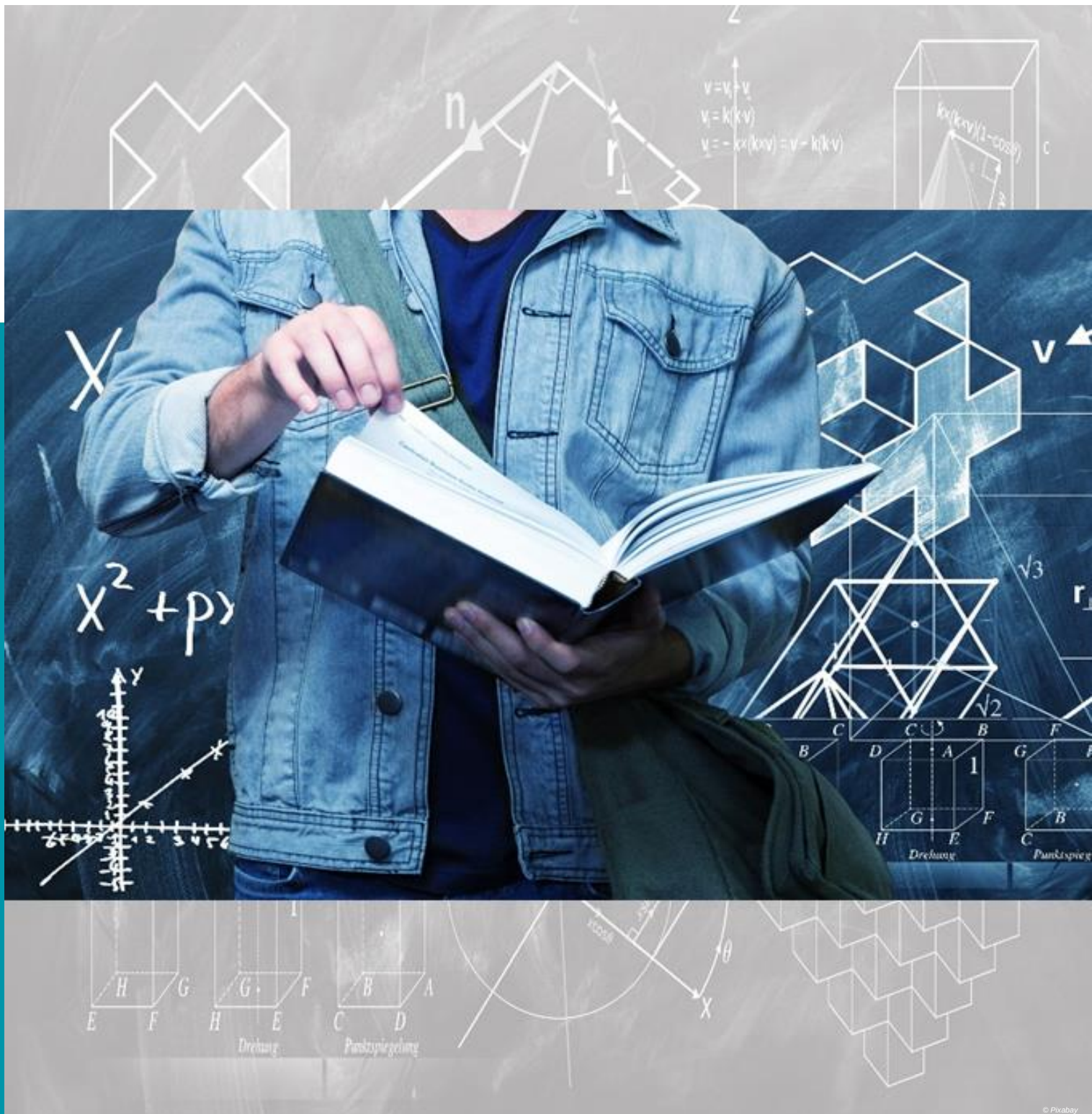
Fig. 1: A dual laser fault injection.

Perspectives

As future work, we will apply this methodology to other devices such as secure components or System-on-a-Chips; and to real-world applications or cryptographic implementations. To this end, we plan to explore different solutions to improve the fault coverage, for example, by extending our fault model database with more complex fault models. Finally, a last perspective would be to improve the fault characterization itself, either with new exploration strategies or new characterization test designs, as this step greatly affects the rest of the methodology.

RELATED PUBLICATIONS:

[1] Vincent Werner, Laurent Maingault, Marie-Laure Potet, "An End-to-End Approach for Multifault Attack Vulnerability Assessment", FDTC Conference (2020).



**O8****PHD DEGREES
AWARDED IN 2020**

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- **Simon BICAÏS**
- **Alexandre DEBARD**
- **David GIBUS**
- **Rawad MAKHOUL**
- **Johan MARCONOT**
- **Loïc MASURE**
- **Kossaila MEDRAR**
- **Moises NUÑEZ-OCHOA**
- **Florian WOLF**



MOHAMMED-REDA BEKKAR

HYBRID ANALOG-DIGITAL BEAMFORMING FOR INTERFERENCE REDUCTION IN NEW GENERATION CELLULAR NETWORKS

Beamforming is a signal processing method used in antenna networks, which favours given signal emission or reception directions by commanding different elements. In mobile phone networks, it is used to reduce the interference at the base station level. Its fully digital implementation meets limitations in terms of energetic consumption and cost as you increase the number of antennas. To solve these issues, hybrid analog-digital implementation can be used in order to decrease the number of radio-frequency (RF) chains and of analog-digital converters. In this implementation, the analog stage can be achieved using different types of devices (dephaser, amplifier/attenuator, variable impedances) and with a varying connectivity depending on the antenna network. Nevertheless, keeping a simple RF circuitry using dephasers only (phase-only) in order to regulate the weights of the analog beam former implies that the problem should become non-convex.

Current works on small cell networks show that the interference between base stations is a limiting factor of both coverage and flow. Moreover, in a full-digital implementation, the presence of strong blockers leads to the saturation or the desensitization of the analog-digital converters. This PhD thesis describes the study of beamforming with a hybrid

phase-only implementation as well as an algorithm for the calculation of beamforming matrices in order to reduce the interferences in reception at the small cell level.

The thesis proceeds with a description of the context and state-of-the-art, followed by a preliminary characterisation of the interference using an algebraic angle between useful signal vectors and interfering signal vectors, which enables to obtain a lower limit of the optimal beam-former performances in RSIB. We then suggested a sub-optimal hybrid phase-only beamforming solution which, in an infinite digital solving model, presents low losses compared to a variable weight in phase and module solution. Subsequently, we introduced a model of analog-digital converter in the reception chain, which enabled us to highlight the limits of the first approach as well as the entirely digital implementation with strong blockers. We finally developed an optimization algorithm of the analog stage, which relies on a semi-definite relaxation method. This algorithm show performances in RSIB and in sum-capacity which are close to those of the two-fold module and phase benchmark. In comparison, the solutions of the state-of-the-art, which use non-convex cost functions, remain dependant of the initialization and yield poorer performances.



ALEXANDRE DEBAR

ANALYSIS AND OPTIMIZATION OF SUPERDIRECTIVES COMPACT ANTENNA NETWORKS

The objective of this PhD thesis was to study and improve the superdirective antenna network technology. The latter was recently the center of many attentions in the literature due to the interesting functionalities that it can offer for future telecommunication applications. We studied this type of antennas using the spherical wave decomposition method, which enables the general study of gain or directivity limitations, while considering losses in the antenna. The classical theory of end-fire antenna networks was also investigated in the case of uniform inter-element space and independent excited element networks. This study presented an analytical evaluation of the efficiency and sensitivity to accuracy of excitation coefficients. Infinitesimal dipoles and Huygens sources were considered in a development scheme that linked network theory and spherical wave decomposition. Our contribution provided evidence for the limit in directivity of Huygens source end-fire networks as

well as a superior limit to the directivity of dipole networks when the inter-element distance points towards zero. Moreover, we demonstrated that the classical theory of antenna networks could also be used to extract excitation coefficients, which maximize gain rather than directivity when losses are accounted for in sources. An investigation was also carried out as a function of the size of antennas to highlight the most favourable conditions for using end-fire networks optimized for either supergain or superdirectivity. Subsequently, practical implementations of state-of-the-art superdirective antennas were proposed, which focused on Huygens sources and compact end-fire networks. A implementation architecture based on a parasitic element network was chosen in order to minimize the use of positive or negative resistors. This lead to the design and characterization of five prototypes aiming for maximum gain or directivity, for a limited antenna size, with two, three or four dipole end-fire networks.



SIMON BICAÏS

DESIGN OF THE PHYSICAL LAYER FOR FUTURE SUB-TERAHERTZ COMMUNICATION SYSTEMS

To deploy high-rate wireless services, future communication networks envisage the use of wide frequency bands. Still, the usual frequency bands in the sub-6 GHz spectrum are extremely limited and expensive. To expand its available spectrum, the forthcoming generation of mobile networks with 5G initiates the use of higher frequencies through the exploitation of millimeter-wave bands. In this search for frequency resources, the sub-THz spectrum from 90 to 300 GHz offers unprecedentedly large available bands, several tens of GHz. Wireless communications in sub-THz frequencies are therefore seen as a foremost solution to achieve Tbit/s data rates and meet the requirements of future wireless connectivity. Nevertheless, existing and mature wireless technologies cannot be directly transposed to the sub-THz bands as they do not consider the specific features of sub-THz communications. Additional research is hence required to design efficient communication systems adapted to the constraints of sub-THz frequencies. Some of the major technological challenges brought by using high carrier frequencies and large bandwidths include: the performance limitations caused by the strong phase impairments of high-frequency oscillators; and the problem of high sampling rates required by the analog-to-digital conversion. In this thesis, the conducted research focuses on the development of the physical layer for sub-THz communication systems and attempts to overcome these technological barriers. Our objective is twofold: to increase the communication data rate and to relax the constraints on radio-frequency architectures. To do so, our approach consists in jointly designing signal processing for the analog and digital domains.

The two main contributions of this work are: the optimization of coherent transceivers for strong phase noise

channels; and the proposal of dedicated communication systems with non-coherent and high-rate architectures. First, we have proposed optimized transmission schemes for strong phase noise channels including: the modulation, the demodulation, and the link adaptation. The proposed solutions achieve high spectral efficiency communications with relaxed constraints on radio-frequency oscillators. Our results show that the use of optimized transmission schemes greatly contributes to mitigate the impact of phase noise on coherent transceivers. Consequently, our work describes valuable technical solutions to the development of physical layers with high spectral efficiency for the sub-THz spectrum. Second, we have also targeted low-complexity physical layers readily implementable in sub-THz frequencies. We have studied the design of communication systems specifically dedicated to the sub-THz bands using non-coherent architectures. In order to implement high-rate communications with non-coherent architectures, we have considered the use of spatial multiplexing and wide frequency bands. Our work on spatial multiplexing in sub-THz frequencies demonstrates that high-rate communications can be implemented with low complexity and low power architectures using multi-antenna systems and energy detection receivers. Besides, the use of wide bands strongly constrains the analog-to-digital conversion. In order to reduce the required sampling frequencies of converters and to simplify practical implementations, we have proposed a new receiver for high-rate impulse radio systems. We have shown that the proposed receiver architecture, using parallel projections of the received signal in the analog domain, leads to near-optimal performance with significantly reduced sampling frequencies.



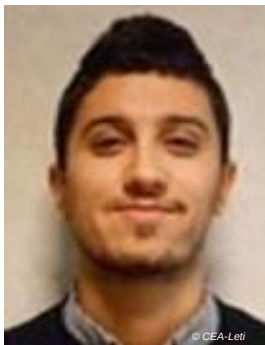
DAVID GIBUS

WIDE-FREQUENCY-BAND VIBRATION ENERGY HARVESTING SYSTEMS IN INDUSTRIAL ENVIRONMENTS

Energy harvested from vibrations may power wireless communicating sensors in places where batteries cannot be used or replaced. In this context, piezoelectric resonating structures enable the harvesting of significant electrical power. However, these performances can only be reached on a very limited frequency band (typically a few percent of the resonant frequency of the harvester). In response to this problem, electrical techniques capable of adjusting the resonant frequency of piezoelectric harvesters have been developed in the past few years. To reach an interesting functioning frequency band thanks to such techniques, piezoelectric harvesters must exhibit a very strong overall electromechanical coupling.

This PhD thesis focuses on the modelling, design and characterization of very strongly coupled piezoelectric energy harvesters for wide-band vibration energy harvesting. We showed that the most relevant configuration to optimize the overall electromechanical coupling coefficient is a semi-embedded cantilever bearing a long mobile mass at its free extremity. We proposed and exploited a dedicated analytical model in order to demonstrate the relevance of the lengthy mass. This model enables in particular to study the electromechanical aspects in a non-dimensional manner and to conclude about the

design and dimensioning of very strongly coupled cantilevers. On another hand, this work shows that for piezoelectric materials commonly used in energy harvesting, the overall electromechanical coupling coefficient of a cantilever increases as the lateral deformations decrease. This effect can be obtained by maximizing the width of the cantilever (plan deformation state) or by functionalizing it with lateral bars. In order to validate the relevance of a long mobile mass experimentally, a very strongly coupled single crystal material (PMN-PT) based harvester was designed. Two ceramic (PZT) based harvesters were also assembled in order to show the influence of the cantilever width on the overall electromechanical coupling coefficient. The harvesters tested with resistive loads in vibrating condition suggest major potential in terms of frequency adjustment (over 10% of their resonance frequency). In the frame of this research work, one of our prototypes was tested along with a dedicated electrical circuit for automatically adjusting the frequency over a large band (over 17% of the resonant frequency). Finally, a non-linear phenomenological model was presented which accounts for the influence of mechanical and dielectric losses on the behaviour and performances (harvested power and frequency range) of harvesters



RAWAD MAKHOUL

GAN BASED VHF CONVERTERS: DESIGN, CHALLENGES AND PERSPECTIVES

The thesis focuses on the study and design of GaN based resonant converters operating in the VHF frequency range (30MHz-300MHz). A particular attention was paid to a single-transistor VHF inverter topology: the class $\phi 2$ inverter. The thesis reports a study of the sensitivity and efficiency of class $\phi 2$ and two novel self-oscillating structures derived from the class $\phi 2$ inverter were introduced. Finally, we demonstrated the use of these self-oscillating structures in the design of VHF DC / DC converters.



JOHAN MARCONOT

NON-CLONABLE PHYSICAL FUNCTION FOR THE LIFECYCLE SECURITY OF CYBER PHYSICAL OBJECTS

This PhD thesis deals with the design of security solutions for essential goods and functionalities of connected objects throughout their lifecycle. The latter cycle is composed of multiple interactions where each actor intervenes and requires access to the object in order to carry out the specific tasks that it was allocated. This process exposes sensitive or proprietary elements to threats, which come along with a confidence loss. Proposed solutions must ensure that a given actor can strictly only access the authorized parts that it requires. In addition to this security need, they must also comply with the resource and performance constraints. Our research brings two main

contributions: it formalises the requirements for lifecycle security of cyber physical objects and proposes a new extraction model for digital PUF whose logical scheme is based on so-called SPN networks. We identified the optimal configurations for this model, which offer a compromise between the area occupied by the circuit, the frequency and security metrics. This study provides solid background to design a strong digital PUF, which is accounted for from the beginning of the lifecycle and ensures the required security properties and performance level. It hence answers the need to secure the lifecycle prior to deployment and usage phases, while meeting cost constraints.



LOÏC MASURE

TOWARDS A BETTER UNDERSTANDING OF DEEP LEARNING FOR SIDE-CHANNEL ATTACKS

Recent progress in deep learning have impacted the landscape of side-channel attacks in embedded security. Noticeably, their “blackbox” character prevents us from identifying the implicitly exploited flows in the implementation. Additionally, it remains difficult to analyse the results of such attacks on the security level of the target implementation. For all these reasons, the scientific community remains relatively sceptical towards the relevance of these techniques in the frame of security evaluations.

This PhD thesis shades a new light and offers a better comprehension of deep learning in this context. We showed how the learning of such estimators can be analysed through the prism of a security evaluation, so as to estimate *a priori* the complexity of an attack based on neural networks

without having to actually carry it out. We also observed on simulations that these models, which were trained without prior knowledge of countermeasures, could reach the theoretical security limits foreseen by the literature, validating (or not) the relevance of certain countermeasures, such as secret sharing or dissimulation against neural network.

Finally, we explained how to exploit a trained network in order to carry out an efficient characterisation of information leaks in observations, while in the presence of countermeasures which would make other classical techniques inefficient. This enables to better understand the information leaks exploited by the network and to refine the evaluator’s or developer’s diagnostic, in order to suggest suitable corrections.



KOSSAILA MEDRAR

TERAHERTZ FREQUENCY AND MILLIMETRE WAVE HIGH DIRECTIVITY INTEGRATED ANTENNAS

The emergence of applications in the millimetre wavelength range, such as high rate point to point communications, 5G and 6G networks, high definition television, automotive radars or imaging, have promoted the study of high gain antenna solutions, in particular efficient, cost-saving, compact, integrated antennas.

In this context, this PhD thesis presents a new antenna architecture including a network of transmitters and a focal source, both printed on a unique stack of printed circuit boards (PCB). This architecture enables the development of an efficient, monolithic, high gain, millimetric front-end module. It is compatible with low cost PCB technologies used for mass production and relieves us of technical and cost constraints related to antenna assembly. The first focus of the thesis is the definition, analytical modelling and analysis of the architecture in terms of typical performances. We then pursued to validate experimentally the antenna architecture and its model. In order to do so, four V-Band (60 GHz) prototypes were developed and characterized. Their size was 40 x 40 x 13.2 mm³ and they were designed with various polarisations and phase quantification levels for an exhaustive analysis of their performances. Measurements showed gains between 17.8 and 22.1 dBi at 60 GHz, opening efficiencies from 15 to 35% and -3 dB bandwidths going from 14 to 18%. These results convincingly paved the way towards adapting this antenna architecture to superior millimeter bands.

So we moved on to develop integrated transmitarrays on dielectric substrates

for D-bands (140 GHz) and H-band (300 GHz). We built elementary cells composed of a resonator designed in the centre of two orthogonal polarizing grids, which formed a Fabry-Perot cavity. These cells showed excellent performances both in D-band and in H-band, in terms of bandwidth (about 50% at -1 dB for most cells), of insertion losses (0.5 dB on average) and of phase quantification (3 bits). They also exhibited a strong robustness in face of fabrication dispersion related to both substrate and etching, compared to elementary cells traditionally used in the literature to design transmitarrays. Based on these cells, prototypes were designed, fabricated and characterized: they were assembled on a single low cost PCB stack with 5 metal layers, of size 20 x 20 x 4.52 mm³. In D-band, a gain of approximately 20 dBi with an opening efficiency close to 29% and a -3 dB bandwidth better than 17.4% were measured. In H-band, different size prototypes showed gains between 20.5 and 23.1 dBi with opening efficiencies from 12 to 17.6% and -3 dB bandwidths going from 17 to 26.3%.

The monolithic architecture proposed for the antenna was thus validated and we demonstrated its relevance for designing highly integrated, compact, efficient, high gain (> 20 dBi) and large bandwidth millimeter and sub-millimeter front-end modules. Moreover, this architecture is compatible with low cost and mass production technologies. As a result, this topology of antennas represents a promising solution for very high rate, very high frequency wireless communication applications.



MOISES NUNEZ OCHOA

ADAPTIVE PROTOCOLS FOR SELF-DEPLOYED WIRELESS SENSOR NETWORKS IN HIGHLY CONSTRAINED ENVIRONMENTS

Wireless Sensor Networks (WSNs) frequently deployed in harsh environments need to be autonomous with optimized lifetime, reliable connectivity, and robust to interference. The objective of this thesis is to make WSN deployments easier in harsh environments by self-deploying and adapting these networks to the context. In this thesis, we started by comparing LPWAN technologies and we focused on LoRa offering several degrees of freedom on its communication parameters and making a good candidate for adaptive networks. Five contributions have been achieved throughout this work, as follows.

In the first contribution, we analytically investigated the energy efficiency for different network topologies to improve energy consumption by adapting LoRa communication parameters in star and mesh topologies. The impact on energy consumption of the network density and network coverage is also investigated.

The second contribution is the development of a LoRa network simulator based on WSNNet, an event-driven simulator for large scale WSN. It implements the required communication protocol layers and simulates the network behavior with a high level of accuracy. In that sense, we integrated new features of transceivers such as LoRa Semtech and reconfiguration functionalities in the WSNNet simulator.

In the third contribution, we investigated performance and limitations of LoRa networks by taking into account only the Physical layer and by including the protocol Adaptive Data Rate (ADR) proposed by LoRaWAN. First, we investigated LoRa deployments of nodes with homogeneous parameters. This investigation allows us to obtain the performance of each spreading factor individually to calculate their capacity for each network size assuring a given packet delivery ratio. Second, we investigated LoRa deployments of nodes with heterogeneous parameters.

This investigation explores more spreading factor allocation protocols to improve network performance by exploiting LoRa physical layer features such as spreading factor quasi-orthogonality. Finally, we investigated in detail performance analysis of the spreading factor allocation protocol based on the link budget that corresponds to ADR of the LoRaWAN under steady-state assumptions. This analysis allows us to understand the impact of allocating the spreading factor using ADR on the network performance in several aspects: (i) network deployment, (ii) environment, (iii) multiple channels, and (iv) bidirectional communications.

In the fourth contribution, we propose enhancements by allocating spreading factors optimally to improve reliability and fairness taking into account deployment constraints and exploiting LoRa properties. The objective is to avoid the strong impact of the network deployment on network performance. We proposed several strategies to deploy LoRa networks by adapting the parameter spreading factor at the initialization when all nodes join the network. We also proposed improvements to the classical spreading factor allocation, the ADR mechanism that depends on the network deployment impacting the network performance. They improve the network capacity and transmission quality in terms of packet delivery ratio.

In the last contribution, we proposed a strategy to self-deploy LoRa networks by adapting the spreading factor parameter over time when nodes join progressively the network. The strategy is based on the link, network, and distribution metrics of previous joined end-devices to set up the configuration of joining end-devices to self-deploy LoRa networks according to the context. We can use current network performance metrics to configure an end-device joining the network.



FLORIAN WOLF (AWARD WINNING STUDENT)

MULTI-CHANNEL RANGING SYSTEM FOR THE LOCALIZATION OF WIRELESS CONNECTED OBJECTS IN LOW POWER WIDE AREA NETWORKS: FROM MODELING TO FIELD TRIALS

The Internet of Things (IoT) is an enabler to new applications, such as smart metering and environmental monitoring, intended to address current and future societal and ecological challenges. Things, possibly mobile or in distant locations, require wireless connectivity for data collection and remote control. Low Power Wide Area (LPWA) networks provide city-scale long-range, narrowband radio transmissions respecting the energy constraints of battery-powered low-cost objects. Being capable to localize these objects will add value to their data, enables tracking applications and is therefore a demanded and recent research topic. Precise and accurate radio signal delay based positioning without integrating additional hardware but taking advantage of intrinsic wireless communication signals is appealing in terms of device complexity, cost and energy consumption. However, radio localization within LPWA networks is challenging due to narrowband transmissions, resulting in a lack of delay precision as well as due to radio propagation channels, which degrade the accuracy of location estimates. This work addresses both challenges by investigating a multi-channel ranging system for LPWA networks. Coherently combining multiple sequentially transmitted narrowband signals on different radio channels

improves delay estimation precision and allows resolving multipath channels for refined positioning accuracy. This scheme, based on instantaneous narrowband signals, conserves the LPWA long-range feature and is hence compatible with LPWA networks. A detailed signal model considering hardware imperfections as well as the required protocol exchanges for time, frequency and phase synchronization is developed. Based on this model, the requirements on radio transceiver architectures regarding the necessary phase coherence for multi-channel ranging are discussed. Lower bounds on the ranging precision are derived for both, free-space and multipath propagation channels, illustrating the improved precision compared to narrowband single channel ranging. Numerical simulations of radio signals for the two-way multi-channel ranging protocol illustrate that the performance of developed range estimators attains the theoretical precision bound and pave the way towards implementation. A flexible Software Defined Radio (SDR) based demonstrator is implemented to validate simulation results. Field trials in real urban outdoor environments are in accordance with simulation results and prove how scalable multi-channel ranging, in combination with advanced signal processing methods, will be an enabler towards precise and accurate localization in LPWA networks.

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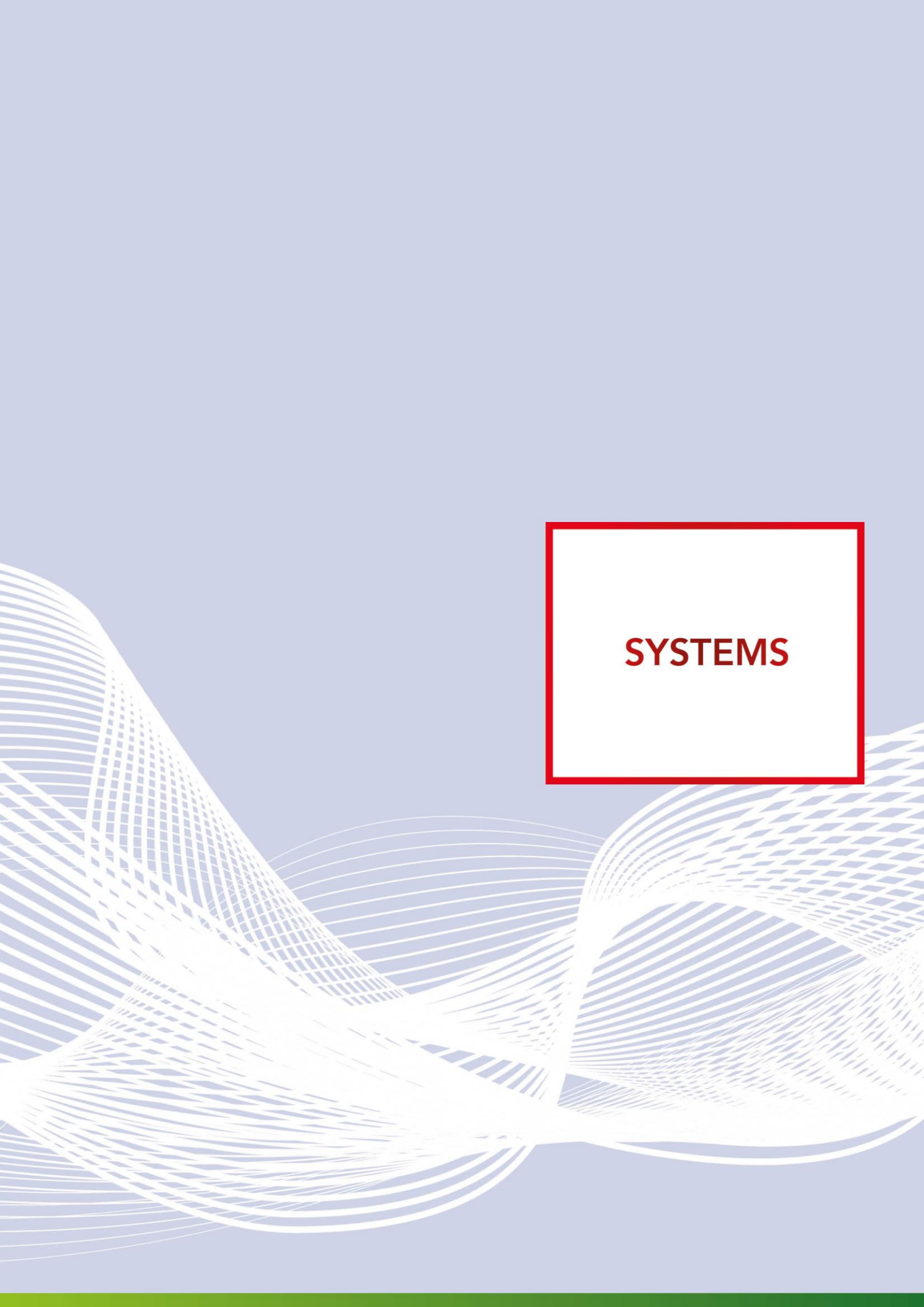
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The background is a solid light blue color. In the lower half, there are several overlapping, wavy white lines that create a sense of motion and depth. These lines are composed of many thin, parallel strokes that curve and flow across the page. In the upper right quadrant, there is a white square with a thin red border. Inside this square, the word "SYSTEMS" is written in a bold, red, sans-serif font.

SYSTEMS

2020

SCIENTIFIC REPORT

SYSTEMS

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