leti
cea tech

TECHNOLOGY
RESEARCH
INSTITUTE

SYSTEMS

2021

SCIENTIFIC
REPORT

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 1,870, a portfolio of 3,200 patents, 11,000 sq. meters cleanrooms, and a rigorous IP policy, CEA-Leti has launched 71 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

IS0 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

1,870
researchers

3,200 patents
in portfolio

11,000
sq. meters of cleanrooms
100-200-300 mm wafers

71
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 industrial anchoring and aims to provide a global and valuable "system perspective" on technological trends, based on microelectronics technologies issued from Leti's cleanrooms.

Our expertise relies on four major pillars which are (i) wireless communication technologies, (ii) innovative sensor-system design and integration, (iii) power management and electronics for energy and (iv) security solutions for electronic systems and components. Our 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, the System Division is particularly attractive for industrial partners who are facing the challenges of the Internet of Things (IoT) associated with artificial intelligence at the system edge (edge AI), 5G and beyond-5G communications, as well as cybersecurity. Our partners range from SMEs to major international companies, which are looking for a high level of technical expertise and a strong project management experience in a business-compatible environment.

As a result, our research and innovation activities span a wide panel of applications at the interface between the physical and the digital world, 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 centres, virtual reality, e-health. In recent years, environmental consciousness and eco-innovation have gained in importance up to the point where they now pave our daily practices.

Finally, the System Division 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 vision of forthcoming technical, societal and environmental challenges for the digital world.

SYSTEMS

FOREWORD

Régis GUILLEMAUD
Head of the Systems Division

The context of 2021 was peculiar in very many ways. In the wake of the recessing pandemic and the sudden – long-awaited – rebound of the industrial sector, the industry of microelectronics has faced one of its greatest challenges of the past decades: the worldwide shortage of components has precipitated profound and probably persistent transformations of the Deep Tech industry. For Leti's System Division and its industrial partners, this was an opportunity to reinforce collaborative actions towards Europe's sovereignty in critical, technology-dependent, areas. In this context, 2021 both comforted us in domains where we already were broadly recognized and encouraged the launch of new strategic research routes with ambitious technological targets in all our domains of expertise.

In this report, all the teams from Leti's System Division are pleased to present you a selection of their best scientific achievements of 2021. This scientific report is divided into 6 chapters presenting about 60 significant scientific contributions in our main areas of research and innovation.

Substantiating the benefits of a continuous and significant expansion over the past few years, 2021 has seen the maturation and reinforced international recognition of our cybersecurity laboratories. Our field of action spans a wide range of top priority subjects for our industrial and academic partners, as well as governmental institutions, regarding the protection of hardware against physical attacks and the evaluation of electronic system security against advanced adversarial attacks. Chapter 1 presents some of our latest state-of-the-art results in X-ray single bit attack detection, side-channel analysis, isogeny-based cryptographic implementations resistant to fault, Hardware-In-the-Loop (HiL) platform for cybersecurity awareness & training, to name a few.

Emmanuelle PAULIAC-VAUJOUR
Scientific Director of the Systems Division

In the field of telecommunications, year-after-year Leti's System Division reaffirms its leading position in designing, developing and evaluating innovative technologies for the forthcoming generations of beyond-5G wireless connectivity. A wide variety of recently published work is presented here, covering radio and network architectures for sustainable beyond-5G connectivity, compact and integrated technologies for sub-THz (millimeter-wave) communications, novel high-performance antenna designs and transmitarrays, integrated circuit and design for RF, power amplifier modules, etc. Not withstanding disruptive and application-centered solutions for radio localization and industrial IoT: in addition to V2X communications and indoor-outdoor localisation, this report sees an interesting inflexion towards GNSS and LPWA related technologies, modulation and coding, or improved localization continuity through reconfigurable intelligent surfaces (chapters 2 and 3).

SYSTEMS

FOREWORD

Finally, chapters 4 and 5 focus on the subjects of **energy** and **human-digital interactions**, two domains which also address important challenges of the digital world in relationship with societal and environmental transitions. On the 'energy' side, while continuous emphasis is put on power electronics and energy conversion and storage (piezoelectric DC-DC converters, GaN technologies, online state estimation for batteries and fuel cells), our teams also published remarkable advances in the alternative fields of energy harvesting (electronic architectures for vibrational harvesting) and both electrodynamic and acoustic wireless power transfer. Concomitantly, with a view to increase the seamless character of interfaces between the living and the digital worlds – in an environment-conscious manner – we conclude by reporting studies of purposeful and system-driven sensing (for health and environment monitoring) and learning (affective computing, anomaly detection, deep learning for temporal multidimensional signals with applications in mental state monitoring, dextrous manipulation, dysgraphia detection or transport).

We would like to thank our industrial partners, institutional fellows and academic collaborators, who have worked closely with us in 2021 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 Systems 2021 Scientific Report inspiration for your future developments and research.

CONTENTS

KEY FIGURES

© CEA-Leti

220 permanent staff

58 PhD students and postdocs

38 temporary employees

© Pixabay

40 M€ budget

73 % external funding

69 direct industrial partners

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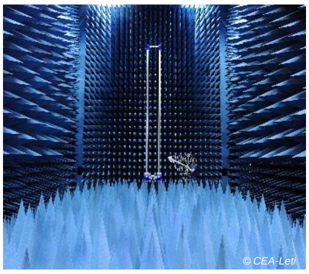
62 patents granted in 2021

595 patents in portfolios

48 book chapters and journals

123 conference communications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3 anechoic chambers

1 connectivity platform

1 IT Security Evaluation Facility

1 electronic test platform

SCIENTIFIC ACTIVITY

Publications

171 scientific communications in 2021, including 149 scientific publications in 46 top journals and over 100 international conferences. Non-exhaustively:

IEEE journals (ex. Access, Communication Letters / Magazine, IoT Journal, Open Journal of Antennas and Propagation, Wireless Communications Letters, Transactions on: Green Communications and Networking, Information Theory, Intelligent Transportation Systems, Magnetics, Power Electronics, Signal Processing, Wireless Communications, Antennas and Propagation), Applied Physics Letters, Quantum Information & Computation, Review of Scientific Instruments, Smart Materials and Structures, Earth Planet & Space, World Electric Vehicle, MDPI journals, ACM journals, Ultrasonics, ACM conferences, IEEE conferences (IEDM, RFIC, TAP, VTC, PowerMEMS, PIMRC, SPAWC, ANTEM, APS-URSI, DFT, ICC, IoTaIS, ISCAS, ISIT, ISTC, LASCAS, NEWCAS, etc.), International Conference on Affective Computing and Intelligent Interaction (ACIIW), Analog VLSI conference, IFAC Symposium on System Identification (SYSID), European Conference on Power Electronics and Applications (EPE-ECCE), European Microwave Week (EuMW) / Conference (EuMC), European Microwave Integrated Circuits Conference (EuMIC), International Conference on Artificial Neural Networks, International Conference on Predictive Maintenance and Machine Learning, European Solid State Circuits Conference (ESSCIRC), European Conference on Antennas and Propagation (EuCAP), European Conference on Networks and Communications (EuCNC) & 6G Summit, Smart Card Research and Advanced Application Conference (CARDIS), C&ESAR @ European Cyber Week (ECW), International Workshop on Constructive Side-Channel Analysis and Secure Design (COSADE), Design Automation and Test in Europe (DATE), Euromico Conference on Digital System Design (DSD), GLOBECOM, etc.

Prize and awards

F. Munoz, S. Bories, M. Caillet, JF. Pintos, “Anechoic Chamber Reflectivity Analyses below its minimal frequency using the Matrix Pencil Method”, Best Innovative Paper Award at IEEE CAMA conference 2021.

E. Calvanese Strinati, N. Cassiau and co-authors, “6G in the Sky: On-demand intelligence at the edge of 3D networks”, ETRI journals 2021 Best Paper Award.

F. Frassati and co-authors, “Beamforming with AlN-based bimorph piezoelectric micromachined ultrasonic transducers”, Best Paper Award at SSI conference 2021.

Experts

6 CEA Fellows, 23 Senior Experts and 25 Experts, among which 15 Research Directors and professors (HDR).

Scientific committees

Reviewing & Technical Program Committees and jury or board members of: National Research Agency (ANR), IEEE ICECS, IEEE NEWCAS, IEEE ESSCIRC, IEEE RFIC, IEEE IMS, IEEE VTC Spring/Fall, EuCAP, IPIN, CHES, GDR-ISIS, RISC-V Week, AMUSEC, SSI, MDPI journals, AsiaCrypt, JCEN, Swarm ESL (Expert Support Laboratories) and DISC (Data, Innovation and Science Cluster) at the European Spatial Agency (ESA), MIAI Grenoble Alpes, MSTIC pole at UGA, EuRAAP “propagation” Working Group, ECSO “basic and disruptive technologies” Working Group.

Conference and Workshop organization

Workshop or Special Session co-organizers & chairpersons at: EuCNC & 6G Summit, IEEE RFIC, IEEE IMS, EuMW, ESSCIRC, ISSCC, GDR-ISIS, IEEE PIMRC & ICT, IEEE SPAWC, EuCAP, ISAP, ICASSP, GDR-SoC2, JNRSE.

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 Tech University (Japan), University of Florida (USA), Université Catholique de Louvain UCL (Belgium), Arizona State University (USA), MIT (USA), EPFL (Switzerland), University of Granada (Spain).

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01 SECURITY OF EMBEDDED SYSTEMS

- Hardware and physical attacks
- Security evaluation against advanced advsersarial attacks
- Tools for analyzing and preventing security
- Security and deployment technologies for the Internet of Things (IoT)
- Security and cryptographic primitives
- Security of microarchitectures
- Learning and deep neural networks (DNN) for security
- Data security management

Laboratory X-rays operando single bit attacks on flash memory cells

RESEARCH TOPIC:
Cybersecurity, smart card, security evaluation, Xrays

AUTHORS:
L.Maingault, M. Sulmont, L.Salvo[1], J. Clediere, P. Lhuissier[1], E.Beliard, J.L. Rainard**, S. Anceau**

The need to increase the level of digital security standards requires a sustained research effort on new means of perturbations likely to disturb the processing of integrated circuits. X-rays modification is a powerful semi-permanent and reversible fault injection technique with a high spatial accuracy, which allows an adversary to modify efficiently secret data from an electronic device. Experimental results demonstrate that faulted results on single bit with a synchrotron and on several bits with X-rays laboratory source can be injected in code and data with corrupting flash memory, even with a spot of less than 10 µm in diameter for the X-rays laboratory source.

SCIENTIFIC COLLABORATIONS: [1] Université Grenoble Alpes, CNRS UMR5266, Grenoble INP, Laboratoire SIMaP, 38000 Grenoble, France

Context and Challenges

Laser light can be synchronized and focused in order to induce transient and persistent faults in integrated circuits. During the security-evaluation practice, these attacks may give powerful results. In order to further investigate the wavelength spectrum of perturbations, we have study the effects of ionizing radiation like X-rays.

Compare to fault perturbations induced in a circuit by a laser light, where the spot size is few microns, X-rays beam allows to obtain a spot size down to 50 nm using synchrotron source and down to 400 nm in laboratory nano sources. It is physically possible to modify one single bit transistor with the Xrays and the limitation is only coming from the way used to focus the beam. Security countermeasures can be deactivated in the flash memory or in the registers of the glue logic.

The second advantage of X-rays is their potential to penetrate deeply through materials and induced semi-permanent faults on flash memory cells and NMOS transistors. This semi-permanent perturbation of the X-rays is reversible with a simple heat treatment and no physical modification is visible after the X-rays perturbations.

Main Results and Perspectives

X-rays interaction with electronic circuits has been analyzed, but its use for security evaluation has been mainly restricted to die and package imaging before the single bit semi-permanent fault injections performed at the European synchrotron facility [1] and in XRays laboratory equipment [2].

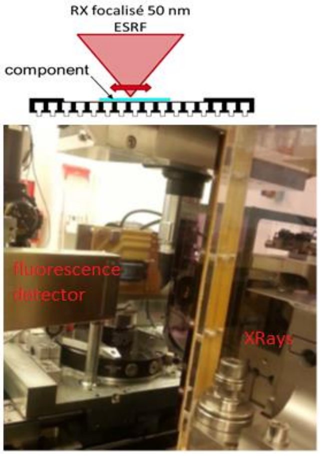


Fig. 1: Chip at synchrotron Xray focal point

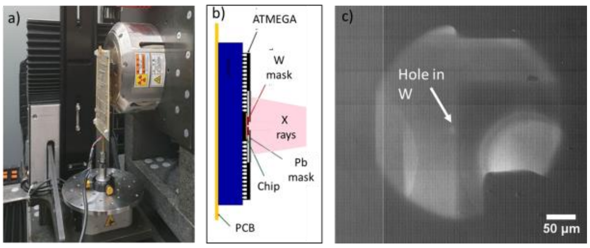


Fig. 2: X-ray source laboratory experiment

RELATED PUBLICATIONS:
[1] S. Anceau, P. Bleuet, J. Clédière, L. Maingault, JL. Rainard, R. Tucoulou, “Nanofocused X-ray Beam To Reprogram Secure Circuits”, CHES, 2017.
[2] L. Maingault, S. Anceau, M. Sulmont, L. Salvo, J. Clediere, P. Lhuissier, E. Beliard, J.L. Rainard, “Laboratory X-rays operando single bit attacks on flash memory cells”, CARDIS, 2021.
[3] S. Anceau, “Modification non-invasive de circuits intégrés par rayons X (MITIX)“, STAFEED, 2021.

Wavelet frame estimation applied to side-channel analysis

RESEARCH TOPIC:

Security evaluation, cryptographic implementations, wavelet

AUTHORS:

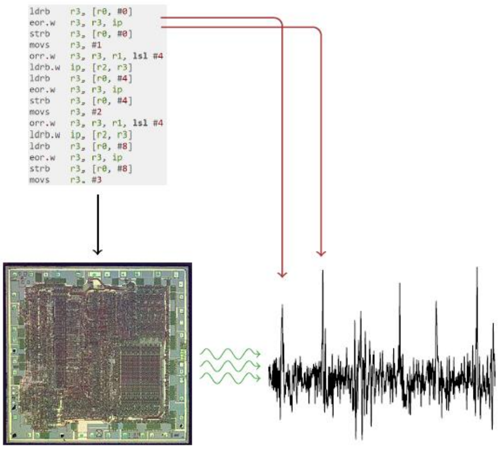
G. Destouet, C. Dumas, V. Perrier[1], **A. Frassati**

In the context of the security evaluation of cryptographic implementations onto electronic devices, side-channel attacks represent a relevant threat. They exploit physical leakage released by the device to gather information about secrets they store, e.g. cryptographic keys. In order to improve the treatment of this gathered information, we propose a wavelet-based method. A maximum likelihood approach is proposed for the inference of a frame of Generalized Morse Wavelets; this way we abstract the limitation for some experiments to choose between many wavelet families, while answering the need to embed prior information on the time-frequency properties of signals. This method is tested on the retrieval of sensitive information in side-channel analysis.

SCIENTIFIC COLLABORATIONS: [1] Univ. Grenoble Alpes, CNRS, Grenoble INP, LJK

Context and Challenges

During the execution of a cryptographic algorithm onto the targeted device, sensitive variables are processed. They depend on some chunks of a secret value (e.g. a key) and optionally on piece of public data (e.g. a plaintext). When performing a side-channel attack, an attacker can measure the physical leakage (e.g. time, power consumption, electromagnetic emanation), then retrieve information about a sensitive variable. This measured information is gathered into signals whose dimension and complexity are big and need to be reduced. To that end, a method is proposed by inferring a wavelet-based subspace containing most of the pertinent information.



```
ldrb    r3, [r0, #0]
eor.w   r3, r3, ip
strb    r3, [r0, #0]
movs    r3, #1
orr.w   r3, r3, r1, lsl #4
ldrb.w  ip, [r2, r3]
ldrb    r3, [r0, #4]
eor.w   r3, r3, ip
strb    r3, [r0, #4]
movs    r3, #2
orr.w   r3, r3, r1, lsl #4
ldrb.w  ip, [r2, r3]
ldrb    r3, [r0, #8]
eor.w   r3, r3, ip
strb    r3, [r0, #8]
movs    r3. #3
```

Fig. 1: Information leaks in side-channel attack

Main Results

Building on the theory of wavelets and statistical theory, a maximum likelihood approach has been proposed to automatically infer a frame of wavelets. In particular, the superfamily of Generalized Morse Wavelets has been chosen to build frames. We aim with this work at facilitating the use of wavelet frames in larger statistical models with optimization methods based on gradient descent.

This method is then applied to perform information retrieval in side-channel signals: the wavelets-based obtained model is used as a dimension reduction technique to facilitate side-channels and compared with other methods of compression.

In order to counter side-channel attacks, developers implement random clock jitters in order to desynchronize signals and perturb their statistical analysis. So first, a simple wavelet-based method is proposed to re-synchronize the signals. Then, the reduction technique is applied and a Template Attack Is performed, which efficiency is better than when other reduction techniques are used.

Perspectives

The obtained results are promising but the optimization by gradient descent need to be improved in order to reduce the calculation which remains expensive in terms of computation.

RELATED PUBLICATIONS:

[1] G. Destouet, C. Dumas, A. Frassati, V. Perrier, “Generalized Morse Wavelet Frame Estimation Applied to Side-Channel Analysis”, International Conference on Frontiers of Signal Processing (ICFSP), 2021

A static analysis approach to detect fault injection vulnerabilities in embedded software

RESEARCH TOPIC:
Source code audit, static analysis, dynamic symbolic execution, multi-fault injection

AUTHORS:
G. Lacombe[1], ML. Potet[1], E. Boespflug[1], **D. Féliot**

Source code auditing is a difficult task to achieve manually in an efficient and reliable way. Some code analysis techniques can be used to define security properties, and automatically detect insecure execution paths caused by malicious data and multi-fault injection. The latter brings more complexity to the analysis, leading to reliability and scalability issues (i.e. undetected vulnerabilities and failed analyses). We present a new method that mitigates these issues by providing a powerful fault model allowing the detection of many vulnerabilities, and reducing the number of fault injection points to only the relevant ones relatively to the security properties.

SCIENTIFIC COLLABORATIONS: [1] Univ. Grenoble Alpes, CNRS, VERIMAG, F-38000, Grenoble (FR)

Context and Challenges

The evaluation of a secure component by an ITSEF entails auditing the source code of the embedded software to explore all the execution paths that result from malicious input data combined with fault injection, and to detect attack paths that lead to dangerous behaviours violating security properties. Finding such attack paths in a program can be automated using Lazart, a tool that efficiently simulates multi-fault injection with DSE (Dynamic Symbolic Execution). Once faults are injected in the whole program as symbolic variables perturbing the control and data flows, DSE can find which faults are required to violate a security condition.

DSE has difficulty in scaling with the program size, and the risk of path space explosion and infinite loop increases in large programs. These issues get worse with the number of symbolic variables, and therefore the number of fault injection points. Code slicing is a static analysis technique that could help by reducing the size of a program while preserving its semantics for a given security condition (i.e. the slicing criteria). However, slicing is inappropriate as it removes non reachable code locations that have to remain in the analysis perimeter because fault injection makes them potentially reachable. Therefore, our solution needs to keep the program intact, while reducing the number of fault injection points, and should not miss any attack path for a given fault model.

Main Results

First, our method defines a new fault model that perturbs the result of any expression in the program. This model is more general than the models provided by Lazart, and detects more vulnerabilities to fault injection, in particular when control and data flows need to be both perturbed. The injection points are expressed at the source code level using the C language, which allows a precise localisation of every injection point in the source code, and a compatibility with Lazart. This model can be applied with the same semantics in Lazart, and in any C static analysis tool, in particular the Frama-C platform.

Then, based on this fault model, our method selects a subset of injection points having an impact on the property. Our fault model perturbs the control and data flows, but does not modify the CFG (Control Flow Graph). Therefore, an overapproximation of the impactful injection points subset can be obtained by a data and control dependency analysis that starts from a security condition verified at some point (i.e. an assertion) and goes backward along the data and control flows to select all the instructions the assertion depends on, and according to an all-branch coverage as fault injection perturbs the control flows. This dependency analysis is the first static analysis step of our method which is done by the Frama-C PDG (Program Dependency Graph) plugin.

A second step of static analysis can be attempted to make a further reduction of the injection points subset by running a value analysis with Frama-C Eva to remove every injection point that does not make the property unproved. However, this selection heuristic requires that Eva can prove the property, and only works for a single fault injection.

Some experiments have been conducted on three real-life code bases. The results show that the dependency analysis and the selection heuristic strongly reduce the total duration of the analysis. In one case, the analysis only succeeds with our method, otherwise it runs out of memory.

Perspectives

More experiments on real code bases in the context of security evaluations are needed to measure and understand more precisely the gains in time and memory provided by the method. Future works could improve the resolution of path explosions, without missing some attack paths. Challenging perspectives would be to find new selection heuristics compatible with multi-fault, and define new fault models to detect more vulnerabilities, in particular those modifying the CFG.

RELATED PUBLICATIONS:
[1] G. Lacombe, M-L. Potet, E. Boespflug, **D. Féliot, "Combining Static Analysis and Dynamic Symbolic Execution in a Toolchain to detect Fault Injection Vulnerabilities", PROOFS WORKSHOP (SECURITY PROOFS FOR EMBEDDED SYSTEMS), 2021.**

Fast calibration of fault injection equipment with hyperparameter optimization techniques

RESEARCH TOPIC:
Embededd security, fault attacks, perturbation, cybersecurity, machine learning, voltage glitch, parameters optimization

AUTHORS:
V. Werner, ML. Potet[1], **L. Maingault**

Although fault injection is a powerful technique to exploit implementation weaknesses, this is not without limitations. The equipment parameter space is large and usually explored with naïve methods. We apply and evaluate new optimization techniques for glitch voltage injection on three different microcontrollers. Results show better glitch waveforms than with any other algorithms. In addition, we propose a two-stage optimization strategy under black-box conditions to reduce the dimensionality of the parameter space and speed up the equipment calibration. This approach demonstrates breaking code read protections inside a built-in bootloader; faster than with genetic algorithms

SCIENTIFIC COLLABORATIONS: [1] Université Grenoble Alpes (UGA), Grenoble (FR)

Context and Challenges

In security evaluations of embedded devices, fault injection is widely used, but still needs a long and tedious calibration step. The parameter space to properly calibrate the injection equipment is often too large to be entirely covered manually during time-constrained security evaluations. The most commonly used methods to explore the parameter space are Grid Search and Random Search. Several approaches have been proposed to reduce the time spent on the equipment calibration, using more complex optimization techniques, such as Genetic Algorithms (GA). However, the latter algorithms are inherently chaotic and can suffer from premature convergence. Accordingly, Bayesian and Successive Halving (SH) techniques are typically preferred over metaheuristic algorithms to optimize hard combinatorial problem solvers or machine learning models. We proposed to apply these new optimizations techniques in fault injections for the first time.

Main Results

The comparison of different methods [1] is performed on a specific glitch injection platform on microcontrollers, with custom waveforms (left inset of the figure). The parameter space is huge (10^{18}) and cannot be explored comprehensively, making this set-up a perfect test for methods comparison. A specific Bayesian method, called Sequential Model-based Algorithm Configuration (SMAC), particularly well applied to fault injection presents the best performances as seen on the figure. Other methods are slower to converge and enable to reach a high fault probability.

We demonstrate this improvement in a real world attack on a microcontroller bootloader. To simplify and speed up the equipment calibration, we have proposed splitting fault injection optimization into two stages [2], the calibration stage and the exploitation stage. We optimize fault injection parameters independently of the target application with a fault characterization test and then, once the best configurations are identified, we find fault injection timings to exploit vulnerabilities on the target application. In our case, SMAC succeeds an attack on a bootloader twice as fast as the previous best method (GA), not to say that random search failed to find any vulnerability in a restricted time budget.

Perspectives

This set-up will be further used for evaluations of secured chips to quickly assess targets resistance. The specific glitch waveforms found with these methods could disable countermeasures against glitch injection. Only applied for glitch injection so far, the whole procedure will also benefit to other fault methods such as laser, or electromagnetic injections where an even laser parameter space shall be explored.

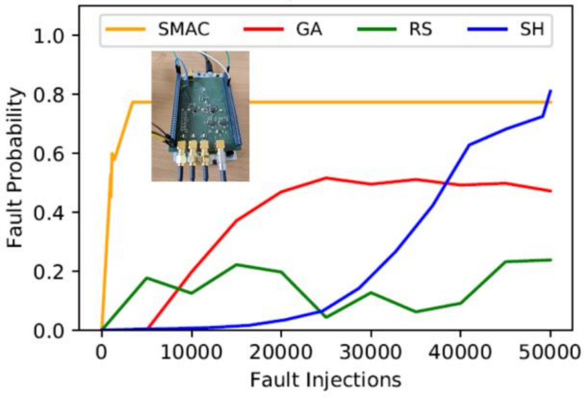


Fig. 1: Successful glitch injection probability

RELATED PUBLICATIONS:
[1] V. Werner, L. Maingault, ML. Potet, "Fast Calibration of Fault Injection Equipment with Hyperparameter Optimization Techniques", CARDIS, 2021.
[2] V. Werner, L. Maingault, ML. Potet, "An End-to-End Approach for Multi-Fault Attack Vulnerability Assessment", FDTC, 2020.

Resistance of isogeny-based cryptographic Implementations to a fault attack

RESEARCH TOPIC:

Post-quantum cryptography, SIKE, elliptic curve, isogeny, fault injection attack

AUTHORS:

E. Tasso**[1,2]**, L. De Feo[3], N. El Mrabet[4], **S. Pontié**[1,2]

The threat of quantum computers has sparked the development of a new kind of cryptography to resist their attacks. In the NIST Post-Quantum Cryptography Standardization Process, SIKE is the only isogeny-based protocol. While all candidates are believed to be mathematically secure, their implementations may be vulnerable to hardware attacks. In this work we show for the first time that Ti's 2017 theoretical fault attack is exploitable in practice by recovering the secret thanks to electromagnetic fault injection on an ARM Cortex-A53 using a correct and an altered public key generation. Moreover we propose a suitable countermeasure to detect faults that has a low overhead as it takes advantage of a redundancy already present in SIKE implementations.

SCIENTIFIC COLLABORATIONS: [1]CEA Tech, Centre CMP, Gardanne, (FR), [2]Université Grenoble Alpes, CEA, Leti, 38000 Grenoble, (FR), [3]IBM Research, Zürich, Switzerland, [4]Mines Saint-Étienne, CEA-Tech, Gardanne, (FR)

Context and Challenges

Starting in 1994 with Shor's factorization algorithm, quantum computers have been shown to threaten classic asymmetric cryptography. Even if a quantum computer powerful enough to break such protocols does not exist yet, if an attacker were to save encrypted data now, they could wait and decrypt it later. Thus the NIST launched the Post-Quantum Cryptography Standardization Process in December 2016 to select encryption and signature algorithms that can be implemented on classical computers but resist quantum computer attacks. Among them, SIKE (Jao et al., 2020) is the only candidate based on isogenies. It is a key encapsulation mechanism (KEM) based on the SIDH key exchange (Jao and De Feo, PQcrypto 2011). It has the smallest key size by far (Alagic et al., NIST, 2020), but is comparatively slow. Like the other candidates, it is believed to be mathematically secure, but vulnerabilities may appear once implemented and in its 2020 2nd round report, "NIST hopes that […] the public review period will include more work on side-channel resistant implementations". Hardware attacks assume that the attacker has physical access to the device where the algorithm is being executed. For instance, in fault attacks, the execution of the algorithm may be disrupted by various methods to get information. We will focus on investigating whether such an attack by Ti (PQcrypto 2017) is exploitable in practice to check if it is a threat to the SIKE protocol.

Main Results

In Ti's attack, the public key is generated twice using the same secret key, once correctly and once with a perturbation. The secret key is then recovered using both keys. We provide the first experimental realization of this theoretical attack by carrying out a campaign in a laboratory: we induce faults on the SIKE round 3 implementation optimized for ARM64 on a system on chip (SoC) with four Cortex-A53 cores with electromagnetic fault injection. In the best configuration, one secret key can be recovered every 3 min 10 s. However, SIKE is not broken as launching two public key generations is impossible in a properly implemented KEM API. It is a threat in the case of a multipartite key exchange though as a user has to generate one public key with the same secret for each partner. We propose then a countermeasure that detects faults in both cases by checking the coherence of an existing redundancy in SIKE. If the result of that second computation is different from the first value, then a fault has been detected. This countermeasure has a 1.5% overhead and a high probability to detect a fault. These results were presented at the 3rd NIST PQC Standardization Conference and at the COSADE workshop.

Perspectives

We validated Ti's theoretical fault attack in a laboratory and assessed its dangerousness for SIKE. We shall look further for other implementation vulnerabilities of SIKE and develop fitting countermeasures.

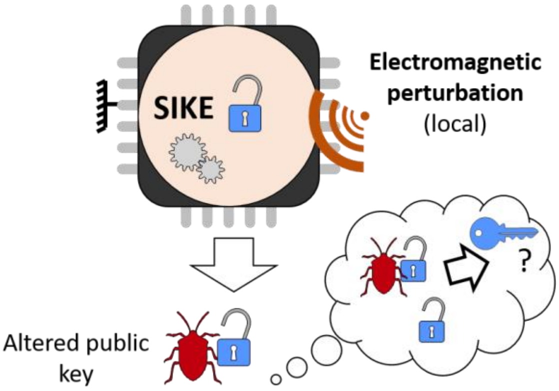


Fig. 1: Electromagnetic fault injection on SIKE

RELATED PUBLICATIONS:
[1] TASSO, Élise, DE FEO, Luca, EL MRABET, Nadia, *et al.*, « Resistance of isogeny-based cryptographic implementations to a fault attack », In: International Workshop on Constructive Side-Channel Analysis and Secure Design. Springer, Cham, p. 255-276, 2021.

Scramble cache: an efficient cache architecture for randomized set permutation

RESEARCH TOPIC:
Cybersecurity, Hardware Vulnerabilities, Software Attacks, Cache Memories

AUTHORS:
A. Jaamoum, **T. Hiscock**, G. Di Natale[1]

Driven by the need for performance-efficient computations, a large number of systems appeal to cache memories. Unfortunately, those are not designed for security and can leak information, compromising the confidentiality of applications running on the system. Many countermeasures exist in literature, most of which do not cope with the constraints imposed by embedded systems. We proposed a novel cache architecture that leverages randomized set placement to defeat cache side-channel analysis. A key property of this architecture is its low impact on performance and its small area overhead. We demonstrated that this countermeasure mitigates cache side-channel attacks, while guaranteeing small overheads, making this solution suitable also for embedded systems

SCIENTIFIC COLLABORATIONS: [1] Univ. Grenoble Alpes, CNRS, Univ. Grenoble Alpes, Grenoble INP, TIMA, 38000 Grenoble, (FR)

Context and Challenges

Advanced micro-architectures are common in embedded systems. The development of the Internet of Things (IOT) tends to make these processors accessible internet-wide. While physical attacks (such as side-channel analysis) have been considered for decades in the design of embedded systems, remote micro-architectural attacks only became relevant recently. Moreover, compared to side-channel attacks which usually require a physical access to the system, micro-architectural vulnerabilities may be exploited remotely. This makes these threats even more dangerous since they may allow a distributed attack on a large number of systems at the same time.

Cache memories are among the largest source of micro-architectural leaks and these components are shared among different processes and security domains. The state of a given cache is easily modifiable (by memory accesses or flush instructions) and is also easily observable (by measuring memory access times). This is why so many micro-architectural attacks target caches. Many solutions have been proposed in the literature to cope with this type of attack. They mainly rely on cache partitioning (where a process cannot access a partition dedicated to another process), or on randomization of the content of the cache (so as to add noise to the attacker's measurements and increase the extraction time of useful information from the leakage). Partitioning solutions are very robust against cache attacks, but they require important hardware redesign and can have a significant impact on performances. On the other hand, randomization generally has a much lower overhead, but it is more difficult to prove its efficiency in terms of security.

Main Results

The ScrambleCache implements an efficient randomization of the set locations. In contrast to partitioning techniques, this approach allows full cache sharing, which favors performance. The ScrambleCache uses a lightweight seeded permutation to modify the set addresses. The permutation can be renewed at any moment by changing the seed value. This can be done either after a fixed number of cycles, a fixed number of accesses to the cache, on interruptions or context switches. Ideally, the ScrambleCache would change the permutation as frequently as possible in order to spread memory accesses over the whole cache. Interestingly, randomization tends to reduce internal cache collisions because addresses are not mapped to a fixed location anymore.

However, changing the cache address mapping introduces several issues. For example, changing the mapping frequently increases the cache miss rate, which decreases the cache performances. We propose a history mechanism, which is the core element of the ScrambleCache design. It allows reducing the miss rate when changing the permutation by enabling older data to be moved directly to their new location.

To evaluate the security and the performance overheads we model our solution in the Gem5 simulator, we observed that CSCAs, such as Prime+Probe attack, are made much harder. The benchmarks demonstrated that the history mechanism allows a trade-off between security and performance (under the assumption that changing the seed more frequently improves security). Indeed, with the permutation changing every 8192 memory accesses, the worst-case overhead on the execution time is below 4%, and we already observed security improvements. Compared to existing remapping architectures, the Scramble Cache achieves a similar security level as best-known solutions. Furthermore, its access latency is drastically reduced due to a cheap permutation, making this architecture usable as a first level cache in constrained environments. This new cache architecture was published in DATE21 conference [1].

Perspectives

The ScrambleCache design was implemented to secure the first-level caches (data and instruction) against CSCAs. Future works include the implementation of the ScrambleCache on FPGAs. In addition, we also plan to analyze the security and performance of the ScrambleCache in the last-level caches.

RELATED PUBLICATIONS:

[1] Jaamoum, A., Hiscock, T., & Di Natale, G., "Scramble Cache: An Efficient Cache Architecture for Randomized Set Permutation" in IEEE Design, Automation & Test in Europe Conference & Exhibition (DATE), pp. 621-626, 2021.

SCADA Cybersecurity Awareness and Teaching with Hardware-In-The-Loop Platforms

RESEARCH TOPIC:
Cybersecurity, IIoT, SCADA, Evaluation, Emulation

AUTHORS:
P-H. Thevenon, S. Mocanu[1], M. Gallissot, C. Sivelle, **M. Puys**

Awareness and teaching in the field of SCADA cybersecurity have become a major focus. Recent attacks have shown that lack of preparation by vendors, integrators and owners greatly increases their severity. To allow awareness and training, we present two twin demonstrators based on the same technology: (i) WonderICS, an Advanced Persistent Threat (APT) platform used for awareness demonstrations and (ii) G-ICS, a flexible lab used for students training and pentesting. Both are based on a common Hardware-In-the-Loop (HIL) technology which combines simulation, emulation and real devices to reproduce realistic industrial environments. In this paper, we demonstrate the implemented scenarios and describe in detail the execution of demonstrations and teaching.

SCIENTIFIC COLLABORATIONS: [1]Laboratoire d'Informatique de Grenoble, Univ. Grenoble Alpes, CNRS, Inria, Grenoble-INP, Grenoble, (FR)

Context and Challenges

Industrial Control Systems (ICS) are often used to monitor and control a physical process such as energy production and distribution, manufacturing or transport systems. Due to their recent interconnection need and the discovery of the Stuxnet malware [Langner, 2011], ICS are increasingly facing cyberattacks from a variety of intruders, including terrorists or enemy governments. Hands-on training and attack scenario demonstrators have been proven to be the most effective tools for industrial cybersecurity awareness. Yet, the main challenge is to be able to train on realistic environments and as it is clearly not viable to launch attacks on a real facility, cyber-range initiatives have emerged to enable the building of proper research and training environments. Depending on their virtualization degree (simulation, emulation, use of real devices), these testbeds will not all have the same realism.

Main Results

We introduce two twin demonstrators based on the same technology: (i) WonderICS, an Advanced Persistent Threat (APT) platform used for awareness training and (ii) G-ICS, a flexible lab used for pentesting and student training. Both are based on a common Hardware-In-the-Loop (HIL) technology which combines the benefits of virtualization and real cyber-ranges. Industrial components (electrical circuit breakers, valves, etc.) are simulated using Python and are connected to real industrial control devices using open source electronic interface boards. These boards integrate a quite large set of digital and analog inputs/outputs (0/24 V digital and -10/+10 V analog signals) as well as industrial serial interfaces (Modbus RTU and CAN) and can communicate with the simulated components through an Ethernet-based connection. To allow more flexibility and realism in the platforms, we also introduce WonderCloud, a firmware emulation framework, allowing to run the firmware of real devices taken from vendor websites without the need of the actual real physical devices. WonderCloud is built upon the well-known Firmadyne framework [Chen, 2016]. We present various attacks implemented on both platforms (software man-in-the-middle attack using *ettercap* [Ornaghi, 2001] as well as hardware man-in-the-middle attack using a dedicated hardware module, phishing emails, corrupted USB stick, etc.) and describe the feedback we received during demonstrations and student teaching.

Perspectives

Future work on the Hardware-In-The-Loop platforms will aim at enhancing realism. Many directions are worth studying, such as deeper integration of the emulation framework in the existing scenarios (with support for hardware architectures found in industry, such as VxWorks), support for both platforms by integrating IIoT devices communicating over wireless media (e.g., ZigBee, Bluetooth), or real-world industrial malware based demonstrations.

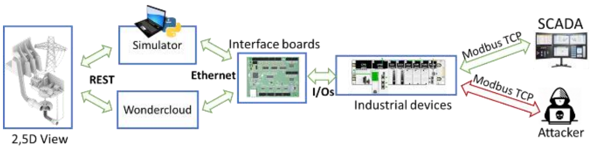


Fig. 1: Composition of WonderICS platform

RELATED PUBLICATIONS:
[1] M. Puys, P-H. Thevenon, S. Mocanu, M. Gallissot, and C. Sivelle, "SCADA Cybersecurity Awareness and Teaching with Hardware-In-The-Loop Platforms", Journal of Wireless Mobile Networks, Ubiquitous Computing, and Dependable Applications, To appear in 2022.
[2] M. Puys, P-H. Thevenon, & S. Mocanu "Hardware-In-The-Loop Labs for SCADA Cybersecurity Awareness and Training", In *The 16th International Conference on Availability, Reliability and Security*, pp. 1-10, 2021.

Protecting IoT & IIoT devices against software attacks targeting hardware vulnerabilities

RESEARCH TOPIC:
Cybersecurity, IoT, IIoT, Hardware Vulnerabilities, Software Attacks, Machine Learning

AUTHORS:
N. F. Polychronou, **PH. Thevenon**, M. Puys, V. Beroulle[1]

The increasing complexity of modern microprocessors created new attack areas exploited by attackers through Software Attacks Targeting Hardware Vulnerabilities (SATHV). By targeting the hardware, especially the microarchitecture to extract privileged information, these attacks cannot be detected by antivirus software. We can take advantage of Hardware Performance Counters (HPCs), which measure events related to hardware components, integrated in modern systems to monitor and protect the system by detecting an abnormal behavior. In the literature, many solutions use HPCs to detect SATHV, but they only protect the microprocessor against a limited set of SATHV. We propose a new detection mechanism using hardware signals to protect against a wide variety of attacks.

SCIENTIFIC COLLABORATIONS: [1] Univ. Grenoble Alpes, Grenoble INP, LCIS, (FR)

Context and Challenges

In the past, attackers exploited software vulnerabilities or hardware vulnerabilities. Software attacks exploit flaws or defects in the software code. They allow attackers to exploit the Operating System (OS) or applications in the system, to obtain some privileges. On the other hand, hardware attacks target flaws present in the hardware components of the system. Hardware attacks allow attackers to directly exploit the interaction with the system electronic components, without relying on a software vulnerability and independently of the OS. Apart from traditional hardware attacks, it exist ways to exploit hardware vulnerabilities using software code. We call this new class of attacks SATHV. SATHV are more challenging to counter, as software tools such as Antivirus cannot detect them, and patching the hardware is costly and would only protect future systems. To defend against a wide variety of attacks, designers profit from HPCs, which provide low-level Information. However, existing solutions are not able to secure the system against a wide variety of threats, and they do not scale to all existing devices requiring protection.

Main Results

Before implementing a new solution for the protection of IoT/IIoT devices, we studied the existing SATHV and existing solutions addressing the vulnerabilities targeted by SATHV. Further, we studied the side effects that SATHV introduce into the system during its execution. The term "side effects" refers to the difference in the behavior of the system under normal operation and under attack. We classified the side effects based on different criteria. Finally, we ranked the detection mechanisms on a different set of criteria. This study, published in the journal TODAES [1], allows us to find the weak points of each detection mechanism. In [2], we presented our methodology used for the evaluation of the different hardware events and existing solutions that implement detection mechanisms based on HPCs. Our evaluation of two State Of the Art solutions showcased that small changes in the architecture, without fine-grain analysis of the normal applications and intended attacks, could result in many false positives or give attackers the opportunity to bypass the mechanisms. Further, we presented our findings regarding software implementations of HPC-based mechanisms, including noise during measurement extraction due to the OS, lack of security of the detection mechanism against software vulnerabilities, and performance overhead due to system resource sharing between the mechanism and apps. Finally, we proposed a Malware Detector, which gathers information from HPCs to detect a large set of SATHV [3]. As our target is IoT/IIoT devices, complex solutions might give us better accuracy but also increase the load on already resource-limited systems. Therefore, our implementation relied on a simple Machine Learning algorithm to detect a wide variety of SATHV. MaDMAN successfully detected attacks with a 96.3% F-score and also successfully defended against evasive malwares.

Perspectives

Future work includes evaluating a new solution to detect not only SATHV but also other software and hardware attacks on resource-constrained environments such as IoT and IIoT devices. Furthermore, since software is not protected against software attacks, any detection mechanism implemented in software is vulnerable. This is why a hardware implementation of the detection mechanism should be considered.

RELATED PUBLICATIONS:
[1] Polychronou, Nikolaos-Foivos, et al. "A Comprehensive Survey of Attacks without Physical Access Targeting Hardware Vulnerabilities in IoT/IIoT Devices, and Their Detection Mechanisms." ACM Transactions on Design Automation of Electronic Systems (TODAES) pp. 1-35, 2021.
[2] Polychronou, Nikolaos Foivos, et al. "Securing iot/iiot from software attacks targeting hardware vulnerabilities." 2021 19th IEEE International New Circuits and Systems Conference (NEWCAS). IEEE, 2021.
[3] Polychronou, Nikolaos Foivos, et al. "MaDMAN: Detection of Software Attacks Targeting Hardware Vulnerabilities." 2021 24th Euromicro Conference on Digital System Design (DSD). IEEE, 2021.

Impact of spatial frequency based constraints on adversarial robustness

RESEARCH TOPIC:
Machine Learning. Deep Learning. Neural network, Security. Integrity. Adversarial Examples

AUTHORS:
R. Bernhard, M. Mermillod[1], Y. Bourrier[1], R. Cohendet, M. Solinas, M. Reyboz, **PA. Moëllic**

Adversarial examples exploit changes to inputs, humans are not sensitive to, and arise from the fact that models use uninterpretable features. Interestingly, cognitive science reports that the process of interpretability for human classification decision relies predominantly on low spatial frequencies (SF). We investigate the adversarial robustness of models enforced during training to leverage information corresponding to different SF ranges. We show that it is tightly linked to the SF characteristics of the data at stake. We conduct several experiments to enlighten influential factors such as the level of sensitivity to high frequencies, and the transferability of adversarial perturbations between original and low-pass filtered inputs.

SCIENTIFIC COLLABORATIONS: [1] LPNC, CNRS, Université Grenoble Alpes, Université Savoie Mont Blanc, Grenoble, (FR)

Context and Challenges

Adversarial examples are malicious perturbations to inputs that fool a neural network decision. Interestingly, there is a strong link between robustness and interpretability: the features robust models rely on are interpretable by humans, and vice versa. Previous works highlight a link between robustness for models and some frequency properties. For models trained with Adversarial Training, low spatial frequency (LSF) information related to interpretable notions (e.g. shape) is more important than non-interpretable concepts associated with high spatial frequency (HSF) information. For humans, experimental evidence in neural computation and cognitive psychology suggests the importance of LSF to perform efficient classification. Therefore, a natural hypothesis would be that a model trained specifically to rely more on LSF information might present an improved adversarial robustness. Some works exploit this hypothesis but stay agnostic of the intrinsic spatial frequency characteristics of the data.

Our goal is to investigate the link between robustness against adversarial examples and frequency properties of the data at stake. More precisely, we first experimentally question some preconceived hypothesis that state that an adversarial perturbation is a pure HSF phenomenon with data-agnostic spatial frequency characteristics. Second, we analyze the link between the spatial frequency features of the information that a model uses to perform predictions and the robustness against adversarial perturbations offered by spatial frequency-based constraints.

Main Results

We show that a frequency-based regularization induces very different levels of robustness according to the frequency features of the data. As an example, a low-frequency constrained model on CIFAR10 (that covers a broad frequency spectrum) has no robustness, while reaching a 41 % true robustness for SVHN against the l1-PGD attack. By analyzing the sensitivity of a standard model as well as adversarial transferability properties, we observe that enforcing a model to rely on LSF information is not a necessary condition to bring adversarial robustness. We identify key factors which condition robustness when training a model to rely on LSF information. We notice that, depending on the data set complexity, some models spread over the whole frequency spectrum, and show that constraints spanning different frequency ranges can help improving robustness.

Perspectives

The efficiency of frequency-based regularization when combined with existing defense schemes, such as Adversarial Training, is strongly dependent of the nature of these schemes. The work highlights the fact that the intrinsic frequency characteristics of data must be necessarily considered when designing robust defense strategies against integrity-based attacks of supervised models.

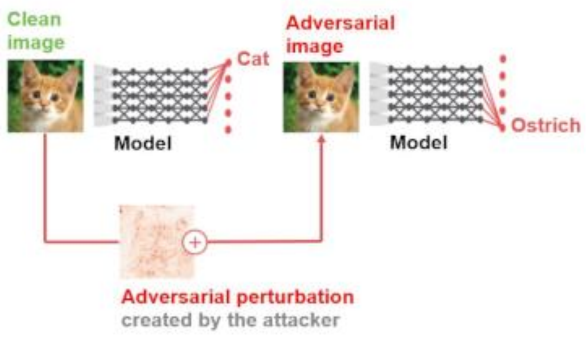


Fig. 1: An adversarial example attack

RELATED PUBLICATIONS:
[1] R. Bernhard, PA. Moellic JM. Dutertre, "Luring transferable adversarial perturbations for deep neural networks", Proceedings of the International Joint Conference on Neural Networks, 2021.
[2] R. Bernhard, PA. Moellic, M. Mermillod,Y. Bourrier, R. Cohendet, M. Solinas, M. Reyboz, "Impact of spatial frequency based constraints on adversarial robustness", Proceedings of the International Joint Conference on Neural Networks, 2021.

Accountability of data issued from a physical device based on TPM and OP-TEE secure hardware components through Ethereum and smart contracts technologies

RESEARCH TOPIC:
Accountability, Privacy, Hardware Security, Device Endorsement, Data Ownership, Smart Contract, Blockchain technologie

AUTHORS:
D. Paulin, T. Franco-Rondisson, R. Jayles, T. Loubier, R. Collado, **C. Hennebert**

Device- or user-centric system architectures allow everyone to manage their confidential data. But how to ensure the necessary trust between the stakeholders who work together in an ecosystem, each one preserving its own business? HistoTrust proposes a system architecture separating confidential data and cryptographic attestations of the data history, enabling each stakeholder to securely endorse its accountability. An Ethereum ledger is deployed to guarantee tamper-resistance, timestamp and order of the digital activity. The ledger creates trust between the stakeholders involved, without revealing confidential data. The root-of-trust secrets used to attest the data are protected at storage in an ST33 TPM and during execution within an ARM Cortex-A7 TrustZone

Context and Challenges

Logs trace the activity of a device through a history of various types of data produced. Their audit engages the accountability of their owner as a legal entity. Within an ecosystem of actors, each one is thus required to provide a trusted history of the data produced by its own devices to an auditor in case of litigation. This context highlights the tension between privacy, which requires the protection of confidential proprietary data, and trust, which requires guarantees between actors working together in a given ecosystem.

Main Results

HistoTrust introduces a device-centric solution based on Ethereum technology and Smart Contracts that conciliates the need for data security and privacy, while providing the necessary trust between stakeholders. The deployed architecture ensures end-to-end security and privacy by design, while satisfying the real-time data transmission required by the embedded industrial application. The design of an enhanced wallet is outlined in [1]. It integrates secure hardware components, such as Trusted Platform Module (TPM) and Trusted Execution Environment (OP-TEE), that ensure the root-of-trust anchoring. The embedded design is evaluated using four STM32MP1 boards, each including an STSAFE-TPM. Each physical device attests to the Ethereum ledger the data it produces.

Perspectives

In the following of this work, a neural network will be embedded on the board and HistoTrust will attest the decisions of the inference engine.

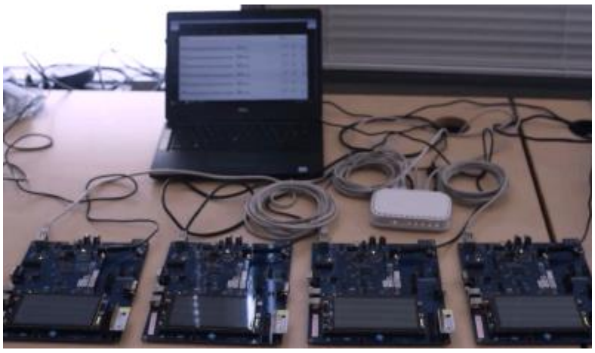


Fig. 1: Histotrust demonstrator

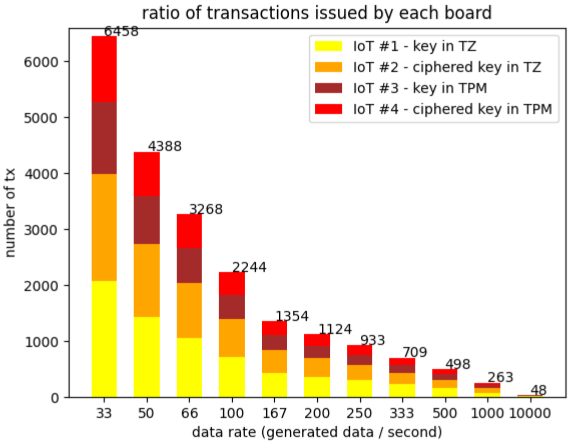


Fig. 2: Attestation real-time processing

RELATED PUBLICATIONS:
[1] Dylan Paulin, Christine Hennebert, Thibault Franco-Rondisson, Romain Jayles, Thomas Loubier, Raphaël Collado, "HistoTrust: ethereum-based attestation of a data history built with OP-TEE and TPM ", In proceedings of the 14th International Symposium on Foundations and Practice of Security (FPS'21), Paris, France, Springer, 2022.

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02 INDUSTRIAL IOT & LOCALISATION

- Vehicular (V2X) communications
- Indoor and Outdoor Localisation
- Traceability
- LPWA
- Millimeter-wave
- THz and sub-THz
- WiFi
- GNSS
- Modulation and Coding

Evaluation of vehicular connectivity for cooperative maneuvering services

RESEARCH TOPIC:

Vehicle-to-Everything (V2X) connectivity, Cooperative, Connected and Automated Mobility (CCAM), Road Side Units (RSUs)

AUTHORS:
F. Poli, V. Mannoni, **B. Denis**

In this work, we assess the potential of Vehicle-to-Everything (V2X) connectivity based on the C-V2X sidelink technology (a.k.a. PC5-Mode 4) for provisioning demanding Cooperative, Connected and Automated Mobility (CCAM) services such as cooperative maneuvering. Relying on a dedicated system-level simulation framework, the performance of both decentralized and infrastructure-based cooperative lane change use cases is then evaluated in terms of radio link reliability and overall service availability in a specific cross-border motorway scenario, under various road traffic conditions and distinct C-V2X penetration rates. Finally, service availability is discussed in light of the minimum required road infrastructure, assuming a gradual deployment of road side units.

Context and Challenges

The socio-economic need to develop mobility corridors with a high level of driving automation at the continental scale has been raising a variety of open challenges for Cooperative, Connected and Automated Mobility (CCAM), with unprecedented requirements in terms of Quality of Service (i.e., high reliability btw. 97%-99%, low latency < 10ms) and seamless continuity. In this context, based on both real field data and system-level simulations in cross-border contexts, we have first illustrated in [1] a few limitations of Vehicle-to-Network (V2N) connectivity based on current network deployments (up to 4G), showing for instance coverage shortages, long-lasting service interruptions between operators and prohibitive latency with respect to pinged servers. These observations thus plead for the adoption of complementary connectivity means, such as direct Vehicle-to-Vehicle (V2V) negotiations among vehicles and/or Vehicle-to-Infrastructure (V2I) communications with respect to Road Side Units (RSUs) based on the C-V2X sidelink radio technology (a.k.a. PC5-Mode4).

Main Results

Relying on a dedicated system-level simulation framework combining both realistic road traffic based on the Simulation Urban MObility (SUMO) tool (calibrated with real vehicles density parameters) and ns-3 network simulations, we have thus assessed in [2] the performance of a canonical cooperative lane merge (CLM) application based on PC5-Mode4 V2V and V2I connectivity in a representative cross-border motorway scenario. Despite rather pessimistic assumptions in terms of channel congestion (especially under high road traffic density) and aggressive technology penetration rates (i.e., assuming all the vehicles as connected), both RSU-assisted semi-centralized V2I-based and decentralized V2V-based CLM operations seem viable to meet typical CCAM requirements, while benefiting respectively from information redundancy/diversity (i.e., from multiple RSUs) and short-range communication links. Then, the previous study has been further extended in [3] to illustrate concrete trade-offs between the availability of such a V2I-aided cooperative maneuvering service and road infrastructure deployment costs, as a function of both road traffic and the percentage of connected cars. These evaluations show typically that a density of 2 RSUs/km could be sufficient to achieve 97% of CLM availability (as an a priori target), whatever the tested configurations.

Perspectives

Still based on system-level simulations in the same cross-border test environment, future works will assess the performance of V2N connectivity based on 5G New Radio (5G-NR) for centralized cooperative maneuvering, in terms of both link reliability and latency, while putting emphasis on multi-service coexistence and network load.

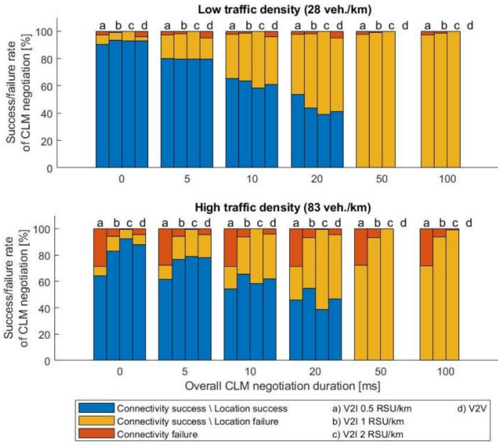

Fig. 1: PC5-Mode4 cooperative lane merge success

RELATED PUBLICATIONS:
[1] J. Hillebrand, et al. "Current 4G Networks Limitations Pleading for 5G for Cross-border CAM Services", Proc. IEEE 5G for CAM Summit 2021, May 2021
[2] F. Poli, et al. "Evaluation of C-V2X sidelink for cooperative lane merging in a cross-border highway scenario", Proc. IEEE VTC-Spring'21, 2021.
[3] A. Chiha Ep Harbi, et al. "Techno-economic and Simulation Study of a V2I-based Cooperative Manoeuvring Case in a Cross-border Scenario", Proc. IEEE VTC-Fall'21, 2021.

V2I-based collective perception

RESEARCH TOPIC:
Vehicular communications, C-V2X, intelligent transport system, system level simulation, cooperative collision avoidance, CCAM

AUTHORS:
N. Mouawad, B. Denis, A. Pereira Da Silva, **V. Mannoni**

Connected vehicles are equipped with sensors that can detect obstacles. However, vehicles perception is limited by sensors range or by the presence of other obstacles and a collective perception can then improve vehicles perception. Vehicles rely on onboard sensors in order to generate local occupancy maps or Collective Perception Messages (CPM) that are transmitted by means of V2X (Vehicle to Everything) connectivity to a fusion center. The latter executes the fusion of successfully received messages in order to generate a global occupancy map or a merged CPM which can reveal obstacles that could not be perceived based uniquely on standalone vehicle's perception means. The resulting map is then broadcast to all connected vehicles to indicate a risk of collision.

Context and Challenges

Nowadays, vehicle accidents increase drastically, especially on road intersections. This is due to several factors such as the obstructed view of vehicles and the limited perception capabilities which can influence negatively the road safety. Connected vehicles can improve their perception capabilities by exchanging traffic safety messages including sensor information via V2X technologies. This is known as collective perception which consists of the exchange of messages between vehicles and/or Road Side Units (RSUs) in order to reveal any hidden obstacles. In this study, we evaluate the performance of a Cooperative Collision Avoidance (CoCA) system in order to provide V2X network-assisted safety information to connected vehicles via the available infrastructure. To do so, two approaches have been investigated based on (i) the calculation of probabilistic occupancy maps or (ii) CPM messages (containing a simple list of obstacles).

Main Results

By means of system-level simulations, we have in a first time evaluated the potential of C-V2X aided cooperation for improving road safety [1]. Accordingly, vehicles equipped with LiDARs sensors share their local occupancy maps, by relying on C-V2X connectivity. A RSU placed at the intersection is then able to merge received maps in order to form a global occupancy map. Performance evaluation showed that messages size (defining the map resolution) of 1685 Bytes with 4 bits per pixel is suitable for global occupancy maps in terms of obstacle mis-detection rate. Moreover, in the considered scenario, message periodicity should be set to 100 ms whenever the number of vehicles does not exceed 70, and to 200 ms otherwise. These values represent the best tradeoff between connectivity performance and obstacle detection. The occupancy maps impose the use of large packets and thus high Modulation Code Schemes, which may affect the connectivity performance. Besides, the proposed fusion of local occupancy maps may induce computation complexity. Thus, in order to enhance V2X connectivity performance and reduce the fusion algorithm complexity, we have proposed in [2] a low complexity fusion algorithm that can merge CPM messages in order to generate a global CPM, which contains more reliable information about vehicles environment. Moreover, the impact of C-V2X connectivity on the fusion results has been studied and the performance evaluation has shown the effectiveness of our fusion algorithm in terms of obstacles detection capabilities. In addition, we showed that the use of CPM is more advantageous than occupancy maps in our scenario [2].

Perspectives

Future work will consist in evaluating the LDM CoCA application with a cellular architecture (V2N - Vehicle to Network) with 5G-NR. Finally, we will integrate more realistic errors in local maps and obstacles detection (GNSS error).

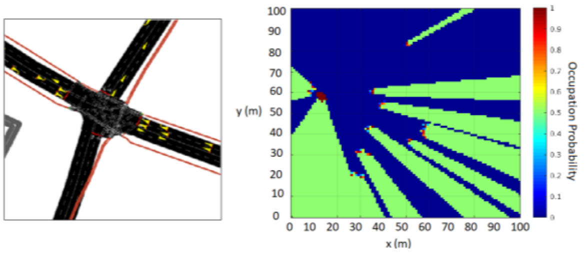

Fig. 1: Intersection and local occupancy maps

RELATED PUBLICATIONS:

[1] N. Mouawad, V. Mannoni, B. Denis and A. P. da Silva, "Impact of LTE-V2X Connectivity on Global Occupancy Maps in a Cooperative Collision Avoidance (CoCA) System," 2021 IEEE 93rd Vehicular Technology Conference (VTC2021-Spring), 2021.

[2] Mouawad, V. Mannoni, " Collective Perception Messages: New Low Complexity Fusion and V2X Connectivity Analysis," 2021 IEEE Vehicular Technology Conference (VTC2021-Fall), 2021.

NB-IoT satellite communications

RESEARCH TOPIC:

NB-IoT, satellite communications, Low Earth Orbit satellites (LEO), Geostationary satellites (GEO), physical layer, Doppler

AUTHORS:

V. Berg, S. Cazalens[1], P. Raveneau[1], **V. Mannoni**

Terrestrial Internet of Things (IoT) communication systems cannot provide worldwide coverage as effectively as satellite systems. Narrowband IoT (NB-IoT) is currently one of the major terrestrial IoT technologies. This work provides an evaluation of the NB-IoT physical layer performance in the context of two satellite scenarios: Geostationary (GEO) and Low Earth Orbit (LEO). GEO scenarios suffer from large distances between transmitter and receiver, while LEO systems exhibit very large magnitude of Doppler Effect. New algorithms are proposed to reliably adapt NB-IoT in these contexts and performance in terms of maximum throughput is evaluated and compared. Finally, NB-IoT main limitations in satellite communication links are identified.

SCIENTIFIC COLLABORATIONS: [1] Centre National d'Etudes Spatiales (CNES), Toulouse, (FR)

Context and Challenges

The IoT revolution offers huge potential benefits in terms of improved efficiency, sustainability and safety for the industry and society. Among the possible IoT connectivity technologies, new approaches often referred to Low Power Wide Area (LPWA) networking have emerged in order to provide a low power connectivity alternative, while covering large areas. The main LPWA communication systems are: NB-IoT and Semtech Long Range (LoRA). While LoRa is a proprietary solution, NB-IoT is an alternative proposed by the 3GPP which uses a subset of the LTE standard but limits the bandwidth to 180 kHz. NB-IoT is therefore designed for a terrestrial deployment. However today, some applications do not have access to a global, reliable IoT connectivity service and are unable to reach remote assets due to erratic or insufficient coverage. Satellite communications will then provide a complementary connectivity for the IoT. New generation of satellite links are therefore being studied and should be deployed in the IoT are therefore being studied and should be deployed in the coming years. This is why we propose to analyze the compatibility of the NB-IoT cellular standard with bidirectional satellite links in GEO and in LEO contexts.

Main Results

In this study, we demonstrated that NB-IoT could be a good candidate for IoT services by satellite. Thus, in a first step, both satellite scenarios have been studied for which multi-spot antenna patterns are considered (Cf Fig. 1). Mechanic analysis of both scenarios are used to derive the key performance criterion specific to satellite communications: these include Doppler levels and link budget. For LEO satellite, a new reception strategy has then been proposed to manage the high level of Doppler and to be able to demodulate and decode the NB-IoT channels in both UL and DL. New dedicated reception algorithms were developed and tuned for this application scenario. To prove how compatible the NB-IoT physical layer was with the LEO and GEO satellite scenarios, we evaluated the performance on the UL and DL. While Doppler levels and variations can be significantly large for the LEO scenario, the link budget is the main limiting factor has been in the link budget for the GEO scenario. Therefore, the LEO scenario presented the best performance in terms of data rate. For the GEO scenario, performance is affected by the distance between the satellite and the terminal. To be able to transmit at a reasonable data rate in this latter case, it is required to increase the UE transmission power.

Perspectives

This first analysis has been performed solely on physical layer performance. In a future work, we intend to include these results to analyze the performance when also upper layers procedures are considered.

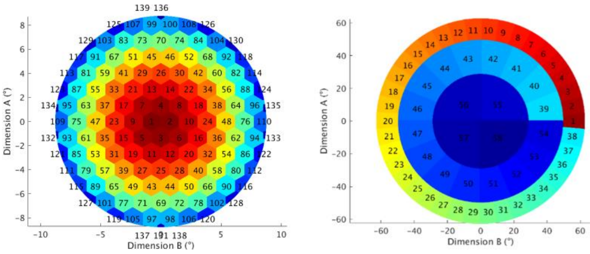

Fig. 1: GEO & LEO spot antenna patterns

RELATED PUBLICATIONS:

[1] V. Mannoni, V. Berg, S. Cazalens and P. Raveneau, "NB-IoT for Satellite Communications: Physical Layer Analysis and Performance," 2021 IEEE 32nd Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), 2021.

Artificial-intelligence-aided FEC decoding for IoT

RESEARCH TOPIC:
LDPC decoding, belief propagation (BP), BP-RNN decoder, parallel decoders, specialized decoder, short LDPC codes

AUTHORS:
J. Rosseel, V. Savin, I. Fijalkow[1], **V. Mannoni**

This work deals with the decoding of short block length Low Density Parity Check (LDPC) codes. It has already been demonstrated that Belief Propagation (BP) can be adjusted to the short coding length, thanks to its modeling by a Recurrent Neural Network (BP-RNN). To strengthen this adaptation, we introduce a new training method for the BP-RNN. Its aim is to specialize the BP-RNN on error events sharing the same structural properties. This approach is then associated with a new decoder composed of several parallel specialized BP-RNN decoders, each trained on correcting a different type of error events. Our results show that the proposed specialized BP-RNNs working in parallel effectively enhance the decoding capacity for short block length LDPC codes.

SCIENTIFIC COLLABORATIONS: [1] ETIS, CY Cergy Paris Université, ENSEA, CNRS

Context and Challenges

Short-packets from machine-to-machine communications, central to the emerging Internet of Things (IoT) technology, have revitalized interest in research and practice of efficient error correcting codes, for messages ranging from a few tens up to a few hundred bits. While important progress has been made over the last years in understanding the limits of coding at short block lengths, the design of efficient short codes and decoding algorithms still raises many challenges. LDPC codes, represented by their factor graph, are a class of error correcting codes well-known for their excellent error correction performance at long block lengths, achieving near Shannon channel capacity performance under Belief Propagation (BP) decoding, in the asymptotic limit of the code length. However, for short codes, short cycles in the factor graph significantly degrade the BP performance. The objective of this study is therefore to propose a neural decoding approach to enhance the performance of short LDPC codes.

Main Results

To reduce the impact of short cycles, a weighted BP decoding has been introduced in the literature, where the weights are optimized using a Neural Network (NN). The topology of the NN mimics the BP decoding process with a Recurrent NN (RNN) approach (Cf Fig. 1). The corresponding decoder is then termed as BP-RNN. To improve the decoding performance, our approach aims at specializing BP-RNN decoders to difficult error events [1]. To do so, we first proposed a classification of the error events, according to the structure of the induced sub-graph. The classification was driven by the impact of the induced sub-graph on the BP decoding performance. Then, we proposed a new decoding strategy consisting of parallel specialized BP-RNN decoders where each BP-RNN was trained for a specific error class. In addition, we introduced a complementary selection method of the trained BP-RNN decoders, proven to be efficient in keeping the most relevant trained decoders in the final parallel structure and thus obtaining a better complexity-performance tradeoff. Simulation results have shown that the proposed structure presents a gain up to 0.5 dB compared to the BP algorithm for a packet error rate of 10^{-4}.

Perspectives

This work is a first step towards a framework of specialized neural BP decoders, and we believe that further work may reveal alternative specialization strategies. The final aim would be to approach maximum likelihood decoding performance at short to moderate code-length, for which we will probably need to rely on a bunch of practical decoders, rather than a unique one.

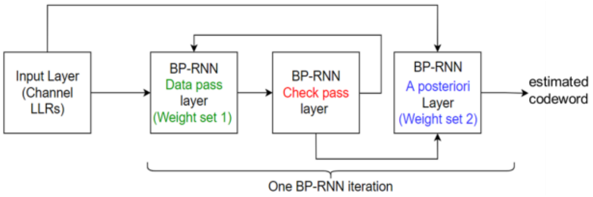
Input Layer (Channel LLRs)
BP-RNN Data pass layer (Weight set 1)
BP-RNN Check pass layer
BP-RNN A posteriori Layer (Weight set 2)
estimated codeword
One BP-RNN iteration

Fig. 1: BP-RNN architecture

RELATED PUBLICATIONS:
[1] J. Rosseel, V. Mannoni, V. Savin and I. Fijalkow, "Error Structure Aware Parallel BP-RNN Decoders for Short LDPC Codes," 2021 11th International Symposium on Topics in Coding (ISTC), 2021.

Non-binary polar codes for spread-spectrum modulations

RESEARCH TOPIC:
IoT systems, CCSK modulation, non-binary polar codes

AUTHORS:
V. Savin

We propose a new coded modulation scheme for reliable transmission of short data packets at very low signal-to-noise ratio, combining cyclic code shift keying (CCSK) modulation and non-binary polar coding. We consider non-binary polar codes defined over Galois fields, and propose a new design methodology, aimed at optimizing the choice of the kernel coefficients. Numerical results show that the system performance is close to the achievable limits in the finite blocklength regime.

Context and Challenges

Recent years have seen an explosive growth in the number of devices connected and controlled by the Internet. The wide range of applications for Internet of Things (IoT) technology is usually divided into two use-cases, known as either “critical IoT” or “massive IoT”. The latter is characterized by a high density of connected devices, small data payloads, and low sensitivity levels, due to stringent constraints on the device energy consumption and cost. Maximizing the spectral efficiency of an IoT network is a key prerequisite for providing massive connectivity. Unfortunately, the first wave of IoT standards are far from achieving the spectral efficiency targets. They implement sub-optimal error correction schemes combined with repetition, or simply omit any error correction capability. In this work, we propose a new approach to achieving low levels of sensitivity with increased spectral efficiency, combining Cyclic Code Shift Keying (CCSK) modulation and non-binary polar coding.

Main Results

The proposed approch, combining CCSK modulation and non-binary polar coding, is introduced in [1], where we also derive the achievable rates in the both asymptotic and finite blocklength regimes. While non-binary polar codes may provide significant coding gains, their construction must be carefully optimized, especially for short data payloads. Therefore, we propose a design methodology for non-binary polar codes, which takes into account both the transmission channel and the modulation scheme. The proposed methodology is aimed at accelerating the polarization speed, through maximizing the difference between the error probability of the synthesized virtual channels. As a result, the constructed non-binary polar codes exhibit an improved error rate performance under successive cancelation (SC) decoding. Numerical results show that the system performance is close to the achievable limits in the finite blocklength regime. The figure shows the achievable effective coding rates (taking into account the spreading factor of the CCSK modulation), for non-binary polar codes defined on different Galois fields ($\mathrm{GF}(2^p)$, with $p = 6,8,10$), and for a target word error rate of 10^{-4}. It can be seen that the proposed approach achieves an effective coding rate within about 1dB of the theoretical maximum achievable rate in the finite blocklength regime (normal approximation curve).

Perspectives

In the short blocklength regime, the SC decoding performance is penalized by the incomplete polarization of the virtual channels. Hence, we expect that the observed gap to the theoretical maximum achievable rate can be further reduced by using more powerful decoders, such as SC-List or SC-Flip decoders. Moreover, the proposed design methodology for non-binary polar codes is generic, thus it might be successfully used for other applications, combining non-binary polar codes and non-binary modulations.

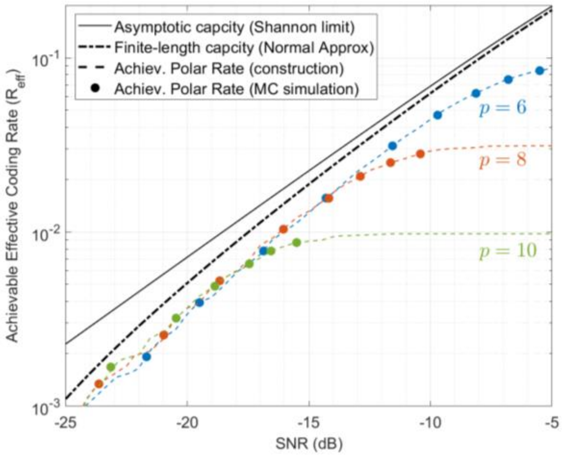

Fig. 1: Achievable effective coding rates

RELATED PUBLICATIONS:
[1] V. Savin, " Non-Binary Polar Codes for Spread-Spectrum Modulations", in Proc. of IEEE International Symposium on Topics in Coding (ISTC), Montreal, Canada, 2021.

Quantum polarization of qudit channels

RESEARCH TOPIC:
Quantum polar codes, Clifford-based channel combining, Pauli channel, successive cancellation decoding

AUTHORS:
A. Goswami, M. Mhalla[1], F. Dupuis[2], **V. Savin**

We provide a generalization of quantum polar codes to quantum channels with qudit-input, achieving the symmetric coherent information of the channel. Our construction relies on a channel combining and splitting procedure, where a two-qudit unitary, randomly chosen from a unitary 2-design, is used to combine two instances of a qudit-input channel. We show that applied recursively, this procedure yields a two-level quantum polarization phenomenon similar to the classical channel polarization. We investigated the quantum polarization of Pauli channels with qubit input, for which an effective method to decode the quantum polar code was proposed, as well as an alternative multi-level polarization based construction, reducing preshared entanglement requirements.

SCIENTIFIC COLLABORATIONS: [1] Université Grenoble Alpes, CNRS, Grenoble INP, LIG, Grenoble, (FR), [2] Université de Montréal, Québec, Canada.

Context and Challenges

In classical information theory, polar codes are the first explicit construction of a family of codes that provably achieve the channel capacity for any discrete memoryless classical channel. Their construction relies on a phenomenon known as channel polarization, resulting from the recursive application of channel combining and splitting operations. These operations recast several instances of the transmission channel into a same number of so-called virtual channels, which tend to become, asymptotically, either perfect or completely noisy. Classical polar codes has been generalized to the quantum case by using Calderbank-Shor-Steane (CSS)-like constructions, first for transmitting classical information over classical-quantum channels, and later for transmitting quantum information over quantum channels. However, these quantum polar coding schemes essentially rely on the classical polarization phenomenon, which happens in the either amplitude or phase basis. Our work strengthens and complements the above generalizations, by answering in the affirmative the question of a polarization phenomenon in which the quantum channel polarizes quantumly, not merely in one basis.

Main Results

In [1], we introduce a quantum channel combining and splitting procedure, where a two-qudit unitary, randomly chosen from a unitary 2-design (e.g., generalized Clifford group), is used as a channel combining operation. Applied recursively, the proposed procedure allows synthesizing virtual channels that tend to become either perfect or completely noisy as quantum channels, not only in one basis. We exploit this polarization phenomenon to construct a quantum coding scheme, in which good virtual channels are used for quantum communication, while bad virtual channels are frozen using maximally entangled pairs of qudits. Hence, our coding scheme is entanglement-assisted, and we show it achieves half the symmetric mutual information of the quantum channel. Moreover, by chaining several quantum polar codes, we provide a coding scheme for which the rate of preshared entanglement vanishes asymptotically and the resulting quantum code achieves the symmetric coherent information of the channel.

In [2], we investigate the above quantum polarization phenomenon for the particular case of Pauli channels with qubit input. To a Pauli channel, we associate a classical symmetric channel with non-binary input, and show that the former polarizes quantumly if and only if the latter polarizes classically. We exploit this equivalence to devise an effective method to decode the quantum polar code on a Pauli channel, making use of the successive cancelation decoding of its classical counterpart. We also provide a fast polarization property ensuring the reliability of the proposed decoding procedure. Quantum polarization using a fixed channel combining operation, instead of a randomized one, is investigated in [3]. For the considered channel combining operation, we show that polarization of Pauli channels happens in multi-levels, in the sense that synthesized virtual channels may also be half-noisy, except being completely noisy or perfect. The half-noisy channels need to be frozen by fixing their inputs in either the amplitude or the phase basis, while preshared maximally entangled pairs of qudits are required for the completely noisy channels as before. This allows reducing the preshared entanglement requirements, compared to our previous construction.

Perspectives

A decoding algorithm for non-Pauli channels, allowing reliable communication at rates close to the symmetric coherent information remains an open problem. Recently, a quantum belief-propagation algorithm has been proposed, which passes quantum messages on the factor graph of the code, and is capable of decoding the classical-quantum channel with pure state outputs. Since the successive-cancellation decoding of polar codes is essentially a belief-propagation algorithm, it would be of interest to devise similar approaches for the family of quantum polar codes proposed here.

RELATED PUBLICATIONS:
[1] A. Goswami, M. Mhalla, and V. Savin, "Quantum polarization of qudit channels," in Proc. of IEEE International Symposium on Information Theory (ISIT), Melbourne, Australia, 2021.
[2] A. Goswami, M. Mhalla, and V. Savin, "Multilevel polarization for quantum channels," Quantum Information and Computation, vol. 21, no. 7-8, pp. 577-606, 2021.
[3] F. Dupuis, A. Goswami, M. Mhalla, and V. Savin, "Polarization of quantum channels using Clifford-based channel combining," IEEE Transactions on Information Theory, vol. 67, no. 5, pp. 2857-2877, 2021.

Precise localization in LPWA networks using phase difference of arrival

RESEARCH TOPIC:
Low Power Wide Area Network (LPWAN), narrowband radio localization frequency hopping, Phase Difference of Arrival (PDoA)

AUTHORS:
F. Wolf, V. Berg, V. Mannoni, S. De Rivaz. JP. Cances[1], **F. Dehmas**

In Low Power Wide Area (LPWA) networks, radio localization based on Time Difference of Arrival has major benefits: energy consumption of the node and spectrum usage are contained. Temporal resolution and hence positioning accuracy is however limited by the bandwidth of the LPWA narrowband signals. Multi-channel ranging, that relies on multiple narrowband signals has recently been proposed to improve temporal resolution and positioning accuracy. Adaptations to multi-channel ranging called Multi-Frequency Phase Difference of Arrival (MF-PDoA) have been studied and proposed. Analyzes of the impact of imperfect synchronization show that MF-PDoA is robust and well adapted to the LPWA scenario.

SCIENTIFIC COLLABORATIONS: [1] Université de Limoges, Limoges (FR)

Context and Challenges

Low Power Wide Area (LPWA) networks are a part of Internet of Things (IoT) technologies that enable wireless connectivity on a large variety of objects. Long range communication is achieved thanks to low levels of sensitivity obtained by low data rates and narrowband modulation schemes.

Precise localization, based on the inherent radio signals of these IoT nodes will enable new applications and enhance network management. However, accurate positioning remains challenging due to hardware imperfections (e.g. carrier frequency offset), low temporal resolution of narrowband signals and multipath propagation scenarios.

A new technique, called coherent multi-channel ranging, has therefore been proposed to significantly improve precision. It relies on multiple narrowband signals that are sequentially transmitted on different channels to virtually increase the bandwidth [1]. This technique, based on multiple phase measurements or Phase of Flight (PoF), significantly improves temporal resolution and ranging precision, while preserving the narrowband modulation necessary for long-range communication.

Main Results

Multi-Frequency Phase Difference of Arrival (MF-PDoA) is an adaptation of coherent multi-channel ranging to Phase Difference of Arrival (PDoA) to allow precise localization with nodes being in transmit only mode [2]. Thus energy consumption and spectrum usage are contained. As this technique requires synchronization between the base stations, a study has been done to see the impact of imperfect synchronization between the receivers in different scenarios (e.g. NB-IoT in Figure 1) and the performance are compared to Cramer-Rao lower bound (CRLB) and classical Time Difference of Arrival (TDoA) techniques.

For a SNR of 10dB, the standard deviation error of MF-PDoA is equal to approximately 2m while the standard deviation error of TDoA is equal to 150m. When synchronization error is set to 10ns (respectively 50ns), the RMS range error floor is equal to 4m (respectively 21m). Both TDoA and MF-PDoA are robust to synchronization timing errors between receivers

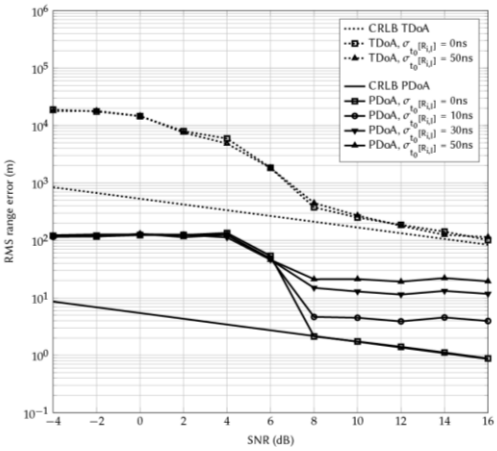

Fig. 1: Different range errors

Perspectives

Further work is needed to implement this technique in a testbench similar to the one used in [1]. It would allow to confirm the hypotheses used for the simulations and the results for range error through laboratory measurements and field trials.

RELATED PUBLICATIONS:
[1] V. Berg, F. Dehmas and F. Wolf, "Coherent Multi-channel Ranging for Precise Localization in Narrowband LPWA Networks: Performance Trials in an Indoor Environment," 2021 Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit), pp. 271-275, 2021.
[2] F. Wolf, V. Berg, F. Dehmas, V. Mannoni and S. De Rivaz, "Multi-Frequency Phase Difference of Arrival for Precise Localization in Narrowband LPWA Networks," ICC 2021 - IEEE International Conference on Communications, pp. 1-6, 2021.

Improved localization continuity through reconfigurable intelligent surfaces

RESEARCH TOPIC:
Reconfigurable Intelligent Surface (RIS), Near-field (NF), Non line of Sight (NLoS), Localization, 6G, Smart Radio Environments

AUTHORS:
M. Rahal, H. Wymeersch[1], B. Uguen[2], **B. Denis**

In this work, considering multi-carrier downlink transmissions from a single base station, we investigate the potential of Reconfigurable Intelligent Surfaces (RIS) to overcome Non Line of Sight (NLoS) propagation in so-called « geometric » near-field conditions. More particularly, via a Fisher information analysis and the derivation of the theoretical Position Error Bound (PEB), we show that while near-field improves localization accuracy mostly at short distances when the direct path is present, it could also provide reasonable positioning performance when this path is blocked by relying on a unique reflection, despite the use of a non-optimized random phase configuration at the reflective RIS.

SCIENTIFIC COLLABORATIONS: [1] Chalmers University of Technology, Gothenburg, Sweden,[2] Université Rennes 1, Rennes, (FR)

Context and Challenges

Non Line of Sight (NLoS) propagation is notoriously responsible for causing large errors in conventional wireless localization systems, when relying uniquely on the hypothetic presence of a direct path. On the other hand, smart radio environments are seen as a key rising concept of next-generation wireless networks, where propagation channels between transmitters and receivers can be purposely controlled. One promising approach to achieve such channel flexibility relies on semi-passive reflective Reconfigurable Intelligent Surfaces (RISs), such as low-complexity reflect-arrays, which can shape the bouncing multipath signals so as to enhance the communication quality of service or to make localization feasible in adverse operating contexts, while limiting the number of active base stations to be deployed on the field. All in all, despite these high expectations, there is still a need to demonstrate how -and to which extent- reflective RISs could be concretely beneficial to localization, especially in case of harmful NLoS conditions.

Main Results

In [1], based on a generic formalism modelling the response of a reflective RIS in both near-field (NF) and far-field (FF) regimes, as well as on a Fisher Information Matrix (FIM) analysis, we have first derived theoretical Position Error bounds (PEBs) in Line-of-Sight (LoS) and NLoS cases. The previous bounds characterize the best achievable localization accuracy of a RIS-assisted downlink positioning system, while considering one single-antenna base station and one single-antenna user equipment (UE). On this occasion, we have shown that, whenever the UE is close enough to the RIS and/or the RIS is large enough, it is possible to directly infer its position in the absence of direct path, even under (random) RIS phase configurations. Although the achievable NLoS accuracy remains relatively modest, these observations pave the floor to seamless and automated NLoS mitigation strategies at system-level to contextually chose the number of controlled elements per RIS (in NF especially) or to activate multi-RIS processing (in FF especially) only if needed, hence minimizing complexity accordingly.

Perspectives

Future works concern the derivation of PEB-based localization-optimal RIS configurations to boost NLoS localization accuracy, the design of practical estimation algorithms to exploit NF capabilities, as a well as joint UE location tracking and location-based RIS configuration adaptation under mobility.

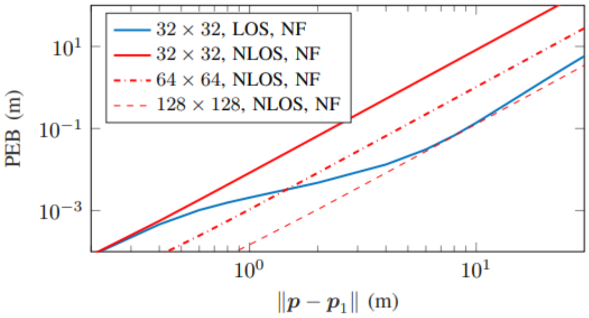

Fig. 1: PEB in NF as function of UE-RIS distance

RELATED PUBLICATIONS:
[1] M. Rahal, et al. “RIS-Enabled Localization Continuity under Near-Field Conditions”, Proc. IEEE SPAWC, 2021.

Radio simultaneous localization and mapping in the terahertz band

RESEARCH TOPIC:
Radio-Slam, Indoor Localization, Mapping, Terahertz

AUTHORS:
M. Lotti, G. Pasolini[1], A. Guerra[1], F. Guidi[2], **R. D'Errico**, D. Dardari[1]

We introduced and validated experimentally a Simultaneous Localization and Mapping (SLAM) algorithm based on the processing of radar data captured in the Terahertz (THz) band. We describe a measurement setup and campaign to investigate the main properties of the signal backscattered in an indoor environment in the THz band and assess the performance of the proposed radio-SLAM (R-SLAM) algorithm. Numerical results show that a mobile radar can track itself with high accuracy in a real scenario, without the need for any localization infrastructure, and map the surrounding environment at the same time. This validation represents one of the very first attempts that experimentally characterize THz SLAM as a solution for realizing the automatic mapping of the indoors.

SCIENTIFIC COLLABORATIONS: [1] DEI, WiLab-CNIT, University of Bologna (IT), [2] CNR-IEIIT, Wilab, Bologna (IT)

Context and Challenges

In the near future, mobile devices are expected to revolutionize our experience, by creating the digital maps of their surroundings in an autonomous way and, thus, avoiding the deployment of dedicated infrastructures, that would practically infeasible for all the indoors. An alternative solution to laser, Simultaneous Localization and Mapping (SLAM) is the so-called radio-SLAM (R-SLAM) which leverages massive arrays working in the mm-wave bands, whose adoption is envisioned is 6G devices.

Main Results

We developed an R-SLAM algorithm that can be applied to radio signals generated by a mobile radar device. An ad hoc measurement campaign in the THz band was carried out to assess the performance of the proposed R-SLAM algorithm in a real scenario. The frequency-step radar measurement setup covers the 235 - 320 GHz band (Figure 1), operating a mechanical steering of directive antennas, at each position. Figure 2 shows the trajectory estimate obtained from measurements taken in a rectangular room, where the radar is located. An auto-positioning error in the order of 10-20 cm was achieved, while the occupancy grid map is consistent with the actual shape of the considered scenario.

Perspectives

Numerical results prove the feasibility of infrastructure-less localization and mapping with a personal radar, in the perspective of 6G systems were integrated communication, localization and mapping capabilities will be required.

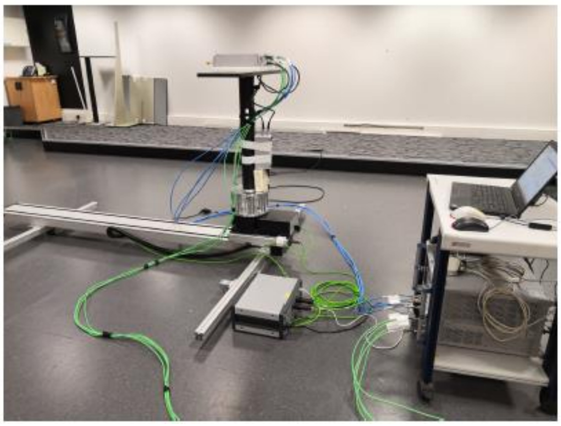

Fig. 1: THz-basckatteing measurement setup

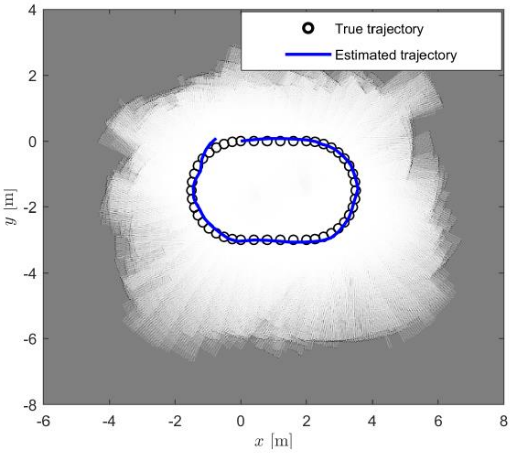

Fig. 2: Localization and mapping result

RELATED PUBLICATIONS:
[1] M. Lotti, G. Pasolini, A. Guerra, F. Guidi, M. Caillet, R. D'Errico, D. Daradari "Radio Simultaneous Localization and Mapping in the Terahertz Band" 25th International ITG Workshop on Smart Antennas, 2021.

A novel RF spectrum monitoring architecture for an ultra-low-power Wi-Fi geopositioning system

RESEARCH TOPIC:

End-to-end experimentation, LTE handover, open and reconfigurable software defined radio environment

AUTHORS:

N. Pekcokguler, M. Maman, A. Burg[1], C. Dehollain[1], **D. Morche**

Wireless radio consumes the highest power in many systems and must be activated wisely to save power especially in battery-powered systems. Hence, gathering insight into the spectrum activity is needed to control the wireless radio. In this work, classic full-band FFT and sequential digital spectrum scanning systems are presented with their high energy consumption and latency drawbacks. A context-aware, multi-layer-duty-cycled, multi-channel, ultra-low-power analog spectrum monitoring architecture is proposed as a solution to the drawbacks of the classic systems with the emphasis on Wi-Fi signal detection for a BSSID-based geopositioning shipment tracking application.

SCIENTIFIC COLLABORATIONS: [1] Ecole Polytechnique Federale de Lausanne, CH-1015 Lausanne (CH)

Context and Challenges

Global positioning system (GPS) has proved very successful for outdoor positioning purposes. However, due to its limitations in enclosed spaces, indoor Wi-Fi based positioning systems were developed. Outdoor Wi-Fi based positioning has also proven to be feasible. However, all the existing solutions depend merely on a Wi-Fi modem as hardware, which is effective but highly inefficient. Classic full-band FFT and digital spectrum scanning methods are presented in the literature. However, these methods constitute high power consumption and implementation complexity drawbacks.

Main Results

The proposed approach is to use an intelligent multi-step context-aware system that divides the operating conditions into different complexity categories and configures the system according to the current spectrum condition. The first step is devoted to signal existence detection to be used in sparse spectrum conditions. The second step is signal recognition, that is activated when a signal is detected. The third step is the main Wi-Fi radio, that is to be used to perform a complete Wi-Fi scanning and, if available, the BSSID extraction. The proposed receiver architecture to implement signal detection resolves the drawbacks of the classic sequential digital scanning through parallel processing and extraction of the signal energy in the analog domain before the ADC. It provides more than 3 order of magnitude power.

Perspectives

Activity is ongoing to be able to Implement Signal Recognition with the same architecture.,

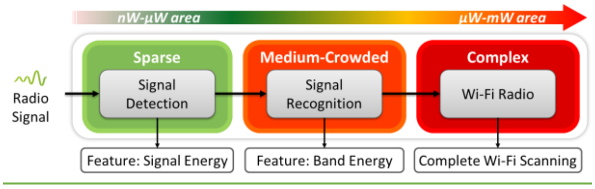

Fig. 1: Multi-step spectrum scanning system

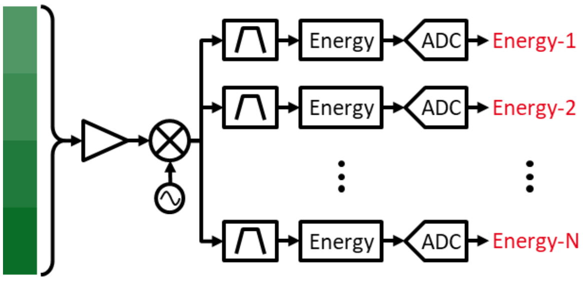

Fig. 2: Parallel analog spectrum architecture

RELATED PUBLICATIONS:
[1] N. Pekcokguler, D. Morche, A. Frischknecht, C. Gerum, A. Burg and C. Dehollain, "Dynamic Range and Complexity Optimization of Mixed-Signal Machine Learning Systems," 2021 IEEE International Symposium on Circuits and Systems (ISCAS), 2021.

Satellite selection for GNSS vehicle navigation

RESEARCH TOPIC:

Global Navigation Satellite System (GNSS), Fault Detection and Exclusion (FDE), Receiver Autonomous Integrity Monitoring (RAIM)

AUTHORS:
C. Combettes, **C. Villien**

Due to the presence of outliers in GNSS measurements, a fault detection and exclusion module (FDE) is mandatory for applications such as vehicle navigation. A navigation processor with two different FDE is proposed. A first FDE based on the EKF innovation used when the convergence is ensured taking the benefit of the covariance matrix information. A second FDE with a standalone approach is used if the convergence is not ensured. Then, the performance of the proposed approach is evaluated with a large database of experiments.

Context and Challenges

Although GNSS positioning is quite an old system, it recently gained some attention due to emerging applications like UAV, autonomous vehicles, new technologies such as Galileo constellation, consumer grade RTK and/or dual-band receivers which bring levels of accuracy and performances previously limited to expensive receivers, to everyone. The new low-cost receiver for accurate positioning paradigm offered by those evolutions requires to revisit some standard algorithms used for positioning in this context. In particular, satellite vehicle (SV) selection used to compute the position, velocity and time (PVT) solution is among the key aspects of processing, since those architectures neither benefits from Receiver Autonomous Integrity Monitoring (RAIM) modules, nor from selective antenna that significantly helps at mitigating reflected signals and outliers. As a consequence, SV selection performed at the navigation processor stage should receive some attention to ensure an accurate positioning, by using an efficient Fault Detection and Exclusion (FDE) algorithm.

Standalone approaches have sub-optimal performances due to the limited amount of prior information for SV selection and significant computational costs. To enhance the process, it is legitimate to use some prior information delivered by the predicted position but this increases the risk of algorithm instability. We thus propose a navigation processor based on an EKF algorithm that contains both a standalone FDE approach and a FDE based EKF approach.

Main Results

In the proposed approach, there is a switching between the two FDE based on the covariance matrix. For normal operation, when the algorithm has a good convergence level indicated both by the amplitude of the residuals and the covariance matrix of the PVT solution, an innovation test will be used to detect and remove any outlier. In this mode, no additional PVT computation is required beyond the one delivered by the EKF prediction, minimizing the computational cost of the satellite selection process. When the algorithm has poor convergence, then a classical FDE test is used. The two FDE are using a global test first to validate the solution, eventually followed by local tests to exclude outliers if the global test failed. The proposed method was compared with a large database to different FDE schemes from the state of art. The database is composed by 80 sessions, each of them having a duration ranging from 10 minutes and up to 1 hour. The performances of the proposed method are 2.8m (rms) and a P99 of 6.93m versus a 3.18m (rms) and a P99 of 8.24m for the Danish method.

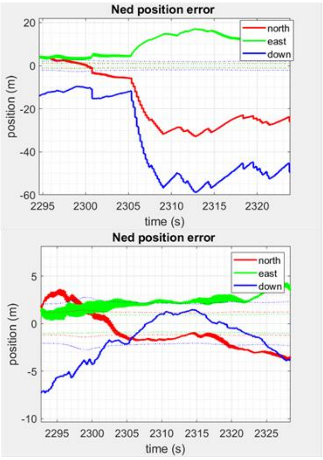

Fig. 1: Position error w.r.t. ned frame

Perspectives

In a future work, we intend to include and develop this approach in a GNSS RTK (Real Time Kinematic) solver.

RELATED PUBLICATIONS:
[1] C. Combettes and C. Villien, "EKF based on two FDE schemes for GNSS Vehicle Navigation," 2021 IEEE 93rd Vehicular Technology Conference (VTC2021-Spring), 2021

New approach in antenna design automation applied to a dual-band GNSS micro-array

RESEARCH TOPIC:
Micro-array antennas, GNSS, multi-band antennas, optimization algorithm.

AUTHORS:
L. Batel, A. Clemente, L. Rudant, **C. Delaveaud**

This work describes a new approach in antenna design automation. We propose to use a micro-array of coupled antennas loaded by impedances and to perform the optimization of these impedance values in order to reach specific design goals. In particular, we present a demonstration for dual-band GNSS that requires good RHCP gain (in the range -2 dBic to 0 dBic) and low LHCP gain (below -10 dBic). The proposed automated design process has been able to meet these requirements jointly in L2 (1215–1240 MHz) and L1 frequency bands (1560–1610 MHz). A prototype has been fabricated, and characterized in anechoic chamber to validate the proposed design methodology

Context and Challenges

Multi-band Global Navigation Satellite Systems (GNSS) is a key technology for future mobility services as it improves accuracy and reliability of geolocation. Multi-band GNSS antennas must meet specific requirements on radiation properties, such as optimized Right Hand Circular Polarization (RHCP) gain towards the sky, as well as low cross-polarization Left Hand Circular Polarization (LHCP). Designers must optimize these properties jointly on several wide frequency bands. As real-time geolocation is critical for all mobility services, multi-band GNSS antenna are expected to be integrated in a wide range of devices and vehicles. This generates a need of affordable and compact antenna solutions for mass production. In this paper, we aim to demonstrate that design automation tool is a promising technology in order to keep antenna low-cost and to achieve the desired performances.

Main Results

We propose a new approach in antenna design automation consisting in the use of coupled micro-array of inverted-F antennas (IFA) loaded with impedances that are automatically optimized in order to reach the required design goals [1]. The effect of these impedance loads can be efficiently computed based on the flow diagram resolution without any electromagnetic simulation. Consequently, we can use an optimization algorithm (e.g. convex optimization, etc.) to find the impedance values that give the better radiation pattern for GNSS application. The cost function in the optimization algorithm is based on Spherical Wave Expansion (SWE), which is a convenient mathematic to describe radiation properties of antennas [2]. The use of SWE method to analyze antenna's radiation modes makes this process suitable for a matching of targeted radiation properties for GNSS application. After optimization, we integrate surface-mounted components into the antenna geometry according to the optimized impedance values. With an application to dual-band GNSS (L1/L2), a prototype of a compact micro-array of eight printed IFA antennas (35 x 35 x 9 mm^3) is presented in Fig.1-a. Radiation measurements is performed at the CEA-Leti anechoic chamber. Measurement results are in a very good agreement with simulations at L1 frequency band (1575 MHz) with respectively RHCP and LHCP gain of 3 dBic and -18 dBic in boreside direction (Fig.1-b). On the other side, simulation and measurement are in acceptable agreement in L2 frequency band (1230 MHz) with a decrease of 0.6 dB and 1.4 dB on RHCP and LHCP gain (Fig.1-c).Those results show that the automated design process is able to achieve promising radiation performances and antenna miniaturization.

Perspectives

This automated antenna design is applied for the development of compact micro-array geometry generating different radiation patterns (directional, omnidirectional) and field polarizations (linear, circular).

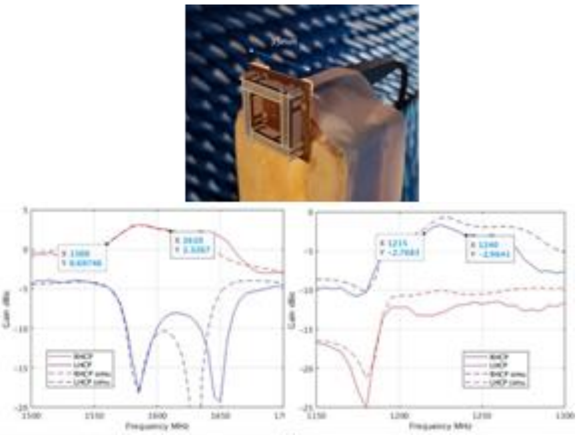

Fig. 1: antenna gain in L1, L2 bands

RELATED PUBLICATIONS:
[1] L. Rudant, L. Batel, A. Clemente and C. Delaveaud, "New Approach in Antenna Design Automation Applied to a Dual-Band GNSS Micro-Array," *15th European Conference on Antennas and Propagation (EuCAP)*, pp. 1-5, 2021.
[2] A. Clemente, M. Pigeon, L. Rudant, and C. Delaveaud, “Design of a super directive four-element compact antenna array using spherical wave expansion", IEEE Trans. Antennas Propag., vol. 63, n. 11, pp. 4715-4722, Nov. 2015.

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03 WIRELESS CONNECTIVITY

Radio and network architectures for sustainable beyond-5G connectivity

- **Sub-THz, millimeter wave communications**
- **5G and beyond 5G, 6G**
- **Learning for Multi-access Edge Computing (MEC)**
- **Network orchestration and higher protocol layers**
- **Antenna and transmitarrays**
- **Beam forming**
- **High performance antennas**
- **Antenna simulation, specific design and characterization**
- **CMOS technologies and integrated circuits**
- **Power amplifier modules**

Energy-efficient edge computing and learning in beyond 5G networks

RESEARCH TOPIC:

Joint communication-computation resource management, beyond 5G, energy-efficient and reliable computing and edge learning

AUTHORS:

P. Di Lorenzo[1], S. Barbarossa[1], F. Costanzo[1], A. Martino[2], N. di Pietro[3], M. Merluzzi, **E. Calvanese Strinati**

This activity investigates the emerging synergy of communication and computing, a paradigm whose popularity is growing at unprecedented pace, especially thanks to new technological enablers such as Multi-access Edge Computing and new mobile systems such as 5G and beyond networks. The study is on computation offloading, by which end devices transmit data to nearby servers that run applications on their behalf, to reduce energy consumption while targeting performance, that include accuracy of learning related tasks running at the edge of wireless networks. A further role is played by the optimization of Reconfigurable Intelligent Surfaces (RIS), to close the loop between application requirements, communications, and wireless propagation environment adaptation.

SCIENTIFIC COLLABORATIONS: [1]Sapienza University of Rome (IT), [2]Italian National Research Council, ISTC-CNR (IT), [3]Athonet (IT)

Context and Challenges

Learning and inference at the edge is a challenging task from several perspectives, since data must be collected by end devices, pre-processed, and finally processed remotely to output the result of training and/or inference phases. This involves heterogeneous resources, such as radio, computing and learning related parameters. In this context, this study aims at devising online learning and adaptation strategies to dynamically allocate radio and computing resources. The goal is to explore emerging trade-offs between energy, delay, and learning accuracy, to enable resource efficient yet reliable Artificial Intelligence at the edge of wireless networks. Part of this research activity is performed in the context of the H2020 project Hexa-X, the European 6G flagship project.

Main Results

A first step to enable energy efficient edge computation offloading of learning tasks is to explore the two-dimensional trade-off entailing energy and service delay. Indeed, offloading applications from end devices to nearby Mobile Edge Hosts (MEHs), incurs in both communication and computation delays and energy consumption, thus calling for a *holistic* resource allocation perspective. Building on this, a joint communication-computation resource allocation framework that dynamically and adaptively selects connect-compute parameters is proposed in contribution [1], exploiting low power sleep modes at devices, access point, and MEH sides. The idea is to shift the MEC paradigm from an *always on* to an *always available* architecture, in which all entities spend the largest amount of time in idle mode, while guaranteeing target performance in terms of service delay. Going further, the specific case of offloading to learn and inference is analyzed in [2-3], where other application performance are considered to extend the study to a three-dimensional trade-off that also involves learning accuracy, by playing on communication and computing, but also on source encoding schemes. An exemplary scenario is shown In Fig. 1, in which multiple sensors offloading data are represented, along with the necessary queueing system needed to characterize the end-to-end delays typical of offloading services. Data are treated by the MEH to output learning and/or inference results (e.g. estimation or classification). Finally, the promising direction of controlling the wireless propagation environment through RIS has been analyzed in [4], with further extensions currently in progress.

Perspectives

Beyond 5G and 6G networks will serve as an efficient AI platform, in which massive amounts of data are continuously exchanged among intelligent agents that cooperate to absolve complex common tasks, with target performance in terms of delay, accuracy, trustworthiness, privacy, etc. The Idea of a sustainable 6G network enabling future services should thus build on such a holistic perspective on communication, computation, learning, and control.

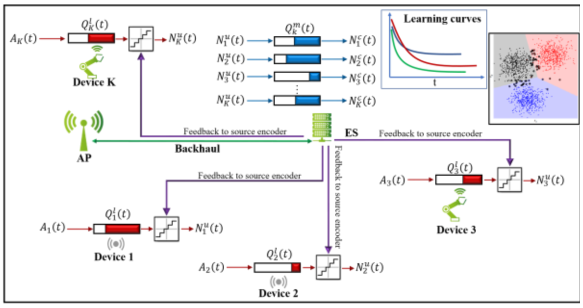


Fig. 1: Network model

RELATED PUBLICATIONS:

[1] M. Merluzzi, *et. al*, "Discontinuous Computation Offloading for Energy-Efficient Mobile Edge Computing," IEEE Trans. Green Comm. and Networking, 2021.
[2] P. Di Lorenzo, M. Merluzzi, S. Barbarossa, “Wireless Edge Machine Learning in 5G/6G Networks”, Chapter 10 of CNIT Technical Report-07: Machine Learning and 5G/6G Networks: Interplay and Synergies. Editors: Barbarossa Sergio, Zanella Andrea. Available on: https://www.texmat.it/collana-cnit.html
[3] M. Merluzzi *et al*., "Dynamic Ensemble Inference at the Edge," 2021 IEEE Global Communications Conference (GLOBECOM), pp. 1-6, 2021.
[4] P. Di Lorenzo, M. Merluzzi and E. C. Strinati, "Dynamic Mobile Edge Computing empowered by Reconfigurable Intelligent Surfaces," 2021 IEEE 22nd International Workshop on Signal Processing Advances in Wireless Comm. (SPAWC), pp. 526-530, doi: 10.1109/SPAWC51858.2021.9593253, 2021.

Efficient resource management in next-generation networks: the central role of distributed learning mechanisms

RESEARCH TOPIC:

Optimisations. Distributed Learning. Machine Learning. Radio Resource Management in Wireless Networks. 5G/6G Networks.

AUTHORS:

M. Sana, M. Merluzzi, N. di Pietro[1], E. Calvanese Strinati

The emergence of new applications and use-cases, with stringent requirements, in wireless network industries makes the management of next-generation networks complex, requiring advanced, flexible, scalable, and low complexity solutions. In this context, traditional *network-centric* approaches, applicable in practice, result in a large signaling overhead and cumbersome centralized computations, thus, becoming inefficient. In contrast, this work adopts distributed *user-centric* approaches, which are scalable, flexible, and robust to environmental artifacts. In particular, our approach enables distributed user devices to learn to collaborate with (or compete against) each other for radio and/or computing resources to optimize targeted network utility functions.

SCIENTIFIC COLLABORATIONS: [1] Athonet, 36050 Bolzano Vicentino (VI), (IT)

Context and Challenges

Wireless communications are experiencing an unprecedented demand for communication bandwidth. It is not only the volume of data traffic exploding, but also the characteristics and nature of communicating objects are diversifying (cf. Fig. 1). In addition, emerging new applications and use cases with stringent requirements, make the management of radio and computing resources complex, requiring advanced, flexible, scalable, and low complexity solutions. We address this problem, focusing on *distributed learning* mechanisms and leveraging *artificial intelligence (AI)* for effective and efficient radio resource management in next-generation networks. In contrast to centralized approaches, distributed solutions are flexible, scalable, and robust to environmental artifacts, which are local. They reduce signaling overhead and strongly limit cumbersome centralized computations. However, distributed learning faces several challenges, especially in dense networks deployments, due to an uncertain wireless environment and limited radio and computing resources, which we propose to tackle.

Main Results

To address the aforementioned challenges, we propose new distributed learning frameworks based on multi-agent reinforcement learning [1]. Our solution jointly considers environment dynamics, including radio channel variations, cell interference, users' traffic and mobility for dynamic radio resource management. Specifically, we endow mobile devices with AI-computing capabilities and model user equipment as independent agents, which collaborate with (or compete against) each other for radio and/or computing resources to optimize network utility functions. To do so, the agents rely on their local and global observations to make autonomous decisions, thereby significantly reducing signaling and computational overhead. In addition, we manage the agents to learn *transferable policies*. It is a key feature, which allows applying knowledge acquired in a specific scenario, to distinct scenarios, without requiring additional learning procedure, further reducing the computational complexity [2]. Numerical results have shown the effectiveness of our solution for solving a wide range of tasks. It can provide up to 80% network sum-rate improvement, outperforming centralized benchmarks when applied to user association problem, i.e. for finding the optimal association between user equipment and base stations [2]. Also, we successfully applied the proposed solution for computation offloading tasks, reaching up to 96,5% of the optimal performance obtained via exhaustive-search and reducing the energy consumption by 10% under strict end-to-end delay constraints [3].

Perspectives

The results of this work are promising for applications in networks with multiple distributed mobile access points, a challenging problem, which requires joint management of the access and backhaul resources.

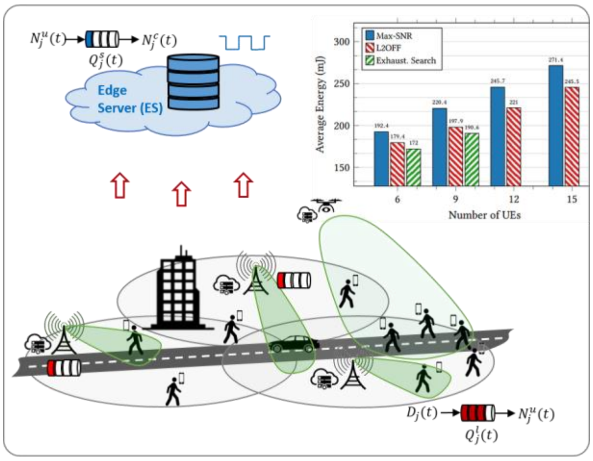


Fig. 1: A heterogeneous network

RELATED PUBLICATIONS:

[1] M. Sana, A. De Domenico, W. Yu, Y. Lostanlen, E. Calvanese Strinati, "Multi-agent reinforcement learning for adaptive user association in dynamic mmWave networks", IEEE Transactions on Wireless Communications, vol. 19, no. 10, pp. 6520-6534, 2020.

[2] M. Sana, N. Di Pietro, E. Calvanese Strinati, "Transferable and distributed user association policies for 5G and beyond networks", Proc. IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), pp. 966-971, 2021.

[3] M. Sana, M. Merluzzi, N. Di Pietro, E. Calvanese Strinati, "Energy efficient edge computing: when Lyapunov meets distributed reinforcement learning", Proc. IEEE International Conference on Communications (ICC) Workshops, pp. 1-6, 2021.

Beyond 5G private networks for the factory of the future

RESEARCH TOPIC:

5G and beyond private networks, smart factories, deployment, operation, flexible usage, resource and infrastructure

AUTHORS:

M. Maman, E. Calvanese Strinati, L.N. Dinh

Future Smart Factories leverages Industry 4.0 and 5G technology to increase the flexibility and efficiency of manufacturing processes, ensuring the global competitiveness of industrial manufacturing. 5G technologies such as network slicing can accommodate industrial applications in public networks, while Private 5G Networks, operating locally and being highly optimized for specific applications, may require disruptive technologies to meet specific and challenging industrial requirements. The 5GCONNI Europe-Taiwan project investigates innovative solutions for Private 5G and beyond Network (e.g. new architecture, ultra-reliable low-latency communications) and validates them with a real-field cross-continental end-to-end industrial Private 5G Network demonstration.

SCIENTIFIC COLLABORATIONS: [1]Fraunhofer, HHI (GE), [2]Sapienza University of Rome, Rome (IT), [3]Robert Bosch GmbH (GE), [4]Athonet (IT) [5]ITRI (TW) [6]Chunghwa Telecom (TW), [7]Alpha Networks Inc. (TW), [8]III (TW).

Context and Challenges

Private networks will play a key role in 5G and beyond to enable smart factories to better deploy, operate and flexibly utilize available resources and infrastructure. 5G private networks will offer a lean and agile solution to effectively deploy and operate services with stringent and heterogeneous constraints in terms of reliability, latency, reconfigurability and resource redeployment as well as issues related to governance and ownership of 5G components, and elements. The 5GCONNI project has selected three private networks use cases for implementation at two trial sites in Europe and Taiwan: Process diagnostics by computer numerical control and sensing data collection, Process diagnostics using virtual/augmented reality and Robot platform with edge intelligence and control.

Main Results

In 5GCONNI, we propose a new approach to operator models, specifically targeting 5G and beyond private networks. The most important dimensions are 5G elements (e.g. 5G network functions, Radio Access Network (RAN) components) and non-5G elements (e.g. enterprise IT), private 5G network lifecycle tasks and involved stakeholders (e.g. enterprise, mobile network operator, service provider). We apply the proposed operator models to different network architecture options and to a selection of relevant use cases offering mixed private-public network operator governance and ownership, taking into account the concerns and requirements imposed by the different stakeholders.

Finally, an important aspect of private networks concerns the technology enablers, which include technological components and optimization methodologies. Some optimization can be performed individually as service placement, network slicing, or jointly at RAN, Mobile Edge Computing (MEC) or core network level as network orchestration. For example, we proposed a new methodology to design an end-to-end orchestrator taking into account the heterogeneity and coexistence of services, the dynamic evolution of needs (e.g., traffic, number of users and quality of service) and the evolution of the environment. The AI-based orchestrator measures, predicts the network performance, dynamically changes network parameters and elastically combines diversity to face to a multitude of (un)predictable impairments.

Perspectives

The 5GCONNI project will offer an unprecedented integrated end-to-end 5G private network to test specifically industrial applications in accordance with the updated 5G standards specifications and will validate its innovative advanced solutions/components with a real-field cross-continental network demonstration between two interconnected industrial manufacturing sites in Taiwan and Europe. In addition, we are investigating dynamic decision maker algorithms and proactive resource scheduling to better exploit the trade-off between end-to-end latency, reliability and resource efficiency for ultra-reliable low-latency communications.

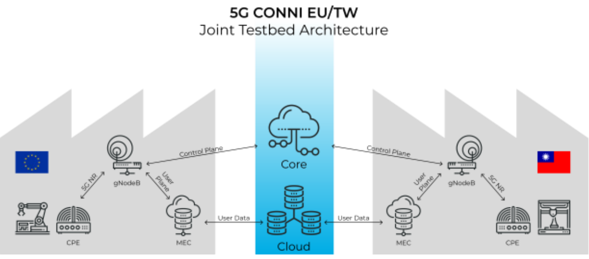


Fig. 1: 5G CONNI Joint testbed architecture

RELATED PUBLICATIONS:

[1] E. Calvanese Strinati, T. Haustein, M. Maman, W. Keusgen, S. Wittig, M. Schmieder, S. Barbarossa, M. Merluzzi, H. Klessig, F. Giust, D. Ronzani, S.-P. Liang, J. S.-J. Luo, C.-Y. Chien, J.-C. Huang, J.-S. Huang, T.-Y. Wang, "Beyond 5G Private Networks: the 5G CONNI Perspective," 2020 IEEE Globecom Workshops, pp. 1-6, doi: 10.1109/GCWkshps50303.2020.9367460, 2020.

[2] M. Maman, E. Calvanese-Strinati, L.N. Dinh, T. Haustein, W. Keusgen, S. Wittig, M. Schmieder, S. Barbarossa, M. Merluzzi, F. Costanzo, S. Sardellitti, H. Klessig, S. V. Kendre, D. Munaretto, M. Centenaro, N. di Pietro, S.-P. Liang, K.-Y. Chih, J. S.-J. Luo, L.-C. Kao, J.-C. Huang, J.-S. Huang and T.-Y. Wang "Beyond private 5G networks: applications, architectures, operator models and technological enablers", J Wireless Com Network 2021, 195. https://doi.org/10.1186/s13638-021-02067-2, 2021.

FPGA implementation of multi Gbps wideband transceiver for 5G

RESEARCH TOPIC:
5G, FPGA implementation,.mmWave

AUTHORS:
JB. Doré, M. Laugeois, N. Cassiau, X. Popon

This work describes a Field Programmable Gate Array (FPGA) implementation of a multi-Gb/s Block Filtered (BF) OFDM transceiver, fully 5G-NR compatible. The main obstacles for such a work are the support of multiple configurations and parameters, the high bandwidth w.r.t the board clock frequency, and the intrinsic complexity of BF-OFDM. We prove that despite these barriers a hardware implementation of this waveform is possible, even with a bandwidth up to 400MHz. We based our developments on the following pillars: complexity minimization of the basic modules, parallelized design of dedicated functions and ad hoc architecture.

Context and Challenges

5G is now being deployed around the world. Cyclic Prefix (CP)-Orthogonal Frequency Division Multiplexing (OFDM) is widely used. Nevertheless, CP-OFDM faces two major drawbacks: it shows poor out-of-band rejection capability and it is not adapted to multi-user / multi-service scenarios without stringent time synchronization. 5G New Radio standard (5G-NR) leaves the door open to other OFDM-based waveforms, provided they satisfy the so-called specification transparency property, i.e compatibility with an OFDM receiver [2]. Block Filtered (BF)-OFDM [3] is one of these candidate waveforms: its subchannel-configurable-polyphase network (PPN) filtering stage allows different services to cohabit in the same band, without interfering on each other. Nevertheless, the design of a 5G-NR compliant transmitter supporting all the numerologies as well as a very large transmission bandwidth is challenging.

Main Results

In this work, we focus on a flexible design supporting on the fly reconfiguration of the numerologies as well as a wideband architecture of the modem (in this case 400 MHz). To deal with very high throughput, far from the hardware clock rate, limited to (100-200MHz) for Field Programmable Gate Array (FPGA), efforts have to be done at the architecture level. Interestingly, the BF-OFDM transceiver architecture can be naturally implemented in parallel. Basically, a BF-OFDM transmitter can be shown as an aggregation of M CP-OFDM sub-channels of size N combined with a PPN. The main difficulty lies in the design of the PPN function, which has to deal with M parallel streams to feed Digital to Analog Converters (DAC) with a high throughput signal. At the receiver side, a similar strategy is applied, knowing that FFT is the most complex module of the decoding chain, like in most of the multi-carrier systems. Here, the FFT processing can be envisaged working in parallel to create P parallel streams, each one being processed independently by a Frequency Domain processor. For the first time, such an implementation with a 400 MHz bandwidth providing a data rate of more than 2.5 Gb/s in the 26 GHz band has been demonstrated as depicted in Fig 1.

Perspectives

FPGAs are suitable for fast laboratory developments and tests, nevertheless this study paves the way for implementation of BF-OFDM on dedicated System on Chips with a mix of hard coded and generic functions. Concerning the latter, a DSP based architecture is under study. Finally, this modem will be interfaced with a transmit array antenna system at 26GHz to demonstrate a truly mmWave multi user MIMO link.

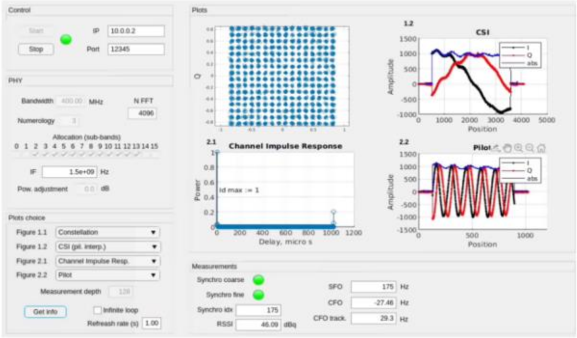

Control
IP 10.0.0.2
Port 12345
PHY
Bandwidth 400.00 MHz
N FFT 4096
Numerology 3
Allocation (sub-bands) 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
IF 1.5e+09 Hz
Pow. adjustment 0.0 dB
Plots choice
Figure 1.1 Constellation
Figure 1.2 CSI (pil. interp.)
Figure 2.1 Channel Impulse Resp.
Figure 2.2 Pilot
Measurement depth 128
☐ Infinite loop
Refreash rate (s) 1.00
Measurements
Synchro coarse ●
Synchro fine ●
Synchro idx 175
RSSI 46.09 dBq
SFO 175 Hz
CFO -27.46 Hz
CFO track. 29.3 Hz

Fig. 1: Wideband 5GNR BF-OFDM transmission

RELATED PUBLICATIONS:
[1] J. -B. Doré, M. Laugeois, N. Cassiau and X. Popon, "FPGA Implementation of a Wideband Multi-Gb/s 5G BF-OFDM Transceiver," 2021 Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit), pp. 502-507, doi: 10.1109/EuCNC/6GSummit51104.2021.9482424, 2021.

Evaluating handover performance for end-to-end LTE networks with OpenAirInterface

RESEARCH TOPIC:

End-to-end experimentation, LTE handover, open and reconfigurable software defined radio environment

AUTHORS:

R. Bertolini, **M. Maman**

We proposed an experimental testbed of the handover (HO) procedure using an open and reconfigurable Software-Defined Radio (SDR) environment. Our implementation is based on OpenAirInterface (OAI), an open-source pluggable cellular network solution, to avoid the limitations of vendor implementations and to allow for protocol customization. OAI provides an end-to-end cellular architecture including the Radio Area Network (RAN) and the core network. The HO procedure via the X2 interface is fully described in this architecture, including the HO conditions, message flow and latency decomposition. The performance, in terms of end-to-end throughput and latency for each step of the HO procedure, is analyzed and compared to the state of the art of X2 HO experiment.

Context and Challenges

Cellular network handover provides continuity of service to users with varying radio or traffic quality by switching the connection from the serving to a selected cell. OAI, an open-source pluggable end-to-end cellular network solution, implements the RAN (i.e. UE and eNodeB) and the core network (i.e. Mobility Management Entity (MME), Home Subscriber Server (HSS), and Serving Gateway and Packet Data Network Gateway (SPGW)). This configuration can represent a private network in a factory where the core is close to the RAN. Our challenge is to optimize HO with this full SDR experimentation setup.

Main Results

We have implemented the X2 handover procedure in the OAI RAN of an LTE network. This includes (but is not limited to) the implementation of multi-eNB management, such as eNB synchronization eNB scanning and selection by the UE RAN, reference signal received power measurement of neighboring cells, contention-free and contention-based random access procedures. Then, realistic pedestrian mobility scenarios are experimented with this end-to-end, full-SDR environment using an accurate channel emulator. Finally, we analyzed the performance in terms of end-to-end throughput and latency for each step of the procedure. For example, the durations of the HO preparation, execution and completion phases are 83ms, 150ms and 8ms, respectively.

Perspectives

We will extend our experimentation to 5G NR networks and include dynamic resource scheduling optimization for ultra-reliable low-latency communications.

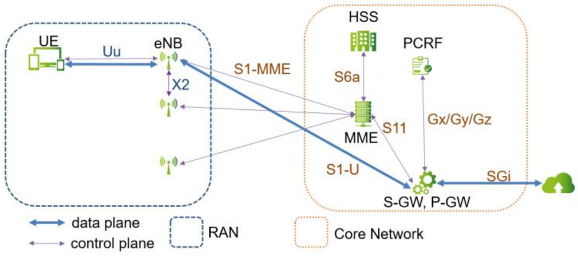


Fig.1: LTE end-to-end architecture

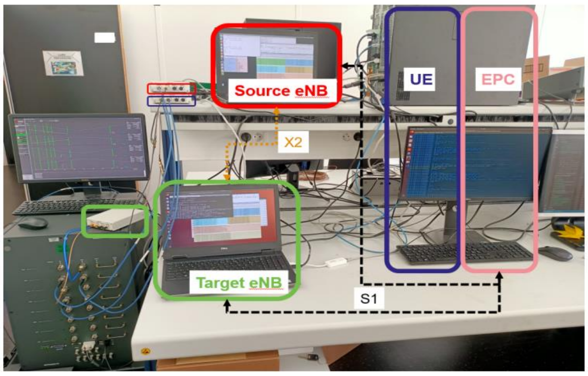


Fig. 2: OAI-Based setup with channel emulator

RELATED PUBLICATIONS:

[1] R. Bertolini and M. Maman, "Evaluating Handover Performance for End-to-End LTE Networks with OpenAirInterface," *2021 IEEE 94th Vehicular Technology Conference (VTC2021-Fall)*, pp. 1-5, doi: 10.1109/VTC2021-Fall52928.2021.9625562, 2021.

Long-range broadband wireless system for maritime communications in the 3.5 GHz band

RESEARCH TOPIC:
Maritime communication, long range, beam steering, testbed deployment, 5G waveform, Time Division Duplexing

AUTHORS:
JB. Doré, L. Lombard, X. Popon, B. Miscopein, D. Kténas, **P. Rosson**

With the increasing requirements for wireless data transfer and the new capabilities of 5G, the maritime transport industry is looking for wireless technologies based on wide-area terrestrial coverage that would offer a better quality of service than satellite solutions. Due to the large distance between coast and vessels, the design of a maritime wireless network based on terrestrial base stations is a challenge. In this study, we demonstrated that it is possible to cover the ship lanes between Ouistreham (FR) and Portsmouth (UK) separated by 180 km with appropriate base station locations and dedicated antenna strategies. The demonstration in the 5G TDD band at 3.5 GHz proved that it is possible to deliver 80+ Mbps with a bandwidth of 40 MHz.

Context and Challenges

Brittany Ferries is a French company operating ferries between France, United Kingdom, Ireland and Spain. For on-board communication, it currently uses satellite systems but they suffer from a high latency (i.e. 700 ms) and are very expensive. To reduce both latency and cost, we propose to demonstrate the coverage of the ferry route between Ouistreham (FR) and Portsmouth (UK) using radio stations located on the coast. The main challenge was to achieve a minimum data rate of 80 Mbps, while the distance between the ship and the coast could be as large as 90 km.

Main Results

Three terrestrial base stations have been designed and deployed along the coasts, using fixed sectored antennas. Two are located in Normandy (France), and one on the Isle of Wight (UK). We designed and installed one radio station on a ferry with beam-steering capabilities (Fig 1). The radio system uses a 5G-NR compatible waveform and a TDD bidirectional protocol. We showed that the entire route can be covered with a downlink rate of 80 Mbps, assuming a bandwidth of 40 MHz (Fig 2). The experiments exhibit fading phenomenon due to the two-ray propagation channel, resulting in the combination of the direct path and reflection path over the sea.

Perspectives

Fading issues can be avoided using spatial diversity using different ground station heights and/or polarization diversity. Also, this system can be adapted to other maritime communications use-cases, using the IMT band 38, located at 2,6 GHz.

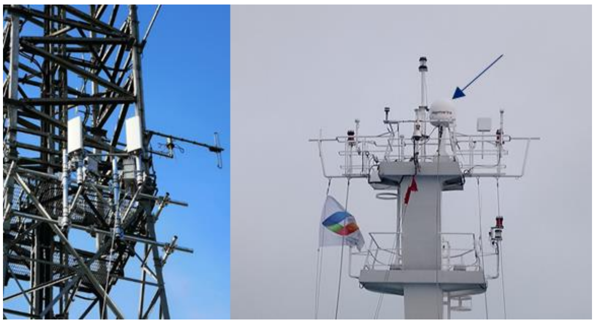


Fig. 1: Terrestrial and on-board stations

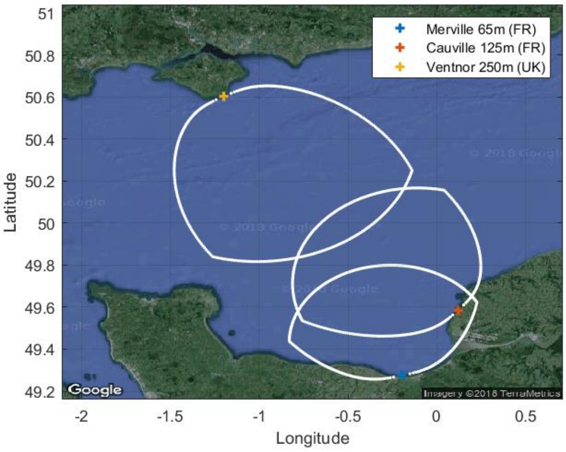


Fig. 2: Overall system coverage

RELATED PUBLICATIONS:
[1] Patrick Rosson, Jérémy Estavoyer, Laurent Lombard, Benoit Miscopein, Xavier Popon, Jean-Baptiste Doré, Dimitri Kténas, Vincent Coquen, Ronan Jegou-Le Bris, "Long-range broadband wireless system for maritime communications in the 3.5 GHz band," 2021 IEEE 94th Vehicular Technology Conference (VTC2021-Fall), pp. 1-5, doi: 10.1109/VTC2021-Fall52928.2021.9625164, 2021.

Design of MIMO systems using energy detectors for sub-THz

RESEARCH TOPIC:

6G, sub-THz wireless communication

AUTHORS:
S. Bicaïs, A. Falempin; **JB. Doré**, V. Savin

The significant amount of unused spectrum in sub-THz frequencies is contemplated to achieve high rate wireless communications for beyond 5g networks. The performance of RF sub-THz systems is severely degraded by strong oscillator phase noise. Therefore, we investigated the use of multiple-input multiple-output (MIMO) systems with energy detection receivers to achieve high rate communications robust to phase noise. Our results show that spatial multiplexing with non-coherent sub-THz transceivers can be achieved on strongly correlated line-of-sight channels using new detection schemes. Thereby, we highlight that high-rate RF sub-THz systems can be implemented with low-complexity and low-power architectures using MIMO systems with energy detection receivers.

Context and Challenges

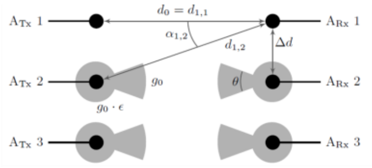
Considering the spectrum shortage in cellular bands, the interest for communications in the TeraHertz (THz) spectrum from 0.1 THz to 1 THz is continuously growing. THz frequencies offer a significant amount of unused bands and represent an opportunity to achieve high data rate wireless communications. Radio-frequency (RF) THz communication systems are envisaged to meet the requirements of beyond 5G networks. To achieve high data rate sub-THz communications, additional research is required to design efficient and new physical layer algorithms. Traditional techniques cannot be directly transposed to sub-THz bands as they do not consider the specific features of RF impairments in sub-THz systems. In particular, they suffer from strong phase impairments due to the poor performance of high-frequency oscillators. In contrast to the conventional approaches using linear RF chains, our purpose is to enable high-rate sub-THz communications using low complexity transceivers, employing energy detectors (ED) and suitable transmission schemes combined with spatial multiplexing.

Main Results

We derive in [1] an analytical model for MIMO systems using ED receivers in sub-THz bands, together with the design of the receiver detection algorithm. A detector corresponding to the studied nonlinear MIMO channel using a Gaussian approximation approach, which we refer to as the Maximum Likelihood Detector with Gaussian approximation (MLD-GA) is proposed and assessed. In addition, we propose an original and yet efficient detector based on neural networks, which does not require any knowledge of the channel or even any assumption on it. The system performance is evaluated through numerical simulations, with, in particular, a realistic scenario modeling a fixed indoor wireless link in the D-band at 145 GHz. Our results demonstrate that communications can be achieved with strong spatial interference between channels using the proposed detection algorithms and very low output power (Fig 1). Moreover, we show that integrating a low-complexity channel coding scheme leads to valuable performance gains in terms of achievable data rate.

Perspectives

It is worth mentioning that the presented techniques and results are relevant to applications beyond sub-THz communications such as visible light communications or optical systems. Visible light communication systems commonly implement intensity modulation and detection. The nonlinear interference between channels in these systems is also a major challenge to realize spatial multiplexing. The proposed detectors could be easily adapted to visible light communication systems in order to achieve spatial multiplexing.



Carrier frequency	f_c	145 GHz			
Bandwidth	B	2 GHz			
Propagation distance	d_0	10 m			
Antenna gain	g_0	32 dBi			
Number of antennas	N	1	4	6	8
Throughput	$N/T \cdot 0.9$	0.9 Gbps	3.6 Gbps	5.4 Gbps	7.2 Gbps
Power by antenna	$P_{A_{Tx}}$	−31.8 dBm	−31.2 dBm	−30.4 dBm	−32.3 dBm
Width of the ULA	ℓ	5 cm	44 cm	50 cm	55 cm
Inter-antenna distance	Δd	∅	13 cm	9 cm	7 cm

Fig. 1: Parameters, key performance indicators

RELATED PUBLICATIONS:
[1] S. Bicaïs, A. Falempin, J. -B. Doré and V. Savin, "Design and Analysis of MIMO Systems using Energy Detectors for Sub-THz Applications," in IEEE Transactions on Wireless Communications, doi: 10.1109/TWC.2021.3123220, 2021.

Frequency reconfigurable low-profile UWB magneto-electric dipole in VHF band

RESEARCH TOPIC:

Compact and directive antenna, frequency reconfigurable, magneto-electric dipole, ultra-wideband antenna

AUTHORS:

AS. Kaddour, S. Bories, A. Bellion[1] and **C. Delaveaud**

Reducing the size of directive and wideband antennas operating in the Very High-Frequency band is a major challenge for small satellite integration. At 100 MHz, the wavelength is 3 m, and the size reduction will make the integration easier and reduces fabrication costs. The original technique presented enables a significant height reduction (up to 50%) of a crossed Magneto-Electric Dipole antenna while maintaining an ultra-wideband operation bandwidth from 93 to 360 MHz (118%). The proposed technique is based on adding frequency reconfigurable capability to a crossed Magneto-Electric Dipole antenna structure. The antenna has been prototyped and experimentally characterized in a large-sized anechoic chamber.

SCIENTIFIC COLLABORATIONS: [1] CNES, 18 avenue Edouard Belin, 31401, Toulouse, (FR)

Context and Challenges

A new generation of "smaller, faster available and cheaper" satellites, capable of carrying out many space missions in addition to conventional large satellite systems, has emerged. Among the numerous challenges, one critical issue deals with the size and weight reduction of satellite antennas, particularly at VHF-UHF frequency bands, where the wavelength involves large-sized radiating elements (antennas of several meters). According to the fundamental theory of small antennas, antenna miniaturization is a major scientific challenge that deteriorates the antenna gain, reduces efficiency and operation bandwidth.

Main Results

In this work, we propose to combine miniaturization techniques known as narrow-band techniques with frequency reconfigurable techniques. Thus, frequency agility techniques make it possible to envisage miniaturization of the radiating structure by synthetizing sequentially a large frequency bandwidth. Also, our technique ensures better stability of the radiation properties with frequency.

The proposed design of a frequency reconfigurable low-profile Crossed "Magneto-Electric Dipoles" MED antenna [1-2] in the VHF band is achieved with the following features: (a) a low-profile thickness, (b) a reconfigurable frequency capability with two instantaneous wideband operation modes (first octave bandwidth In state 1, second octave one in state 2) by 'cutting' the radiating element with pin diodes, and (c) a lightweight prototype.

Fig. 1 shows the realized circular polarization gain for both operation states. Considering an SWR<3, two wideband modes can be achieved from 100 to 180 MHz and 180 to 370 MHz, respectively. The maximum gain achieved is approximately 9.5 dBic when the antenna is operating in State 1 and 11.8 dBic in State 2 [3].

The low-profile frequency reconfigurable wideband reconfigurable antenna is compared to some recent work in terms of electrical thickness, SWR, and Axial ratio (AR) bandwidth, and the proposed antenna offers the best compromise in terms of size and bandwidth. The proposed frequency reconfigurable compact antenna yields to a larger bandwidth of 120% with two fractional bandwidths of 66.2 and 77.3% in dual polarization mode, a low-profile thickness of 0.09λ (minimal frequency wavelength) which corresponds to a 50% reduction factor, in addition to a wide AR bandwidth (AR <3 dB) of 85%. The proposed antenna achieved an effective or 'synthetic' bandwidth of 120% from 93 to 370 MHz while considering a common bandwidth limited by an SWR < 3 and an AR < 3 dB.

Perspectives

New efforts to miniaturize directive circularly polarized antennas are underway based on a narrowband agility envisaged in the context of a new collaboration with CNES.

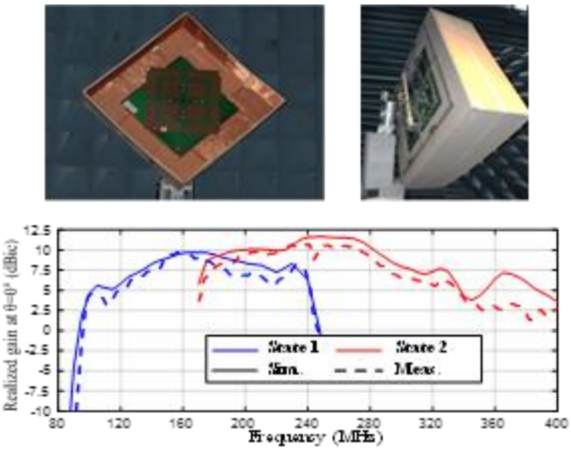


Fig. 1: VHF antenna and measured CP gain

RELATED PUBLICATIONS:

[1] A. S. Kaddour, S. Bories, C. Delaveaud and A. Bellion, "Wideband dual-polarized magneto-electric miniaturization using capacitive loading," in Proc. IEEE Int. Symp. Antennas Propag. USNC/URSI Nat. Radio Sci. Meeting, San Diego, CA, pp. 545-546, 2017.

[2] A. S. Kaddour, S. Bories, A. Bellion and C. Delaveaud, "Low profile dual-polarized wideband antenna," in Proc. IEEE Int. Symp. Antennas Propag. (ISAP), Okinawa, Japan, pp. 86-87, 2016.

[3] A. S. Kaddour, S. Bories, A. Bellion and C. Delaveaud, "Frequency Reconfigurable Low-Profile UWB Magneto-Electric Dipole in VHF Band," in IEEE Access, vol. 9, pp. 61269-61282, doi: 10.1109/ACCESS.2021.3073094, 2021.

Parasitic-based electrically small capacitive loaded loop antenna

RESEARCH TOPIC:

Electrically Small Antennas, fundamental antenna limits, radiation efficiency, IoT devices

AUTHORS:

M. Jadid, S. Bories, A. Bellion[1], **C. Delaveaud**

Based on near-field coupling design strategy, an electrically small antenna (ESA) combining different miniaturization technics is developed. The antenna is composed of a short driven element fed differentially and coupled to a parasitic capacitive loaded loop. The antenna is designed to operate at 868 MHz and presents a maximum dimension of 28.8 mm equivalent to an electrical size ka=0.261. The antenna is optimized using a full-wave EM Computer Simulation to realize maximum radiation efficiency where predictions shows nearly 76% for lossless loading capacitor and 69% for a lossy capacitor. The antenna impedance matching is directly obtained by acting on the antenna geometry resulting in a proper near field coupling between driven element and parasitic element.

SCIENTIFIC COLLABORATIONS: [1] CNES - 18 avenue Edouard Belin Ampère, 31400 Toulouse

Context and Challenges

The demand on Electrically Small Antennas for numerous wireless applications such as IoT devices, RFID, sensors networks, and small satellites is increasing rapidly. As a result, research to reduce the size of antennas has intensified and the emphasis is traditionally placed on obtaining significant bandwidth at the expense of efficiency. A different approach is proposed in this work [1] aiming to complete the first results focusing on the optimization of the ESA efficiency [2-3].

Main Results

Fig. 1 shows the designed antenna structure which is printed on both sides of a dielectric substrate. The near field coupling between the driven element and the parasitic element is used as an impedance transformation seen at the feeding input of the driven element which helps for impedance matching. Antenna miniaturization is obtained from capacitive loading of the parasitic loop. The impact of the capacitor series resistance is optimized versus the parasitic element strip width to improve the radiation efficiency. Simulated antenna properties are displayed in fig. 2 proving a good Impedance matching and efficiency of 70%. The comparison of antenna performances to another ESA designs and fundamental limits highlights the high efficiency level despite its small electrical size.

Perspectives

The antenna has been fabricated to validate the simulated performances and next developments consist in developing a frequency agile technique to enlarge its operating frequency band.

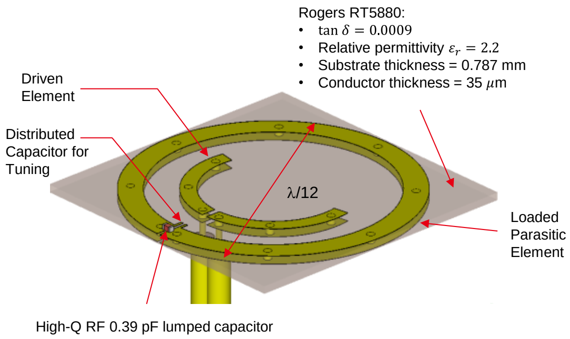

Rogers RT5880:
- $\tan\delta = 0.0009$
- Relative permittivity $\varepsilon_r = 2.2$
- Substrate thickness = 0.787 mm
- Conductor thickness = 35 μm
Driven Element
Distributed Capacitor for Tuning
λ/12
Loaded Parasitic Element
High-Q RF 0.39 pF lumped capacitor

Fig. 1: Capacitive loaded loop antenna

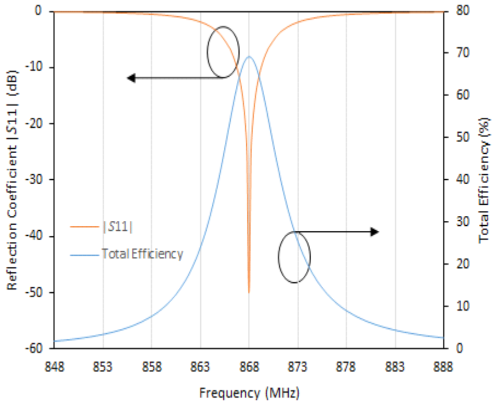


Fig. 2: Simulated results

RELATED PUBLICATIONS:

[1] M. Jadid, S. Bories, C. Delaveaud and A. Bellion, "Parasitic-Based Electrically Small CLL Antenna," 2021 IEEE 19th International Symposium on Antenna Technology and Applied Electromagnetics (ANTEM), pp. 1-2, doi: 10.1109/ANTEM51107.2021.9519052, 2021.

[2] F. Sarrazin, S. Pflaum and C. Delaveaud, "Radiation Efficiency Improvement of a Balanced Miniature IFA-Inspired Circular Antenna," in IEEE Antennas and Wireless Propagation Letters, vol. 16, pp. 1309-1312, doi: 10.1109/LAWP.2016.2633308, 2017.

[3] F. Sarrazin, S. Pflaum and C. Delaveaud, "Radiation efficiency optimization of electrically small antennas: Application to 3D folded dipole," 2016 International Workshop on Antenna Technology (iWAT), pp. 29-32, doi: 10.1109/IWAT.2016.7434792, 2016.

Experimental validation of VHF antenna miniaturization using magneto dielectric material

RESEARCH TOPIC:

Electrically small antennas, magneto-dielectric material, VHF airborne antennas, IoT devices.

AUTHORS:

C. Delaveaud, J-F. Pintos, J-L. Mattei[1], V. Laur[1], A. Chevalier[1], **L. Batel**

This work describes the ability of antenna miniaturization using two different fabricated Magneto Dielectric Materials specifically designed for the VHF band. Those particular materials are used to load two electrically small antennas (ka<0.5): a Monopolar Wire Plate Antenna (MWPA) and an Inverted-F Antenna (IFA) designed respectively around 130 MHz and 70 MHz for airborne systems application. A particular material loading strategy is used showing efficient miniaturization factors of 72% for the MWPA structure and 20% for the IFA. Experimentation carried out in large anechoic chamber confirms the miniaturized antenna performances.

SCIENTIFIC COLLABORATIONS: [1] LABSTICC, UMR CNRS 6285, 6 av. Le Gorgeu, 29238 Brest, FRANCE

Context and Challenges

Reducing the size of antennas at VHF band is an important issue for airborne systems industry, to reduce the weight of the aircraft and improve its aerodynamic shape. Nevertheless, antennas’ integration at VHF band becomes critical since the wavelengths are large at those frequencies (e.g. 6 m at 50 MHz) and will lead to reduced antenna performances following the fundamental laws of Physics. Magneto-dielectric materials (MDM) with a relative permittivity $\varepsilon_r > 1$ and relative permeability $\mu_r > 1$ have been used these last few years as a promising solution for antenna miniaturization [1-5]. Typically, an efficient strategy to miniaturize MWPA loaded by magneto-dielectric material is proposed in [2]. This method consists in loading antenna’s short-circuit and in multiplying the number of loaded short-circuits in order to interact more strongly with the properties of the MDM. On the other hand, an electrically small IFA has been loaded using the same strategy in [3-4] to achieve fine tuning frequency agility in VHF band. In this work, an experimental validation of the miniaturization of two antennas operating in the VHF frequency band is proposed in large anechoic chamber [5].

Main Results

Two types of antenna topologies are designed and fabricated in order to demonstrate the capability of miniaturization using MDM. The first antenna (Fig.1-a) is a MWPA designed at the operating frequency of f_0=136 MHz. It consists of a conductive circular plate with a radius of 105 mm (λ_0/22) and height of 120 mm (λ_0/19), shorted to a circular ground plane. λ_0 is the wavelength computed at the resonance frequency f_0. Six short circuits are used instead of one to optimize the MDM S4 loading effect [2] and to reduce the electrical size of the antenna with limited quantity of MDM. The second antenna is an IFA designed with 3 short-circuits loaded with a MDM S2 for miniaturization close to f_0=70 MHz (Fig.1-b). It includes a rectangular capacitive plate of 40 x 420 mm² (λ_0/107 x λ_0/10) with a height of 120 mm (λ_0/36) from the ground plane. Two different fabricated MDM respectively S2 $(\varepsilon_r = 13, \mu_r = 60, \tan\delta_e = 0.03, \tan\delta_m = 0.7)$ and S4 $(\varepsilon_r = 14, \mu_r = 20, \tan\delta_e = 0.05, \tan\delta_m = 0.035)$, specifically developed for antenna applications in VHF band (30-100 MHz) and (100-200 MHz) led to reduce the electrical size of the antennas. Typically, an IFA loaded with a limited quantity of S2 MDM has been miniaturized by 20% at frequencies below 100 MHz. Moreover, the potential of miniaturization of S4 material has been fully exploited to reduce the electrical size of a MWPA by a factor of 72%. Performances of the miniaturized antennas were measured at VHF frequency band and compared to the predictions by simulation incorporating the material models.

Perspectives

New joint developments of material and miniaturized antennas structure are in progress by integrating the possibility of controlling the properties of MDM to control the operating band of antennas.

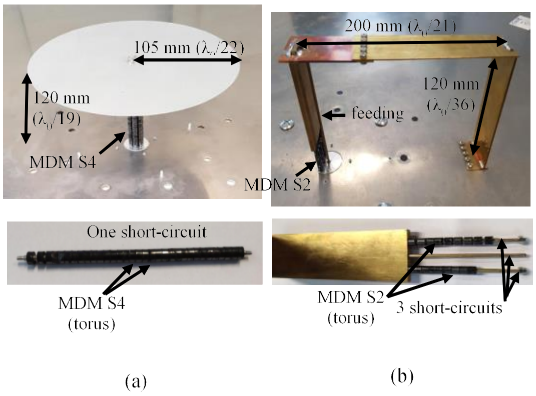


Fig. 1: MWPA and IFA loaded with MDM

RELATED PUBLICATIONS:

[1] L. Batel et al, "Design of a monopolar wire-plate antenna loaded with magneto-dielectric material," European Conf. on Antennas and Propag, EuCAP 2018.
[2] L. Batel et al, "Miniaturization strategy of compact antenna using magneto-dielectric material." European Conf. on Antennas and Propag, EuCAP, 2019.
[3] L. Batel et al, "Frequency reconfigurable antenna loaded with magneto dielectric materials at VHF band," European Conf. on Antennas and Propag, EuCAP, 2020.
[4] L. Batel et al, "Tunable Magneto-Dielectric Material for Electrically Small and Reconfigurable Antenna Systems at VHF Band" Ceramics 3(3), 276-286, 2020.
[5] L. Batel et al, "Experimental validation of VHF antenna miniaturization using Magneto Dielectric Material," Conference on Antenna Measurements & Applications, CAMA, pp. 208-211, 2021.

A Ka-band beam-steering transmitarray achieving dual-circular polarization

RESEARCH TOPIC:
Beam-steering antennas, Reconfigurable Intelligent Surfaces, Transmitarray Antennas, Satellite Communications

AUTHORS:
M. Smierzchalski, J. Reverdy, **A. Clemente, F. Foglia Manzillo**

We present an effective and technologically simple approach for the design polarization-agile beam-steering transmitarray antenna (TAs). The TA interleaves two types of electronically reconfigurable unit-cells (UCs) which receive the same linear polarization but radiate horizontally and vertically polarized waves, respectively. The phase shift introduced by each cell can be varied with a resolution of about 90° (2-bit phase quantization) using two pairs of pin diodes. Dual-circular polarization is obtained by enforcing the proper phase shift among orthogonally polarized cells. A 24×24 TA prototype for Ka-band satellite communications was realized and tested, demonstrating beam-steering and polarization switching capability up to 60°, in all azimuthal planes.

Context and Challenges

Electronically reconfigurable TAs based on switches, e.g. pin diodes, represents an energy-efficient and cost-effective solution, compared to phased arrays, to realize high-gain beam-steering antennas for Ka-band satellite communication terminals [1]-[3]. In general, these architectures cannot not provide both beam-scanning and polarization agility without a significant increase of the antenna complexity or bandwidth and efficiency degradation. For instance, the TA in [1] attains only a 9% aperture efficiency, due to the coarse 1-bit phase quantization.

Main Results

A novel TA design was proposed to mitigate these issues [3]. Dual-circular polarization is achieved using a linearly-polarized 10-dBi horn and two even sets of 2-bit reconfigurable UCs radiating orthogonal linear polarizations. Each UC comprises only four pin diodes and two bias lines. The UCs are randomly distributed to enhance the scanning performance. A 24x24 prototype has been realized in printed circuit board technology and characterized. Beam-steering in all azimuthal planes, up to maximum angle of ±60° was achieve, for both polarization, with a maximum scan loss of 5 dB. For the broadside beams, the measured axial ratio is <1 dB between 28.9 GHz and 31.2 GHz. In terms of aperture efficiency (~15%) and scan range, this prototype outperforms state-of-the-art polarization-agile TAs based on pin diodes.

Perspectives

Solutions based on the near-field illumination of the TA will lead to ultra-low-profile beam-steering antennas.

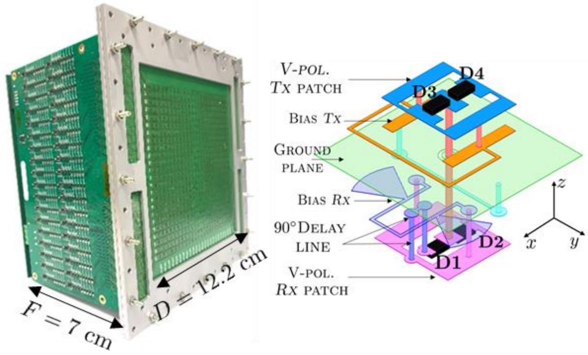


Fig.1: Prototype and V-polarized UC structure

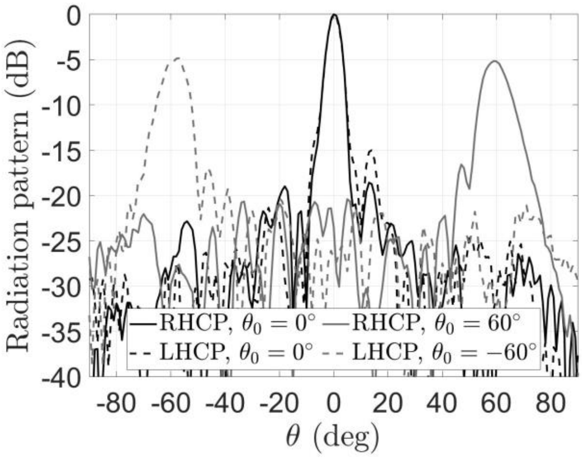


Fig. 2: Several measured patterns at 29.25 GHz

RELATED PUBLICATIONS:
[1] L. Di Palma, A. Clemente, L. Dussopt, R. Sauleau, P. Potier, and P. Pouliguen, “Circularly-polarized reconfigurable transmitarray in Ka-band with beam scanning and polarization switching capabilities,” IEEE Trans. Antennas Propag., vol. 65, no. 2, pp. 529-540, 2017.
[2] F. Diaby, A. Clemente, R. Sauleau, K. T. Pham and L. Dussopt, “2 bit reconfigurable unit-cell and electronically steerable transmitarray at Ka-band,” IEEE Trans. Antennas Propag., vol. 68, no. 6, pp. 5003-5008, 2020.
[3] F. Foglia Manzillo, M. Smierzchalski, J. Reverdy and A. Clemente, "A Ka-band beam-steering transmitarray achieving dual-circular polarization,", in Proc. *15th European Conf. Antennas Propag. (EuCAP)*, 2021.

Analysis and efficient design of sub-THz transmitarrays with three anisotropic layers

RESEARCH TOPIC:

Beamforming antennas, Flat Lens Antennas, Metasurfaces, Circuit Modelling, sub THz

AUTHORS:

O. Koutsos, R. Sauleau[1], A. Clemente, **F. Foglia Manzillo**

We present a mathematical approach for the analysis and optimization of a three-layer anisotropic unit-cell (UC) with applications to the design of low-cost sub-THz transmitarray antennas (TAs). The UC comprises three metal layers and two dielectric spacers. A four-port equivalent circuit model is derived to accurately model it. The analysis theoretically proves that the UC can achieve nearly perfect transmission and any transmission phase. A systematic procedure for optimizing the admittance tensor of the inner layer of the UC is derived. Leveraging on this procedure, a 3-bit highly efficient TA operating at 0.3 THz is designed and fabricated using a standard printed circuit board (PCB) process. As per simulations, the antenna attains a gain of 32.2 dBi.

SCIENTIFIC COLLABORATIONS: [1] Univ Rennes, CNRS, Institut d'Electronique et des Technologies du numéRique (IETR) – UMR 6164, F-35000 Rennes, (FR)

Context and Challenges

TAs reported in the sub-THz spectrum (0.1-0.3 THz) either leverage on costly fabrication techniques or exhibit degraded performance due to poor process resolution and tolerances [1]. UC designs rely on the simultaneous optimization of many geometrical and material parameters using commercial solvers. This blind parametric process is time-consuming, provides limited physical insight and does not guarantee maximum achievable performance.

Main Results

We proposed a rigorous approach for the design of via-less 3-layer UCs, comprising two outer orthogonal wire-grid polarizers and an inner polarization rotator [2-3]. A four-port equivalent circuit of the UC was proposed to describe its anisotropic behavior and derive design guidelines. A closed-form expression for the UC transmission coefficient was found from layers modeled as cascaded sheet admittances. UCs could achieve both nearly perfect transmission and full phase coverage, as opposed to 3 symmetrical layer designs. A procedure to determine admittance tensor of the inner layer for multiple low-loss TA unit-cells was proposed. A 40x40 TA was optimized from eight close-optimal-admittance UCs, for a 10-dBi horn feed and focal distance 2 cm. The prototype outperformed state-of-the-art sub-THz PCB TAs. The measured peak gain and relative 3-dB bandwidth are 32.2 dBi and 25.1%, respectively.

Perspectives

UC model and design will enable low-cost ultra-directive high-efficiency TA and other metasurface-based sub-THz components.

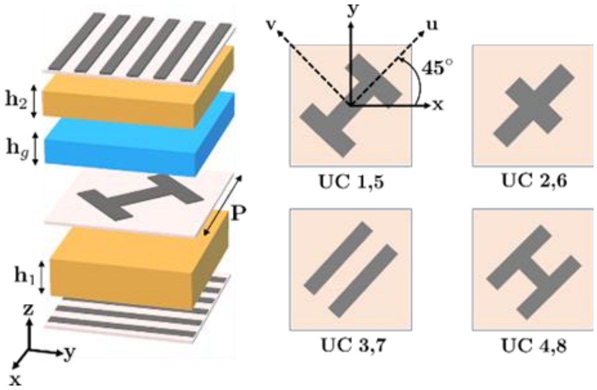


Fig. 1: Structure and designs of the eight UCs

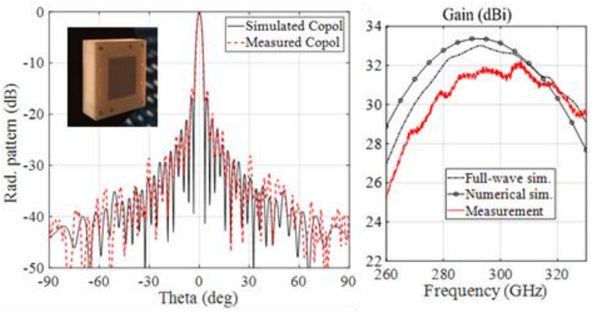


Fig. 2: Cut and gain performance vs frequency

RELATED PUBLICATIONS:

[1] F. Foglia Manzillo, A. Clemente, and J. L. Gonz´alez-Jim´enez, "High-Gain D-band transmitarrays in standard PCB technology for beyond-5G communications," IEEE Trans. Antennas Propag., vol. 68, no. 1, pp. 587–592, 2020.

[2] O. Koutsos, F. Foglia Manzillo, A. Clemente and R. Sauleau, "Analysis and efficient design of sub-THz transmitarrays with three anisotropic layers," in *Proc. 15th European Conf. Antennas Propag. (EuCAP)*, Düsseldorf, Germany, pp. 1-5, 2021.

[3] O. Koutsos, F. Foglia Manzillo, A. Clemente and R. Sauleau, "Analysis, rigorous design and characterization of a three-layer anisotropic transmitarray at 300 GHz," *IEEE Trans. Antennas Propag. (Early Access)*, 2022.

RIS-enabled mmWave channel sounding based on electronically reconfigurable transmitarrays

RESEARCH TOPIC:
Indoor channel, millimiter waves, Reconfigurable Intelligent Surfaces, Transmitarray

AUTHORS:
A. Mudonhi, M. Lotti, A. Clemente, **R. D'Errico**, C. Oestges [1]

In this work, we present a millimeter wave radio channel sounding campaign, enabled by Reconfigurable Intelligent Surfaces (RISs). The measurement setup is based on an electronically reconfigurable Transmitting-RIS (T-RIS) composed by 400 unit-cells. Optimal phase distributions were implemented in order to operate a beam scan over 120 degrees. Two indoor scenarios were investigated in the Ka Band, exploiting the beam scanning capabilities of the antenna. The results in terms of path loss and delay spread are presented and discussed

SCIENTIFIC COLLABORATIONS: [1] ICTEAM-Université catholique de Louvain, Belgium

Context and Challenges

In the development of 5G and beyond networks, millimeter waves technologies are expected to play a main role to attain high-date rate. These technologies are often considered in combination with massive MIMO transmission, beamforming antennas to counteract the poor link budgets and Reconfigurable Intelligent Surfaces (RIS) which are nowadays considered as a new paradigm for wireless communication.

Main Results

Here we exploited a Transmitting - Reconfigurable Intelligent Surface (T-RIS) for beamsteering channel sounding at mmwave. The setup is based on an electronically reconfigurable transmitarray of 400 elements, whose phase distribution is optimized to obtain beamsteering in circular and linear polarizations (Fig.1). The results show that antenna beamforming has a direct impact on both the delay spread (DS) and the path loss (PL) of the channel. When the T-RIS is steering towards the receivers in the main lobe direction, the DS is comprised between 5 and 10 ns, while larger values (up to 32 ns) were observed when steering in other directions. Likewise, the path losses in the main beam direction are reduced thanks to RIS beamforming capabilities, which leads to an improvement in the overall link budget (Fig.2).

Perspectives

Future works foresee a joint antenna-propagation model based on multidimensional description of the multi-paths. These model will be considered for the evaluation of 5G/6G systems leveraging these technologies.

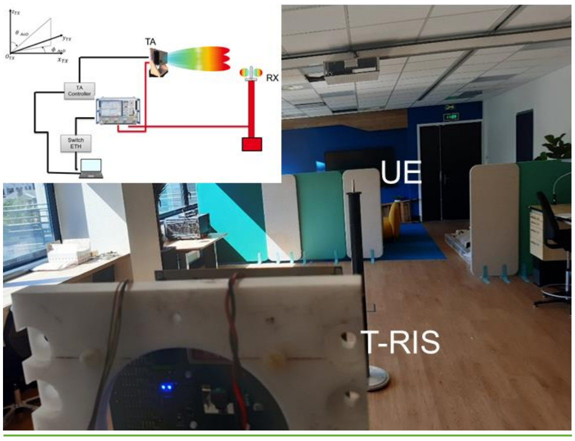


Fig. 1: RIS-enabled channel measurement

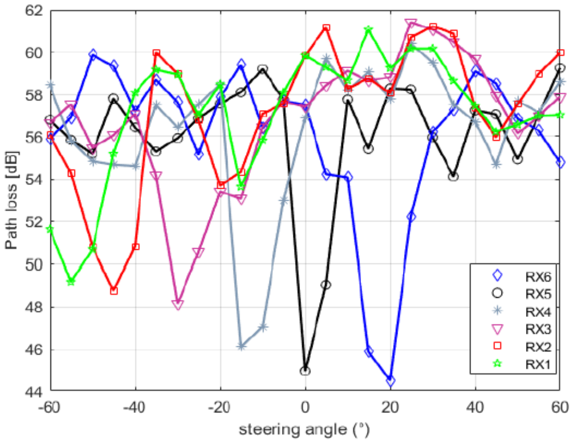


Fig. 2: Path loss for different positions

RELATED PUBLICATIONS:
[1] A. Mudonhi, M. Lotti, A. Clemente, R. D'Errico and C. Oestges, "RIS-enabled mmWave Channel Sounding Based on Electronically Reconfigurable Transmitarrays," 2021 15th European Conference on Antennas and Propagation (EuCAP), pp. 1-5, doi: 10.23919/EuCAP51087.2021.9411218, 2021.

Dual-band dual-linearly polarized transmitarray at Ka-band

RESEARCH TOPIC:

Electronically-steerable antenna for satellite communications, reconfigurable intelligent surfaces, SATCOM antennas, Ka-band

AUTHORS:

R. Madi, R. Sauleau[1], **A. Clemente**

We present the design and the optimization of a dual-band dual linearly-polarized transmitarray antenna with a 1-bit phase resolution (i.e. Two phase states with 180° of relative phase-shift). The antenna operates in both downlink and uplink K/Ka-bands (17 – 21 GHz for the lower frequency band, and 27 – 31 GHz for the upper one) and could be used for satellite communication applications. In order to implement dual-band and dual-polarization, the unit-cell consists of four orthogonal superposed U-slotted patch antennas interconnected by a metallized via hole. A 20×20 transmitarray based on the proposed unit-cell architecture has been optimized by using our in-house tool and validated through full-wave electromagnetic simulations.

SCIENTIFIC COLLABORATIONS: [1] Université de Rennes, CNRS, IETR, UMR 6164, F-35000 Rennes, (FR)

Context and Challenges

Satcom-on-the-move (SOTM) applications require two independent steerable antenna systems for both uplink and downlink. For such applications the transmitarray antenna technology is believed as a good candidate, considering its dual-band and dual-polarization properties. So far only a few fixed beam transmitarrays propose dual-band operating at K/Ka-band.

Main Results

A dual-band dual-polarized unit-cell based on the superposition technique is presented. It consists of four U-slotted patches stacked on different layers. The phase control is obtained by rotating the transmitting layer (a rotation of 180 degrees), achieving 1-bit of phase quantization. The 1-dB transmission bandwidth of the proposed unit-cell reaches 17.4% and 10.5% at 19.5 GHz and 29 GHz respectively with an insertion loss lower than 0.5 dB. A 20×20-element transmitarray antenna with an aperture size of 100×100 mm² is simulated using the proposed unit-cell. It exhibits a maximum gain of 23.4 and 21.4 dBi with an aperture efficiency of 18.7% and 23.7% at 29.1 GHz and 19.75 GHz, respectively. To illuminate the array, two pyramidal horns are used: ATM 34-440-6 for the uplink (11.4-dBi gain) and ATM 51-440-6 (11.2-dBi gain) for the downlink. The two horns are located in the same focal plane at a distance of 60 mm from the array aperture.

Perspectives

For future perspectives, the same concept can be used for circular polarization and by adding active elements we could provide reconfigurability.

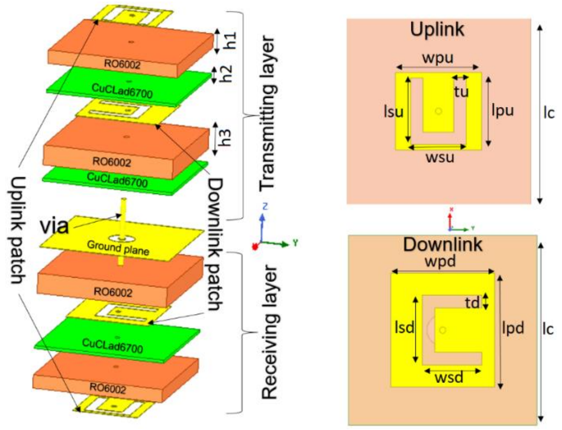


Fig. 1: 3-D view of the 1-bit unit-cell

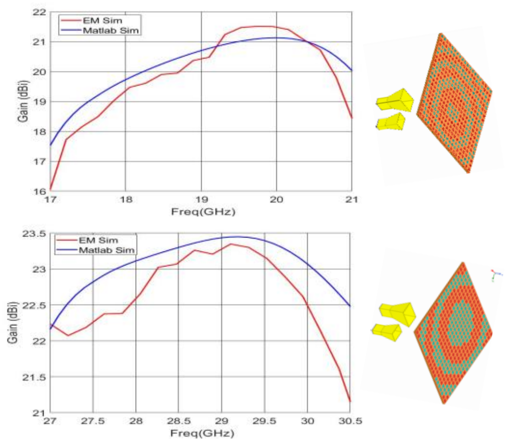


Fig. 2: Peak gain of the transmitarray

RELATED PUBLICATIONS:

[1] R. Madi, A. Clemente, and R. Sauleau, “Dual-band dual-linearly polarized transmitarray at Ka-band,” 50th European Microwave Week (EuMW), 2020.

[2] O. Koutsos, R. Madi, F. Foglia Manzillo, M. Smierzchalski, A. Clemente, and R. Sauleau “Recent achievements on passive and beam steering transmitarrays at millimeter waves,” IEEE International Symposium on Antennas and Propagation (ISAP), 2021.

[3] R. Madi, A. Clemente, and R. Sauleau, “Dual-band, dual-linearly polarized transmitarrays for SATCOM applications at Ka-band,” 16th European Conf. on Antennas and Propag. (EuCAP), 2022.

A switchable linear to circular polarization converter using PIN diodes

RESEARCH TOPIC:
Polarizer, circular polarization, polarization converter, p-i-n diodes, EM-wave manipulation, mm-wave applications

AUTHORS:
R. Madi, R. Sauleau[1], **A. Clemente**

We present a method to design a switchable polarizer using p-i-n diodes. An antenna-filter-antenna architecture with four metal layers (receiving and transmitting radiating elements, ground plane, and bias lines) is implemented to convert an impinging linearly-polarized electromagnetic wave to a circularly-polarized one. Furthermore, by controlling the bias current flowing on the two p-i-n diodes flip chipped on the transmitting radiating element, the transmission wave can be switched to either left-handed circular polarization (LHCP) or right-handed circular polarization (RHCP). Full-wave electromagnetic simulations of a single element show a transmission loss < 0.8 dB for both polarization (LHCP/RHCP) and 180° phase difference in the frequency band (27-31 GHz).

SCIENTIFIC COLLABORATIONS: [1] Université de Rennes, CNRS, IETR, UMR 6164, F-35000 Rennes, (FR)

Context and Challenges

Broadband satellite communications at K/Ka-band are experiencing a growing interest. One of the most important antenna requirement is the ability to radiate a circularly-polarized beam to mitigate Faraday rotation effects, multi-path fading and interferences caused by environmental factors. Furthermore, CP switch is also essential for terminal antennas to handle with cell-to-cell handover.

Main Results

We developed a reconfigurable linear-to-circular polarization converter, whose architecture uses solely two p-i-n diodes and a single bias line to generate the polarization switch. The unit-cell of the polarization converter operates at Ka-band (27 – 31 GHz), with an aperture 5.1 × 5.1 mm^2. The stack consists of two identical substrates, a bonding film and four metal layers. The Rx layer is a linearly-polarized square patch loaded by a U-shaped slot. At the Tx layer, an active patch loaded by an O-shaped slot and two p-i-n diodes (D1, D2) is designed. An asymmetric excitation generates CP. The linear-to-circular polarizer converter operates in RHCP when D1 is ON and D2 is OFF, LHCP when D1 is OFF and D2 is ON. The unit-cell was simulated and optimized using commercial software Ansys HFSS with periodic boundary conditions and Floquet port excitations. We obtain 15.17% and 11.38% 3-dB transmission bandwidth at 29 GHz for the LHCP and the RHCP, respectively.

Perspectives

A similar concept for circular polarization along with active elements could provide reconfigurability

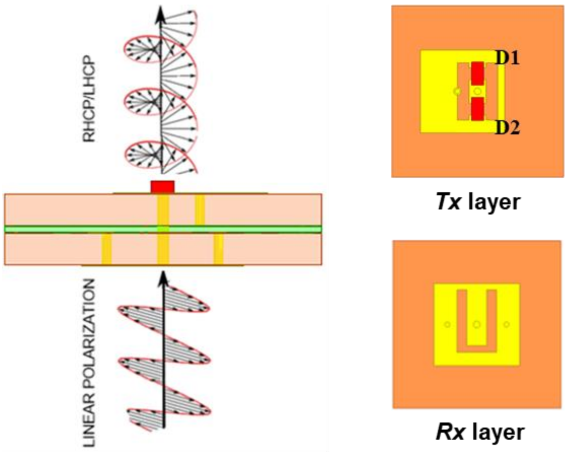


Fig. 1: View of the proposed unit-cell

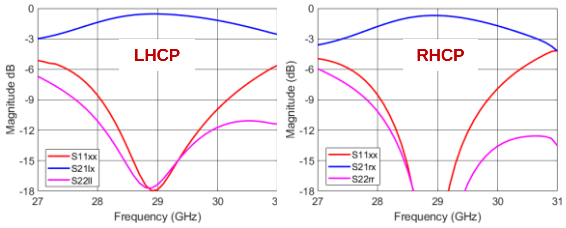


Fig. 2: Transmission and reflection coefficients

RELATED PUBLICATIONS:
[1] F. Foglia Manzillo, M. Smerzchalski, 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.
[2] A. Clemente, F. Foglia Manzillo, M. Smerzchalski, and R. Sauleau, “Electronically-steerable transmitarray antennas for SATCOM terminals: a system perspective,” IEEE International Workshop Antenna Technology (IWAT), 2020.
[3] R. Madi, A. Clemente, and R. Sauleau “Switchable linear to circular polarization converter using pin diodes,” IEEE International Symposium on Antennas and Propagation (ISAP), 2021

Miniaturization of a filter-antenna device by co-design

RESEARCH TOPIC:
Miniature antenna, microwave filter, filter synthesis, high dielectric resonator, quality factor, IoT devices

AUTHORS:
L. Huitema[1], Y. Dia, M. Thevenot[1], S. Bila[1], A. Perigaud[1],
C. Delaveaud

A novel miniaturization approach by co-designing together a filter and an antenna is presented. Indeed, contrary to a classical filter-antenna design, the developed co-design methodology demonstrates that both the antenna and the filter can be optimized on a complex impedance. This complex impedance allows an antenna volume reduction by more than 50% while presenting a high radiation efficiency. Moreover, the filter performance will be optimized on complex impedance loads without being affected compared to a classical 50Ω filter. This new approach is compared to a classical one in order to validate the improvement achieved by this co-design methodology. Prototypes have been manufactured and measurements confirm the benefits observed during the design phase.

SCIENTIFIC COLLABORATIONS: [1] Xlim - Research Institute/UMR CNRS 7252, University of Limoges, 87000 Limoges, (FR)

Context and Challenges

Wireless communication system development leads to an increasing demand on miniaturization and integration of microwave components. Both filters and antennas are among the most important and bulky components of radiofrequency transmitters, and their dedicated volumes are directly related to their performances. An antenna-filter co-design approach is developed with the main objectives of miniaturizing a filter-antenna device while keeping the same performances.

Main Results

Firstly, investigations have been carried out for size reduction of a Monopolar Wire Plate (MWP) antenna. A volume reduction of more than 50% has been obtained on a complex impedance locus while keeping the same radiation efficiency [1]. A second step was to miniaturize a cavity filter structure while keeping a significant quality factor for low insertion loss [2] and to match its impedance to the miniaturized MWP antenna. Prototypes of filters, antennas and filter-antenna devices were manufactured (fig. 2) and characterized experimentally. The co-designed antenna-filter performances were compared to the classical design approach (50Ω) showing similar total efficiency and filtering properties in spite of significant antenna volume reduction (Fig. 1) [3].

Perspectives

The interest of filter antenna co-design demonstrated, the next actions aim to consider the ultra-miniaturization of devices by integrating frequency agility functionalities on both the filter and the antenna.

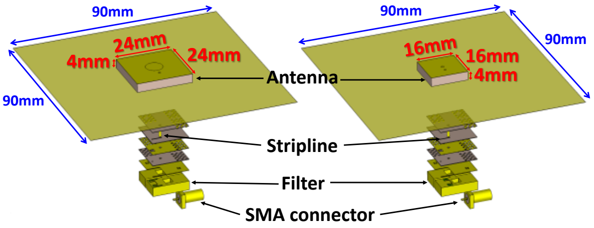


Fig. 1: Co-designed antenna-filter

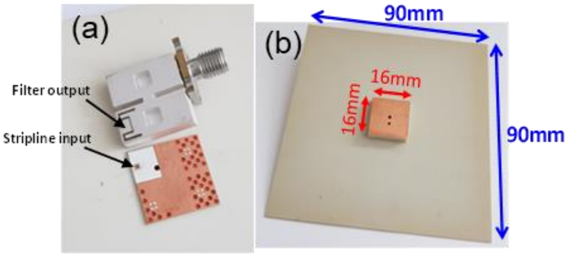


Fig. 2: Zircona cavity filter, MWP antenna

RELATED PUBLICATIONS:
[1] Y. Dia, L. Huitema, C. Delaveaud, S. Bila, M. Thevenot and E. Arnaud, "Methodology to keep the same radiation efficiency while miniaturizing an antenna,"10th European Conference on Antennas and Propagation (EuCAP), Davos, pp. 1-5, 2016.
[2] Y. Dia, L. Huitema, S. Bila, M. Thevenot, N. Delhote and C. Delaveaud, "3D Compact High-Q Filter Made of High-Permittivity Ceramic," 2019 49th European Microwave Conference (EuMC), Paris, France, pp. 304-307, 2019.
[3] L. Huitema, Y. Dia, M. Thevenot, S. Bila, A. Perigaud and C. Delaveaud, "Miniaturization of a Filter-Antenna Device by Co-Design," in IEEE Open Journal of Antennas and Propagation, vol. 2, pp. 498-505, doi: 10.1109/OJAP.2021.3070214, 2021.

An 84.48 Gb/s CMOS D-band multi-channel TX system-in-package

RESEARCH TOPIC:
High data-rate, wireless transmitter, system-in-package, D-band, short range communication

AUTHORS:
A. Hamani, F. Foglia-Manzillo, Al. Siligaris, N. Cassiau, B. Blampey, F. Hameau, C. Dehos, A. Clemente, J. L. Gonzalez-Jimenez

This work presents an in-package D-band wireless module co-integrating an innovative channel bonding transmitter IC in 45 nm CMOS PDSOI technology and a patch antenna fabricated using a low-cost printed circuit board process.

Context and Challenges

Transceivers operating in the D-band are key to unleash high-capacity short-range wireless links providing data rates up to 100 Gb/s with moderately complex modulations schemes [1-3]. Novel efficient architectures suitable for high-yield low-cost semiconductor and packaging technologies are essential for the development of future D-band front-ends. We present a ultra-wideband D-band 45-nm CMOS TX based on channel bonding techniques with on-chip millimeter-wave (mmW) local-oscillator (LO) generation, mounted on a low-cost multilayer PCB comprising a substrate integrated waveguide diplexer and a 2×2 antenna array.

Main Results

In this work, for the first time, the multiple mmW LO signals were generated on-chip (Fig.1). The TX front-end circuit was a two-channel up-converter [1-2]. Multi-channel BB modulated signals were applied at the TX IF input and the transmitted constellations and spectrum were measured at the receiver (RX) using a 20 dBi horn antenna (Fig.2). The RX was placed so as to have suitable SNR ratio for EVM measurement. The multi-channel baseband signal generated by the AWG contained preamble and scattered pilots used to estimate the propagation channel and other signal characteristics. A data rate of 84.48 Gb/s was achieved for multi-channel 64-QAM, with EVM below 10 % for all channels. Similar EVM performance was obtained using a multi-channel 16-QAM signal.

Perspectives

A perspective will be to improve the communication distance by integrating channel bonding directly on the antenna.

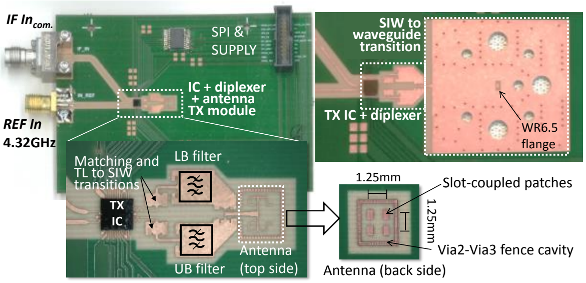
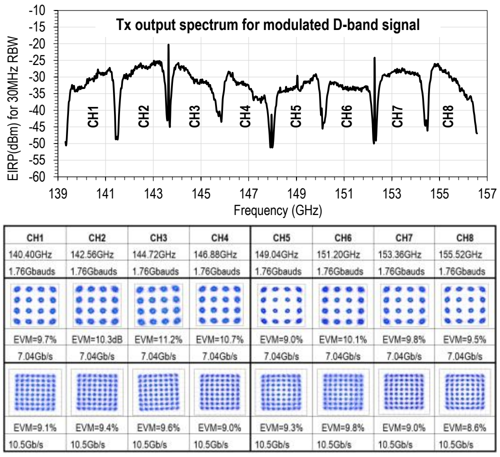


Fig. 1: TX module and WG transition



CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8
140.40GHz	142.56GHz	144.72GHz	146.88GHz	149.04GHz	151.20GHz	153.36GHz	155.52GHz
1.76Gbauds	1.76Gbauds	1.76Gbauds	1.76Gbauds	1.76Gbauds	1.76Gbauds	1.76Gbauds	1.76Gbauds
EVM=9.7%	EVM=10.3dB	EVM=11.2%	EVM=10.7%	EVM=9.0%	EVM=10.1%	EVM=9.8%	EVM=9.5%
7.04Gb/s	7.04Gb/s	7.04Gb/s	7.04Gb/s	7.04Gb/s	7.04Gb/s	7.04Gb/s	7.04Gb/s
EVM=9.1%	EVM=9.4%	EVM=9.6%	EVM=9.0%	EVM=9.3%	EVM=9.8%	EVM=9.0%	EVM=8.6%
10.5Gb/s	10.5Gb/s	10.5Gb/s	10.5Gb/s	10.5Gb/s	10.5Gb/s	10.5Gb/s	10.5Gb/s

Fig. 2: TX spectrum and constellations

RELATED PUBLICATIONS:

[1] A. Hamani et al., "An An 84.48 Gb/s CMOS D-band Multi-Channel TX System-in-Packae," in Proc. IEEE Radio Freq. Integr. Circuits Symp. (RFIC), Atlanta, GA, USA, pp. 207-210, 2021.

[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," IEEE Solid-State Circuits Letters, vol. 3, pp. 346-349, 2020

[3] F. Foglia Manzillo, et al., “Low-cost, high-gain antenna module integrating a CMOS frequency multiplier driver for communications at D-band,” Proc. IEEE RFIC, pp. 19-22, June 2019

[4] Siligaris, et al., "A multichannel programmable high order frequency multiplier for channel bonding and full duplex transceivers at 60 GHz band," Proc. IEEE RFIC, pp. 259-262, Aug. 2020.

A solid state process for 6G challenges

RESEARCH TOPIC:
Beyond 5G/6G KPIs, solid state devices, analog and RF applications

AUTHORS:
D. Belot

We presented a benchmark of RF and millimeter wave solid-state technologies for transceivers, which specifically targets Power Amplifier and Low Noise Amplifier functions, the most demanding RF and mmW solid-state functions in a global system. Firstly, a special focus was put on specific RF process property comparison. Secondly, we analysed the potentiality of the process covering requests from NEREID Roadmap for PA, LNA applied to wireless interfaces. We hence defined which process was the best suited for which function, depending on the target applications. In conclusion, the present trends and what should be the evolution in the next 5 to 10 years were described.

SCIENTIFIC COLLABORATIONS: Collaborations in NEREID Program (https://www.nereid-h2020.eu/roadmap): Grenoble INP, ,Fraunhofer, IMEC, SINANO, ECN, ICN2, Tyndall, VTT, ANEAS, POLITO, EPFL, IUNET, EDAC

Context and Challenges

The connectivity functions are everywhere, making the link between all other electronic functions. From the sensors and actuators to the processors and microcontrollers, from the sensor nodes to the gateways, from the gateways to the cells from the cells to the data centers, and all over the world. Inside each of these units, the connectivity links the computers to the memories, the core of multicores in high performance computing applications, and the peripheral devices to the central computing units.

The connectivity functions can be differentiated depending on the range and the nature. The nature of such function are wireless (in radio frequency mmW, THz bands, or visible light), or wireline (in copper or optical fiber). The range of such functions can be sorted out depending on the distance, the ultra-short range, is in the μm to cm distance; the short range is under 100 m, while the long range covers distances over 100 m.

Presently the largest connectivity market activity is dedicated to data communications, especially for cellular (WAN), WLAN, WPAN, NFC, and incoming WSN and IoT communications. In the data communication field, three main directions are followed, using the link distance criteria: (i) the outdoor and cellular for example 5G and future 6G generation. (ii) the indoor communication mainly represented today by the WiFi links, and (iii) “in devices” communications, which is not visible to the consumer. IRDS structured a dedicated chapter on Outside Systems Connectivity, which mostly covers challenges of high-end wireless technologies, optical technologies and wireline applications. They also anticipate Virtual Reality technology needs. The chapters of More Moore and Emerging Research Materials cover reliable alternatives to Cu-interconnects. The present presentation has very comprehensive road mapping on wireless communications technologies at all scales, anticipating the challenges of 6G.

Main Results

The main outcomes of this presentation was to propose solid state technologies for the physical layers of beyond 5G and 6G connectivity links. Two different examples were given in this summary, the beyond 100GZHzwireless link, and the sub-THz 300GHz wireless link. As an example, for the 100GHz wireless link, the conclusions were the following: FEM: BiCMOS 55x, presents the best compromise, with high altitude metal layers, (passives); Dedicated PIN Diodes for SPnT, High FT-Fmax. The alternative is the S13G2, without any PIN diode, which limits its potentiality for SPnT. ABB & RFE: BiCMOS 55x, presents the best compromise, with high altitude metal layers, for passives, and high speed digital. DSP & MAC: 22 FDX process offers the best FT and has the potentiality to modulate the power consumption to the need, modulating the VT. In addition, the transistors sizes allow high integration level, and the Three LDMOS propose high driving capability for high speed digital. Frequency Generation: BiCMOS 55x, presents the best compromise, with high altitude metal layers, for passives, and high speed digital. VCO: BiCMOS 55x with very high FT and very low 1/f noise presents the best compromise. S13G2 is a good alternative, with similar performances.

Perspectives

In the medium term, GaN/Si processes are ongoing to cover FEM requests up to 100GHz and PD SOI processes are ongoing to cover FEM request up to 150GHz. They are also well placed for RFFE and Frequency generation circuits up to 150GHz.

FDSOI 22nm to 15nm generations, integrating LDMOS, are and will be very attractive for SOC solutions up to 150 – 200GHz. In general, CMOS processes will be limited to applications under 200GHz, in the medium term. BiCMOS processes are and will be very attractive for RFFE, FEM, (especially with PIN diodes), frequency generation and VCO. In medium term, they will cover application up to sub-THz frequency (up to 325GHz).

GaAs/Si processes are the main competitors to BiCMOS processes in medium term, even if their TRL is presently lower. Finally, InP HBT processes, are very interesting for long term, and must find a way to be integrated over silicon.

RELATED PUBLICATIONS:
[1] D. Belot, “Which solid state process for 6G challenges?”, Analog VLSI conference, IMS Bordeaux, 2021.
[2] D. Belot, “Do SOI technologies, (RF-SOI and FDSOI) bring added value for new connectivity challenges?”, EuMW 2020, Advanced RF Technologies for 5G workshop, 2021.

Si and SOI CMOS technologies for millimeter wave wireless applications

RESEARCH TOPIC:
SOI technology, CMOS-only, partially depleted, fully depleted, mm-wave applications

AUTHORS:
D. Belot, **B. Martineau**

This study 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 (~10Ω.cm). Conversely, thanks to a higher resistivity substrate (1-3 kΩ.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.

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[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.
[4] B. Martineau, D. Belot, “Si and SOI CMOS technologies for millimeter wave wireless applications”, IEEE IEDM, 2021.

High power SOI-CMOS power amplifier module for 2.4GHz Wi-Fi 6 applications integrated on a fan-out wafer level packaging

RESEARCH TOPIC:
Power Amplifier (PA), Wi-Fi, SOI, FOWLP

AUTHORS:
P. Reynier, A. Serhan, D.Parat, A.Giry, R. Mourot, M.Gaye[1], P. Kauv[1], A. Cardoso[2], A. Gouvea[2], S. Nogueira[2]

This research presents the first high-power SOI-CMOS Power Amplifier (PA) embedded in a standard-flow Fan-Out Wafer-Level Package (FOWLP) addressing Wi-Fi 6 applications. At 2.44 GHz, the PA delivers up to 35.1 dBm of peak output power with a PAE of 53% under 5 V supply voltage. The PA achieves the highest reported linear output power (>21.5 dBm) with excellent efficiency levels for 802.11 MCS7/9/11 40 MHz Wi-Fi signals without using digital pre-distortion (DPD) while demonstrating robust operation under extreme load-mismatch and temperature conditions. These results demonstrate the potential of FOWLP packaging and SOI-CMOS technologies for low-cost and high power integrated PA modules for Wi-Fi applications.

SCIENTIFIC COLLABORATIONS: [1] Keysight Technologies, Les Ulis (FR), [2] Amkor Technology, Inc. (POR)

Context and Challenges

High-power RF Front End Module design for Wi-Fi has significantly complexified over the last decade due to stringent linearity and power consumption requirements. The PA is required to deliver more than 20 dBm of linear output power with better than -43 dB of EVM under 1024-QAM OFDM signal with high PAPR (>12 dB).

Main Results

We reported the first high-power SOI-CMOS PA embedded in a standard-flow Fan-Out Wafer Level Package (FOWLP) for Wi-Fi6 applications at 2.4 GHz. SOI-CMOS and FOWLP offer a compact and cost-effective PA solution with reduced thickness and increased integration level (Fig. 1). With 2.6 x 3.2 mm^2 package, the PA core is a two-stage linear Doherty amplifier implemented in industrial 0.13µm SOI-CMOS process. The PA module achieves state-of-the-art performance (Fig. 2). Under 5V supply voltage the PA delivers 35.1dBm of peak output power with 53% of PAE and 29.5dB of power gain. The AM-AM and AM-PM remain lower than 0.2 dB and 2° respectively up to 33 dBm. Without DPD, the PA achieves state-of-the art measured performance with 26.5/24.5/21.9 dBm of linear output power for an EVM of -30/-35/-43 dB with an operating current of 336/270/210 mA for MCS7/9/11 40MHz signals respectively. The PA shows robust operation under extreme load mismatch (8:1 VSWR) and temperature (-40 to 80°C) conditions.

Perspectives

Future work is on next generation high-efficiency PA solutions supporting higher operating frequencies/bands and wider signal bandwidth for future Wi-Fi7 and Beyond 5G systems.

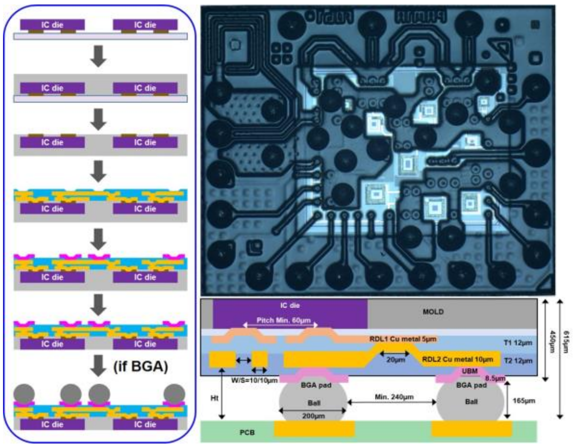

Fig. 1: FOWLP process flow and PA module

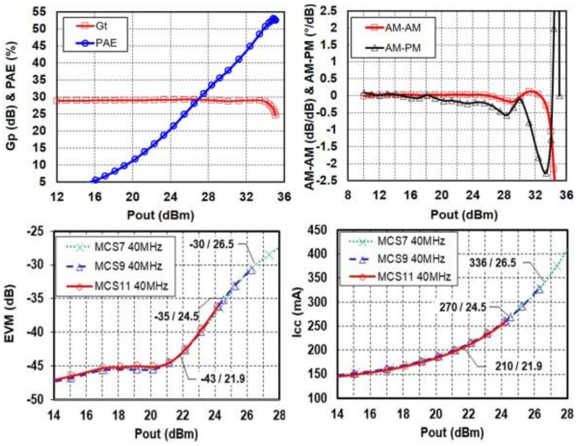

Fig. 2: Measured performance of PA

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

Design and integration of high efficiency power amplifier modules for cellular and Wi-Fi applications

RESEARCH TOPIC:
Front-End Module (FEM), Power Amplifier (PA), 5G/6G, WiFi6/7

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

Cellular and Wi-Fi applications are stimulating major research efforts on next-generation Power Amplifiers (PA) and Front-End Modules (FEM). The need for high-performance RF FEM with reduced size and cost is driving research towards highly integrated PA modules with challenging linearity and efficiency requirements. Integration of high efficiency PA modules is a major research topic at Leti and we are actively engaged in the development of high performance integrated PA solutions addressing multiple wireless standards and frequency bands.

SCIENTIFIC COLLABORATIONS: STMicroelectronics, Soitec, HiSilicon, ASE Group, Amkor Technology Inc.

Context and Challenges

Reduced power consumption and smaller form factor are driving research towards multiband PA modules with high efficiency and integration level. Cellular and Wi-Fi PA modules face significant challenges due to stringent linearity requirements. One main challenge relates to high efficiency linear PA operation under high PAPR signals (>6dB). Another is tackles increasing frequency of operation (>3GHz), output power level (>33dBm), signal bandwidth (>100MHz), and finally performance under load mismatch. To tackle these challenges, we develop high performance integrated PA solutions for multiple wireless standards and frequency bands (Fig.1).

Main Results

Our state-of-the-art reconfigurable PA solutions combine high-efficiency PA architectures with SOI-CMOS technology in order to achieve high efficiency and linearity over an extended frequency range [1]. These compact high-power PA modules present broadband efficiency and linearity performance (Fig. 2), while achieving high ruggedness and reliability [2]. To reduce PA module thickness and further enhance electrical and thermal performance, we also investigate Fan-Out Wafer-Level Packaging PA solutions [3].

Perspectives

Hybrid PA architectures, CMOS-compatible GaN-on-Si process, heterogeneous integration and innovative architecture and circuit design are expected perspectives to tackle increasing operating frequencies and output power requirements.

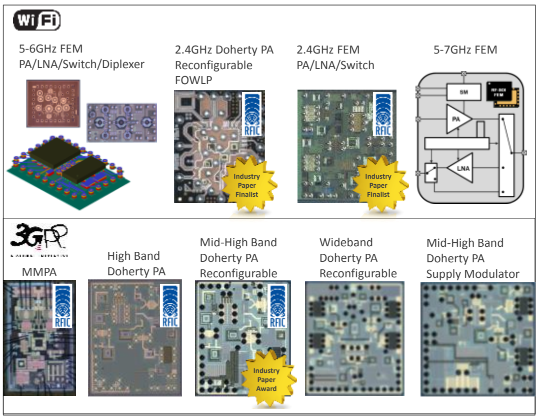

Fig. 1: SOI-CMOS PA/FEM modules

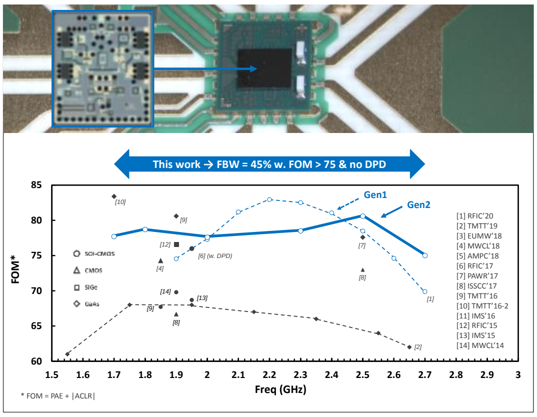

Fig. 2: Wideband reconfigurable Doherty PA module in SOI-CMOS technology

RELATED PUBLICATIONS:
[1] A. Giry, A. Serhan, D. Parat and P. Reynier, "Linear Power Amplifiers for Sub-6GHz Mobile Applications: Progress and Trends," 2020 18th IEEE International New Circuits and Systems Conference (NEWCAS), Montreal, QC, Canada, 2020.
[2] 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," 2021 IEEE Radio Frequency Integrated Circuits Symposium (RFIC), Atlanta, GA, USA, 2021.
[3] A. Serhan et al., "A Reconfigurable SOI CMOS Doherty Power Amplifier Module for Broadband LTE High-Power User Equipment Applications," 2020 IEEE Radio Frequency Integrated Circuits Symposium (RFIC), Los Angeles, CA, USA, 2020.

A highly rugged 39 GHz 19.3 dBm power amplifier for 5G applications in 45nm SOI technology

RESEARCH TOPIC:
Highly rugged power-amplifier, 5G FR2 NR, 45nm SOI process, SOITEC.

AUTHORS:
A. Bossuet, B. Martineau, C. Dehos, B. Blampey, A. Divay, Y. Morandini[1]

We reported a highly rugged power-amplifier for the fifth generation (5G) FR2 new radio (NR) application implemented in a 45nm SOI process (45RFSOI). By using device stacking technique together with an optimized supply voltage reduction, the power amplifier achieves 20 dBm Psat and 23 % PAEmax. A Pavg of 10 dBm and a PAEavg of 8% is achieved in 64-QAM 200MHz bandwidth OFDM at EVMavg of 6.2% (-24.1dB) without the use of digital predistortion. The 4:1 VSWR measurement shows an excellent PA reliability even under the worst mismatch condition. These results enable an efficient, high power and highly reliable power amplifier for 5G applications.

SCIENTIFIC COLLABORATIONS: [1]SOITEC, Crolles, (FR)

Context and Challenges

This work proposes to demonstrate that a 20 dBm output power at the highest 5G frequency band of 40 GHz can be carry out with a high level of robustness with the 45RFSOI technology [1].

Main Results

Implementing a >20 dBm level efficient PA in deep sub-micron CMOS at 40 GHz is a challenging task due to the low breakdown voltage of these technologies 0,9 – 1 V. We present a two stages PA based on the stack topology using the recently added PAFET drain extended devices that present improved hot carrier injection (HCI) performances and an improved off-state junction breakdown. Any devices biased at nominal technology voltage is exposed to reliability issue in large signal operation, making them sensitive to HCI and time dependent dielectric breakdown TDDB [2]. To design a PA conform for manufacturing, this aspect must be take into account when RF performances are benchmarked. In that work, to solve that issue, power supply is derated by 20 % to secure aging and reliability.

The power amplifier is composed of a driver stage followed by a power stage to meet both gain and high output power performances.

It achieved 19.3 dBm output compression point OCP1dB and saturated power of 20 dBm at 39 GHz. The measured gain is 18.5/23.4 dB at 39/42 GHz and the input return loss S11 is <−10 dB over the 36 - 41.3 GHz bandwidth. The maximum PAE is 23 %. AM-AM and AM-PM variations show less than 0.5 dB and 5° up to 14 dBm. For the IMD measurement, two continuous wave (CW) tones with equal tone power and spaced by 100 MHz are applied to the PA input. The IMD obtain is -30.8 dBc at 10 dBm output.

The PA is tested using FR2 5G NR OFDM signals with no Digital Pre Distortion and no equalization is applied before demodulation. The PA non linearity contribution to EVM is extracted from the total EVM, as the setup generated unwanted impairments. Modulation tests of 5G NR FR5 200 MHz frame at 39 GHz are performed, modulated with OFDM 64QAM signal. For a power back-off of 9 dB on ICP1dB, the measured Poutavg is 10 dBm and PAEavg is 8 %, while the nonlinear contribution of the PA to EVM is less than 3 % at 39 GHz. As a comparison in ETSI TS 138 104, the EVM requirement for Base Station is 8% for 64QAM, measured on 50 MHz bandwidth.

For reliability measurement the power amplifier was test with the DCOS department. In a use-case environment, the power amplifier is the latest stage before antenna, making this bloc highly sensitive to load variation. Independently of its performance, its robustness to impedance variation VSWR is of most concern to ensure its functionality. Considering the CCDF of the 5G FR2 modulation scheme, a 0.1-year lifetime at P1dB is evaluated. Two tests have been performed. A soft stress of 27 min loading, and an hard test corresponding to a longer 15 hours stress. No breakdown is observed even after 15h of 4:1 VSWR, which show a very good robustness against load impedance variation. The measurements were made on five PA chips and are perfectly reproducible. Almost no current degradation is observed on the driver current, as this stage is well isolated from output load variation because of the power call stage between. Degradation can be expected if upper limit supply voltage is applied. Consequently, to insure a given lifetime for a specific power amplifier, the DC and RF voltage must be examined carefully and not over-stressed.

These good results were achieved thanks to stacking device technique, offering high output power while securing FET from breakdown. As the author’s knowledge, this is the only PA published at 39 GHz meeting 5G required performances with derating supply voltage and where reliability has been verified.

Perspectives

These results give good confidence to use such technologies for 5G PA Design in mmW frequencies bands, which is one of the main roadmap of the radiofrequency team of LETI. More aging and robustness test could be performed in collaboration with DCOS to test other promising technologies for mmW applications.

RELATED PUBLICATIONS:
[1] B. Martineau and D. Belot, “Si and SOI CMOS technologies for millimeter wave wireless applications”, in IEEE International Electron Devices Meeting (IEDM), 2020.
[2] X. Garros et al., "A Very Robust and Reliable 2.7GHz +31dBm Si RFSOI Transistor for Power Amplifier Solutions," 2019 IEEE International Electron Devices Meeting (IEDM), pp. 25.5.1-25.5.4, 2019.

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04 ELECTRONICS FOR ENERGY

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

Maximum Power Point Tracking Architectures For Piezoelectric-Based Vibration Energy Harvesters

RESEARCH TOPIC:
Piezoelectricity, Energy Harvesting, Vibration, Power Management Circuits, Maximum Power Point Algorithms

AUTHORS:
N. Decroix, A. Ameye, N. Garraud, A. Badel[1], **P. Gasnier**

This work studies novel Maximum Power Point Tracking (MPPT) architectures for piezoelectric-based vibration energy harvesters. The first part of the work is focused on weakly coupled vibration energy harvesters for which the electrical side does not influence the mechanical part. A new and efficient algorithm, called the “I-V curve algorithm”, has been proposed. This algorithm enables a fast calculation of the optimal electrical loads for different extraction techniques (Standard, parallel/series Synchronized Switch on Inductor) without requiring any open circuit measurement. In a second step, this method will be used as a part of a more complex system to dynamically tune and maximize the energy extraction of strongly coupled vibration energy harvesters.

SCIENTIFIC COLLABORATIONS: [1] Univ. Savoie Mont Blanc, SYMME, F-74000 Annecy, (Fr)

Context and Challenges

To convert vibration into electricity, Piezoelectric Energy Harvesters (PEH) are very attractive for their high power density at small scale and high output voltages. PEH design is not the only technological lock for the adoption of such systems in the industry: Power Management Circuits (PMCs) between the PEH and the storage element need to be efficient and must quickly adapt their operation to changing conditions. The challenge of this work is to propose a low power, microcontroller-based PMC which implements a fast and efficient MPPT for weakly coupled PEH.

Main Results

This new MPPT algorithm [1] relies on four voltage measurements (V_{A1}/V_{A3} and V_{B5}/V_{B7}) [2] across the smoothing capacitor C_{rect}. While making the system work at two operating points successively, the microcontroller measures the conduction time across the rectifier and calculates the optimal resistive load R_{opt} to perform an appropriate load emulation (buck-boost). This method enables a fast MPPT tracking compared to other algorithms and the energy is still harvested while the tracking is performed contrary to Fractional Open-Circuit Voltage algorithms.

Perspectives

Perspectives include algorithm implementation on a real hardware and use within a more complex architecture that electrically induces optimal damping and stiffness to reach the MPP in the case of strongly coupled PEH. This work contributes to developing efficient, reactive and versatile PMCs that compensate for aging effects or environmental changes of PEH.

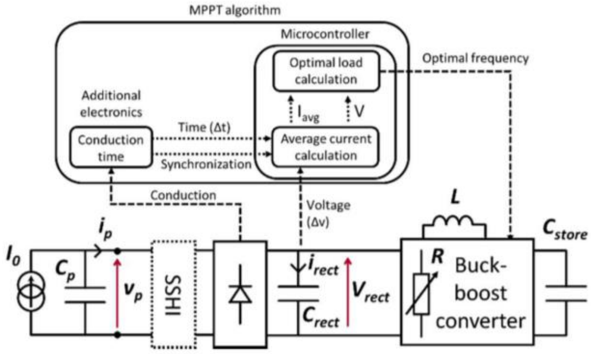

Fig.1: Algorithm architecture and circuit

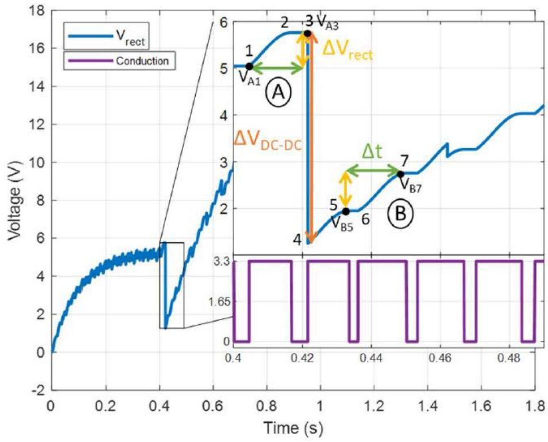

Fig. 2: Simulation of “I-V curve method”

RELATED PUBLICATIONS:
[1] N. Decroix, P. Gasnier, and A. Badel, “Direct optimal resistance calculation MPPT algorithm for piezoelectric energy harvesting,” JNRSE 2021.
[2] N. Decroix, P. Gasnier, and A. Badel, “An Efficient Maximum Power Point Tracking Architecture for Weakly Coupled Piezoelectric Harvesters based on the source I–V curve,” in 2021 IEEE 20th International Conference on Micro and Nanotechnology for Power Generation and Energy Conversion Applications (PowerMEMS), pp. 136–139. doi: 10.1109/PowerMEMS54003.2021.9658370, 2021.

Piezoelectric DC-DC converters

RESEARCH TOPIC:
Power electronics, size reduction, efficiency, DC/DC converters

AUTHORS:
M. Touhami, V. Breton, L. Pereira, M. Bousquet, T. Hilt, T. Lamorelle, A. Morel, G. Pillonnet, F. Costa[1], **G. Despesse**

A new way of storing energy in power conversion is investigated. A mechanical storage is considered instead of the classical magnetic storage in order to increase the level of energy stored per unit volume and thus increase the power density of converters. To transfer energy from the electrical to the mechanical domain and vice versa, a piezoelectric transducer is used. Then, a six-phase cycle is defined to drive the piezoelectric and regulate the output voltage, while a charge and energy balance is provided on the piezoelectric material. PZT (Lead Zirconate Titanate) and LNO (Lithium Niobiate) materials are investigated. In addition, the frequency determination and frequency impact are investigated. An efficiency of 93.6% was achieved at 16 W and 6MHz

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

Context and Challenges

Reducing the weight and the volume of power converters is of main interest. Significant Improvements have been made in recent decades by increasing the operating frequency through the development of fast power switches. Nevertheless, the energy stored in the inductor per unit volume decreases significantly with frequency due to an increase of iron losses; reducing the impact of the frequency increase on the size reduction. 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 [1,3,4].

Main Results

A model of the converter was developed to determine the operating frequency and the step duration of the developed adiabatic 6- phases control cycle dedicated to this converter type [2].

A comparison between PZT and LNO materials shows that PZT is well suited for frequencies up to 1MHz while LNO is suited for frequencies upper than 1 MHz [1]. Bigger the frequency is, the upper the power density is compare to an Inductor. A size reduction about a factor 20 is reached at 1MHz for the storage element [3].

Perspectives

The next steps are to go towards miniaturization thanks to MEMS technology, to increase the operating frequency above 10MHz and to develop isolated converters.

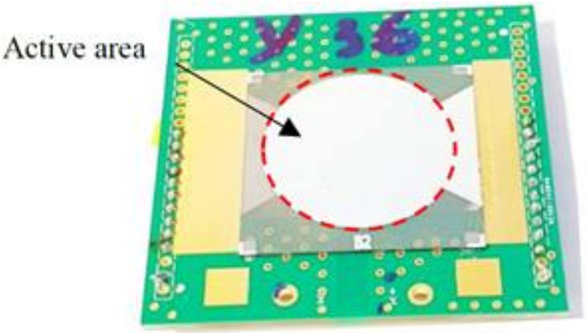

Fig. 1: 6MHz LNO resonator

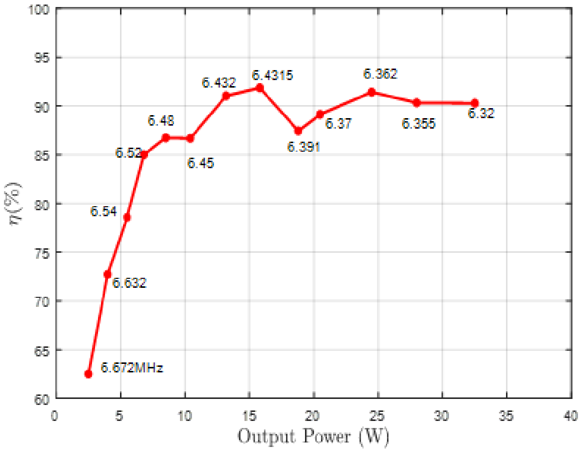

Fig. 2: Efficiency/output power LNO@6MHz

RELATED PUBLICATIONS:
[1] M. Touhami, G. Despesse et al., "Piezoelectric Materials for the DC-DC Converters Based on Piezoelectric Resonators," 2021 IEEE 22nd Workshop on Control and Modelling of Power Electronics (COMPEL), pp. 1-8, doi: 10.1109/COMPEL52922.2021.9645999, 2021.
[2] L. Pereira, A. Morel, M. Touhami, T. Lamorelle, G. Despesse and G. Pillonnet, "Operating Frequency Prediction of Piezoelectric DC–DC Converters," in IEEE Transactions on Power Electronics, vol. 37, no. 3, pp. 2508-2512, doi: 10.1109/TPEL.2021.3115182, 2022.
[3] M. Touhami et al., "Effect of operating frequency on piezo-Based DC-DC converter", 10th National Days on EH and Storage (JNRSE), Grenoble, 2021.
[4] V. Massavie et al., "A new topology of resonant inverter including a piezoelectric component", EPE'21 ECCE conference, pp. P.1-P.10, 2021.

Safe operation of a totem-pole PFC converter using depletion-mode GaN HEMTs

RESEARCH TOPIC:
GaN transistor, normally-ON, converter startup and shutdown, new driving circuit, safe operation

AUTHORS:
R. Monthéard[1], **S. Carcouët**, I. Chorfi[1], M. Gavelle[1], P. Périchon, T. Sutto[2], E. Moreau[2]

We present the design and making of a totem-pole PFC converter featuring depletion-mode GaN power transistors, with an original approach to safely tackle the normally-ON characteristic challenge. Due to its natural Two Dimensional Electron Gas (2DEG) structure, a GaN transistor is normally-ON when its gate-source voltage is zero, which involves short circuit at the converter's startup and shutdown and therefore discourages the use of such devices in most power converters. Nevertheless, normally-ON GaN transistors may exhibit superior performance in terms of switching speed, on-state resistance, manufacturing cost, robustness and reliability. A new driving circuit is implemented and experimented which shows excellent performance and high density.

SCIENTIFIC COLLABORATIONS: [1] CEA TECH OCCITANIE, Labège (FR), [2] EXAGAN, Grenoble (FR)

Context and Challenges

As mentioned earlier, using normally-ON GaN devices in a power converter is challenging: the shutdown sequence is a true short-circuit across the DC link, whereas the startup issue is slowed down by the PFC inductance and the pre-charge circuit (resistor) for the DC bus capacitor bank. Different strategies can be used to address this problem but an ultrafast startup power supply providing a sufficient bias voltage and fast enough is the best solution to prevent any large current in the GaN switches.

Main Results

This solution alone can solve the startup issue and the shutdown short-circuit. The proposed architecture allows to keep control over the GaN switches, and safely wait either for the AC source to recover or for the DC bus voltage to fall below a sufficiently low voltage.

A prototype of the proposed biasing architecture was realized.

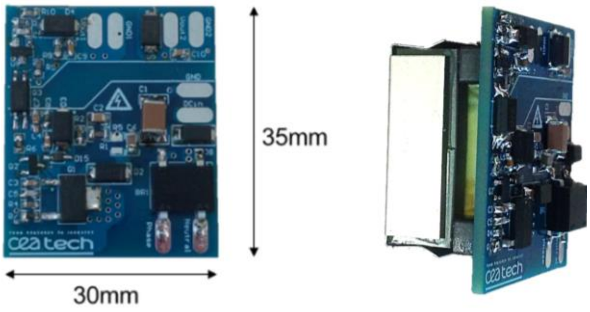

Fig. 1: ultrafast startup power supply

At different AC input voltage phase angles (Fig. 2), the startup time is around 100µs avoiding any overcurrent in the GaN devices.

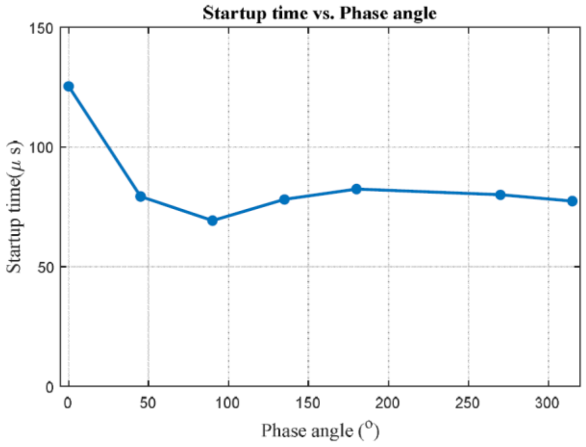

Fig. 2: Startup time vs. phase angle

Proper operation of the proposed startup power supply has been verified by monitoring the short-circuit current in the GaN half-bridge, as well as the two GaN HEMTs gate-source voltages on a totem-pole PFC converter.

Perspectives

Future work will target optimization and greater integration of the ultrafast startup power supply using a custom-made transformer, and will also include the optimization of the presented totem-pole PFC converter and the adaptation of the presented architecture to a higher power version

RELATED PUBLICATIONS:
[1] R. Monthéard, S. Carcouët, I. Chorfi, M. Gavelle, P. Périchon, T. Sutto, E. Moreau, "Safe operation of a totem-pole PFC converter using depletion-mode GaN HEMTs", Proceedings of EPE'21 ECCE Europe conference, 2021.

State-of-Charge and State-of-Health online estimation of Li-ion battery for the More Electrical Aircraft based on semi-empirical ageing model and Sigma-Point Kalman Filtering

RESEARCH TOPIC:

Lithium battery, state indicator estimation algorithms, performance & density & safety of battery systems

AUTHORS:

A. Laurin, **V. Heiries**, M. Montaru[1], S. Fiette[1], P. Kanzler[2]

This paper proposes an online method to estimate the State-of-Charge (SoC) and State-of-Health (SoH) of a Li-ion battery for the More Electrical Aircraft (MEA) application. Based on an extended characterization of Li-ion cells, precise electrical and ageing models are established and used in the state estimation method. The SoC algorithm is based on a Sigma-Point Kalman Filter (SPKF) that handles the non-linearity of the electrical model. The results show stable SoC and SoH estimation precisions, respectively less than 1% and 2% for most of the temperature and ageing conditions. The algorithm is built to meet the requirements of the MEA in terms of robustness, reliability, precision, hardware integration and low maintenance.

SCIENTIFIC COLLABORATIONS: [1] Univ. Grenoble Alpes, CEA, LITEN, F-38000 Grenoble, France, [2] Fraunhofer Institute for Integrated Systems and Device Technology IISB, Intelligent Systems, Battery System Group, Erlangen, Germany

Context and Challenges

With challenges such as reducing CO_2 emissions, noise pollution and maintenance cost, aircraft industries value the development of More Electrical Aircrafts (MEA), where electric actuators replace hydraulic and pneumatic systems, raising electricity generation and distribution onboard. Integration of Li-ion battery technology for highly demanding aeronautical applications requires optimized solutions and particularly Battery Management Systems (BMS), from the point of view of safety. The BMS monitors the State-of-Charge (SoC) and State-of-Health (SoH), indicating the present condition of the battery relatively to its initial one. Kalman filters based on Electrical Equivalent Circuit (EEC) models are known to bring a good tradeoff between high precision estimation and moderate algorithm complexity. They are relevant towards MEA applications considering its robustness, reliability, low computational burden and low maintenance. Emergency profiles in the MEA context are very demanding in terms of energy and power, hence the battery is relatively oversized and, in opposition to Electric Vehicle application for example, is sparsely and mildly used with only a few percents of Depth of Discharge (DoD) on a typical profile. That implies a poor observability of the system and online SoH estimation becomes challenging.

Main Results

We introduced a state estimation method which is precise, robust and consistent with the goal of a BMS software solution all along the battery lifetime. It appeals to a Sigma Point Kalman Filter (SPKF) based on an equivalent electrical circuit model and combines with a SoH estimation method, which follows capacity and resistance evolution during battery usage. SoC and SoH estimation errors remained respectively under 1% and 2% in most ageing conditions. Battery chemistries were Nickel Manganese Cobalt (NMC) and Nickel Cobalt Aluminum (NCA).

Perspectives

Our study showed precise and stable results for the SoC and SoH estimation algorithms, regardless the progressive degradation of the battery, which proves the relevance of the method for the MEA application and opens the way to generalization at the battery pack level and hardware integration.

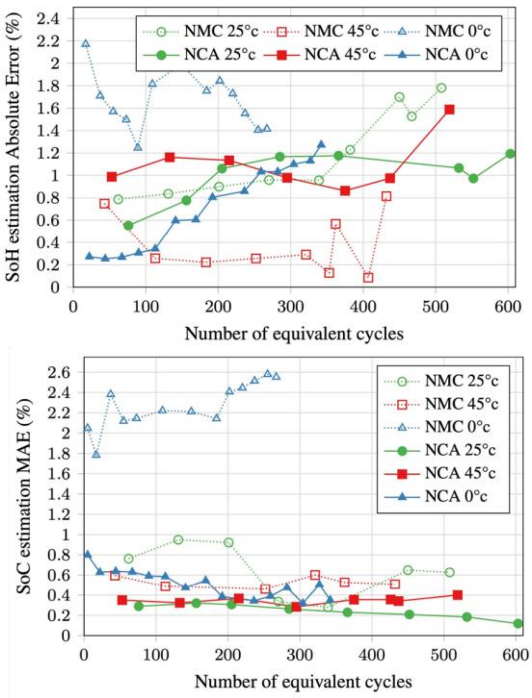

Fig. 1: SoH and SoC estimation errors

RELATED PUBLICATIONS:

[1] A. Laurin, V. Heiries, M. Montaru, "State-of-charge and state-of-health online estimation of li-ion battery for the more electrical aircraft based on semi-empirical ageing model and sigma-point kalman filtering", Smart Systems Integration (SSI), 2021.

[2] V. Heiries, PH. Michel, A. Delaille, F. Karoui, "15 Définition des algorithmes d'état d'un système batterie et méthodes de calcul associées", *Batteries Li-ion: Du présent au futur*, Les Ulis: EDP Sciences, 2021.

Acoustic Power Transfer through metal walls

RESEARCH TOPIC:
Power transfer, metal walls, acoustic waves, piezoelectric transducers, new topologies, efficiency, robustness

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

Acoustic power transfer (APT) through metal layers is of great interest in applications where the integrity of metal boxes, tanks, pipes or walls must be preserved by avoiding through-hole electrical connections. APT systems are composed of two aligned piezoelectric transducers which are glued on both sides of a metallic wall. An AC electrical excitation applied on the first transducer results in the emission of acoustic waves in the wall. These waves propagate and reach the second transducer which converts this mechanical excitation into electricity that can be used to power electronic devices. Proofs of concepts exist in the state of the art. We report missing advanced modeling to develop efficient systems, and the design of topologies robust to misalignment.

Context and Challenges

Powering and communicating with sensors behind metal walls is useful in various applications such as submarine hulls, pressurized tanks or pipes. Acoustic power transfer (APT) is an option to supply these sensors without making through-holes (Fig.1). However, the power transfer performances of APT systems are strongly degraded by the destructive interferences of emitted waves, due to emitter and receiver misalignment or diameter discrepancy. Advanced modeling of APT systems combined with new topologies allow to tackle these challenges.

Main Results

We reported the first study of APT through metal walls using multiple transmitters. Instead of using multiple independent piezoelectric elements, the electrodes of piezoelectric discs were divided into electrically independent areas, supplied by different electrical excitations (Multiple Input Single Output configurations, Fig.2). Analytical expressions to maximize efficiency and transmitted power were established. Results show that when transducers are aligned, performance enhancement is important (factor two) for a 40 mm diameter transmitter and a 10 mm diameter receiver. When transducers are misaligned, performance enhancement reaches 450 times that of Single-Input-Single-Output configurations.

Perspectives

Higher performances and reduced dependence to the alignments make this solution particularly suited for industrial applications, where high power and robustness are essential. It paves the way toward the power supply of distributed sensor nodes.

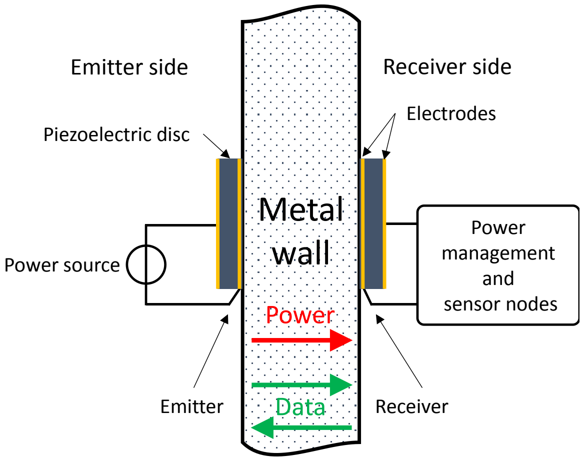

Fig. 1: APT system principle

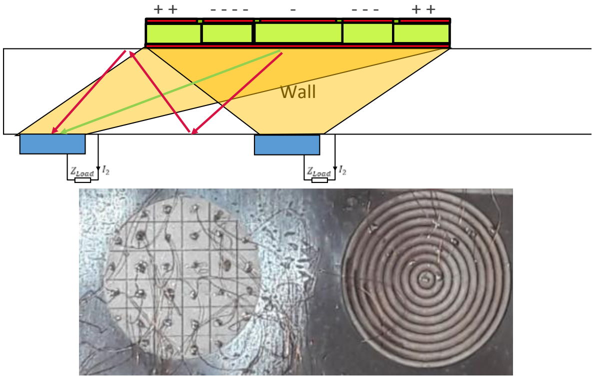

Fig. 2: APT with non-aligned transducers

RELATED PUBLICATIONS:
[1] Freychet O, Frassati F, Boisseau S, Brulais S, Despesse G, Multiple input single output configurations to improve performances and robustness of acoustic power transfer, Ultrasonics 116 106524, 2021.
[2] Freychet O, Frassati F, Boisseau S, Garraud N, Gasnier P, Despesse G, Analytical optimization of piezoelectric acoustic power transfer systems, Eng. Res. Express 2 045022, 2020.
[3] Freychet O, Frassati F, Boisseau S, Garraud N, Gasnier P, Despesse G, Piezoelectric stacks to increase the transmitted power of acoustic power transfer through metal walls, Proc. PowerMEMS, 2021.

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05 SENSING & LEARNING

- E-Health
- Environment
- Stress management
- Intelligence at the edge
- Robotics
- Education
- Earth Magnetic Field

Convergence project: Health and Environmental monitoring with wearable low-power sensing platform

RESEARCH TOPIC:
Health monitoring, Environmental sensors, Integration, Wearable, Flexible electronics, Low-power, autonomous sensing platform

AUTHORS:
L. Jouanet, A. Faucon, A. Vidal, A. Pereira, S. Boisseau, T. Ernst, **E. Saoutieff**

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

SCIENTIFIC COLLABORATIONS: Members of the CONVERGENCE consortium: ENEA (IT), GINP (FR), IMT (RO), UCL (BE), EDI (LT), EPFL (project coordinator, CH)

Context and Challenges

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

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

Main Results

CEA-LETI has developed low power, wireless demonstration platform for wearable IoT flexible systems compatible with various kinds of sensors developed by consortium partners [1; 2].

The wearable platform (fig.1) is a modular multi-sensors platform with: (i) data acquisition and visualization in real-time with specific App developed by CEA, (ii) Bluetooth Low Energy 2.4 GHz communication [3], (iii) antenna circuit designed by G-INP and (iv) low-power system.

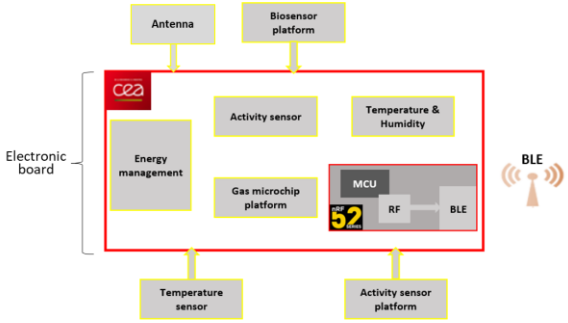

Fig. 1: Schematic of the sensor platform

The platform (fig.2) supports both analog and digital sensors: Gas (NO2, NH3, CO), pH, Temperature, Humidity and Activity sensors. For the integration, the design was chosen to be worn as a wristband on the Arm, and the platform was encapsulated into Sylgard® 184 silicon.

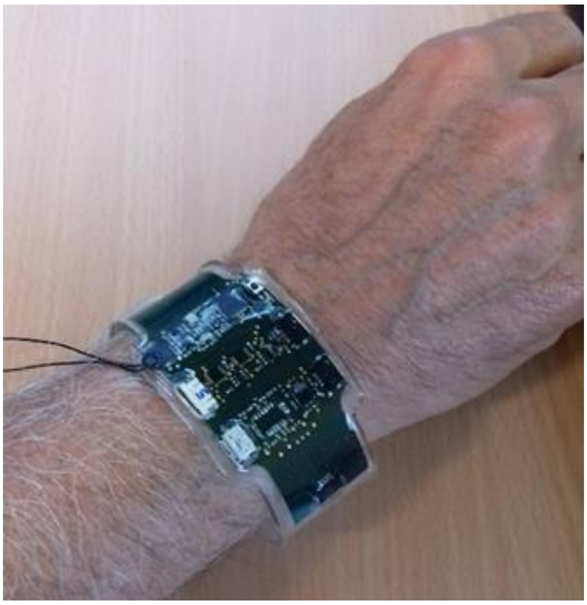

Fig. 2: Sensing platform integration

Perspectives

Over the longer term, such devices will offer unique solutions for new generations of non-invasive quasi-continuous healthcare applications.

RELATED PUBLICATIONS:
[1] E. Saoutieff et al., “Wearable Smart Sensing platform for environmental and health monitoring: the Convergence project”, Sensors 21(5):1802, 2021.
[2] T. Polichetti, M.L. Miglietta, B. Alfano, E. Massera, S. De Vito, G. Di Francia, A. Faucon , E. Saoutieff, S. Boisseau, T. Walewyns, N. Marchand, L. A. Francis, " A Networked Wearable Device for Chemical Multisensing", Lecture Notes in Electrical Engineering - Volume 539, Pages 17-24, 2019.
[3] A. Ancans, J. Ormanis, R. Cacurs, M. Greitans, E. Saoutieff, A. Faucon, "Bluetooth Low Energy throughput in densely deployed radio environment", Elektronika IR Elektrotechnika, 2019.

Monitoring human mental states: from sensor signal quality to stress management program evaluation

RESEARCH TOPIC:
Affective computing, stress, emotion, wearable, signal quality, multimodal fusion, privacy, continual learning

AUTHORS:
S. Hamieh, M. Mainsant, G. Vila, V. Hoareau, V. Heiries,
C. Godin

Human affects play a central role in well-being, mental health, inter-personal and human machine interactions. Finding new ways to assess human emotions and stress levels could help to develop better intervention systems that would foster better functioning, facilitate human machine interactions, and prevent mental disorders. With the recent development of sensors and artificial intelligence, affective computing appears as a new opportunity to develop such human mental states evaluation methods. From sensors to the final application, we consider here several aspects of such development stages: sensor signal quality assessment, multimodal fusion, incremental learning dealing with privacy issues, and a real application for stress management methods assessment.

SCIENTIFIC COLLABORATIONS: [1] LPNC UMR 5105, Univ. Grenoble Alpes, Grenoble (FR), [2] Gipsa-Lab, Univ. Grenoble Alpes, Grenoble (FR), [3] University of Ottawa, Ottawa (CA), [4] French Armed Forces, IRBA, Bretigny-sur-Orge (FR)

Context and Challenges

With the development of affective computing, it is now possible to evaluate human emotions and stress with more or less accuracy. The challenge today is to enhance this accuracy in everyday situations. More particularly we have to put the systems out of the laboratory, and deal with less controlled situations. For example, it is mandatory to use less intrusive sensors. Wearable sensors exist but are subject to motion artifacts. One of the challenges is to detect those artifacts and build algorithms robust to them. Speech, facial expression, and physiological sensors give complementary information about the inner state of the person. A good multimodal fusion scheme is the key to take advantage of the complementarity of several information sources. Most emotion and stress recognition algorithms come from supervised learning from an annotated database. In real-life applications, it is possible that not all learning samples will not be available from the beginning and that we will have to adapt the models to continually learn from new incoming data. One of the main challenges is learning with new examples without forgetting lessons learned from old ones and respecting privacy issues. Finally, the adaptation of the algorithms to real problems will show their relevance to daily life.

Main Results

We propose a Simulatneous Localization And Mapping (SLAM)
One of our contributions is about quantifying the quality of heart rate monitoring sensors. In [1], we propose an original quality index adapted to heart rate monitoring. For the final application, this index will be relevant to evaluate several sensing configurations (positions, nature of the sensors, sampling frequency, motion of the user). It will also enable to decide to use or not the measure based on its quality.

In [2], we propose a new multi-modal fusion scene relying on each modality's relevance. We applied this scheme to the audio-visual data from the MUSE2021 challenge for the assessment of the emotional valence and arousal of participants during a stressful laboratory task. The strength of our model is to evaluate, for each modality, the difficulty to reconstruct the incoming signal using an auto-encoder and use this indicator as a weight in the fusion. With this scheme, we reach a better accuracy than the baseline on the test set of the challenge.

To deal with continual learning, Dream Net [3] is a new privacy-preserving model. As human do, this algorithm, based on a pseud-rehearsal approach, capitalize on previously learned information without storing the examples. This capability is particularly interesting for the affective computing domain. As databases are most of the time covered by privacy issues, it is not possible to use them permanently.

One application of affective computing can be to assess the effectiveness of stress management methods. In [4] we use the heart rate variability indicator RMSSD (root mean of successive differences). In this study, 160 firefighters were allocated to one of the stress management method group: TOP (tactic of optimized potential) or HC (heart coherence) or a control group receiving a placebo. We showed that both TOP and HC increased RMSSD for most of the subjects. However, for participants with high RMSSD at the beginning of the study neither program had a significant effect.

Perspectives

From better sensors to providing new services, there are several open research directions. Sensors should be comfortable and robust. This can be obtained by new sensing principles like using radar technology for nearable measurements for example, but also with relevant signal processing schemes. New advances in artificial intelligence will enhance the accuracy of the estimates. Some of our current works are about personalization, learning with subjective labels, and anomaly detection. Concerning applications, it is necessary to adapt the algorithms to the targeted application. Actual research projects focus on driver monitoring, stress management for athletes, stress evaluation for children equipped with exoskeleton, and bipolar disorders monitoring.

RELATED PUBLICATIONS:

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[3] M. Mainsant, M. Solinas, M. Reyboz, C. Godin, M. Mermillod, « Dream Net: a privacy preserving continual leaming model for face emotion recognition », in 9th International Conference on Affective Computing and Intelligent Interaction Workshops and Demos (ACIIW), p. 01-08, 2021.

[4] V. Hoareau, C. Godin, F. Dutheil, M. Trousselard, « The Effect of Stress Management Programs on Physiological and Psychological Components of Stress: The Influence of Baseline Physiological State », Appl Psychophysiol Biofeedback, 2021.

Deep learning for temporal multidimensional signals

RESEARCH TOPIC:
Fusion, Deep Learning, CNN, Transport Mode Detection, GPS, inertial sensors, spectrogram

AUTHORS:
H.Moreau, L.Chen[1], **A.Vassilev**

In Transport Mode Detection, a great diversity of methodologies exist according to the choice of sensors, preprocessing, model used, etc. In this domain, the comparisons between each option are not always complete. Experiments on a public, real-life dataset are led here to evaluate carefully each of the choices that were made, with a specific emphasis on data fusion methods. Our most surprising finding is that none of the methods we implemented from the literature is better than a simple late fusion. Two major and impactful selections are the the choice of a sensor and the choice of a representation for the data: we found that using 2D convolutions on spectrograms with a logarithmic axis for the frequencies was better than 1-dimensional temporal representations.

SCIENTIFIC COLLABORATIONS: [1] Ecole Centrale de Lyon, Lyon, France (FR)

Context and Challenges

Transport mode detection is a classification problem aiming to design an algorithm that can infer the transport mode of a user given multimodal signals (GPS and/or inertial sensors). It has many applications, such as carbon footprint tracking, mobility behavior analysis, or real-time door-to-door smart planning. The signals are collected from an embedded device (either the sensors of a mobile phone, or a dedicated device), and processed by a Transport Mode Detection Algorithm, in order to know the transport mode of the owner of the device. This algorithm has multiple steps that often include a preprocessing step, and classification in itself. The classification step is where algorithms differ the most from each other. All algorithms use Machine Learning i.e., methods that use a certain amount of labeled data to learn how to predict the output transport mode, before making predictions on unseen samples. Contrary to domains like Computer Vision, the approaches in this domain differ greatly from each other: preprocessing, model, chosen sensors, recording conditions, etc. This diversity of variables further prevent fair and efficient comparisons between publications. Recently, in 2018, the Sussex-Huawei Locomotion (SHL) team published a dataset containing data from inertial sensors (accelerometer, gyrometer, magnetometer, etc.), in order to organize a challenge: they published a certain amount of labeled and unlabeled data, and asked researchers to make predictions on the unlabeled data set. We exploit this dataset to study the influence of sensor choice, preprocessing method and data fusion method on the classification performance.

Main Results

We studied the application of Convolutional Neural Network on a Transport Mode Detection problem. By fixing all but one choice in each of our experiments, we could evaluate each of the choices a practitioner can make. We found the more important choices to make are the sensor choice (the accelerometer being the best) and the preprocessing method (the use of spectrogram, with a logarithm axis for the frequencies), However, after evaluating 13 different data fusion methods, we found that no fusion method significantly outperforms the others.

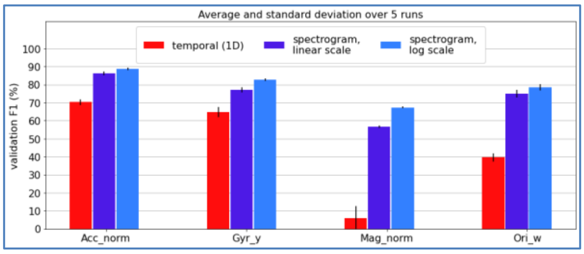

Fig.1: Different preprocessing on SHL2018

Perspectives

Future work might consist in applying our methodology to other classification problem involving also the fusion of temporal multidimensional sensor signals.

RELATED PUBLICATIONS:
[1] H. Moreau, A. Vassilev, L. Chen, « The Devil is in the details : an efficient convolutional neural network for transport mode detection », IEEE Trans. Intell. Transport. Syst., pp. 1-11, doi/10.1109/TITS.2021.3110949, 2021.
[2] H. Moreau, A. Vassilev, L. Chen, « Data fusion for deep learning on transport mode detection : a case study", EANN, 2021.
[3] H. Moreau, A. Vassilev, L. Chen, "When neural networks using different sensors create similar features", EAI MobiCASE, 2021.

Early detection of dysgraphia in children through AI analysis of handwriting traces

RESEARCH TOPIC:
BHK test, Graphomotor test, Children, Diagnosis, Dysgraphia, Handwriting, Machine Learning, Artificial Intelligence.

AUTHORS:
R. Lambert, C. Jolly[1] E. Labyt, V. Brault[2], **J. Boutet**

Dysgraphia is a writing disorder affecting 5 to 10% of the population. It is currently insufficiently diagnosed, partly because of the cumbersomeness of the existing tests. To simplify these, we developed two detection methods of dysgraphia. The first one relies on the analysis of a text written by the child on a digital tablet by a supervised learning algorithm. After training on a dataset of 461 children, our model was capable of inferring dysgraphia on 119 children with a sensitivity of 91% and a specificity of 81%, comparable to a human examiner. The second detection method, targeting younger children, analyses drawings (lines, circles) and was able to infer dysgraphia with a sensitivity of 75% and a specificity of 71% on a database of 305 children.

SCIENTIFIC COLLABORATIONS: [1] LPNC - Laboratoire de Psychologie et NeuroCognition, Grenoble (FR), [2] Univ. Grenoble Alpes, CNRS, Grenoble INP, LJK, 38000 Grenoble, France

Context and Challenges

Dysgraphia represents the inability or difficulty in producing legible writing affecting 5 to 10% of school-age children, boys more than girls. Many of its mechanisms are still poorly understood, which leads to late detection. It also impacts the learning of other skills (syntax, grammar, etc…) and reduces self-esteem. The current diagnostic (BHK test) is done at the hospital and is unsuitable for a large screening of the children population.

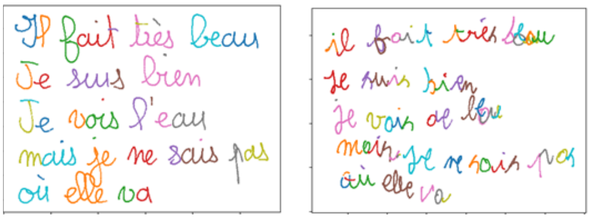

Fig.1: BHK test: typical / dysgraphia

Main Results

Two diagnostic tools of dysgraphia were developed, targeting different ages. The first one targets children in primary school, having already learned to write. To develop this tool, we collected the written tracks of 580 children, including 122 with dysgraphia (world largest database) performing the BHK test on 4 digital tablets (Wacom). 90 features relevant of dysgraphia were extracted from these written tracks and analyzed by a supervised learning classifier (Support Vector Machine). After a training phase on a dataset of 461 children our model was capable of inferring dysgraphia on a second dataset of 119 different children with a sensitivity of 91% and a specificity of 81% (comparable to a human examiner) [1].

The second diagnostic tool targets younger children, having not yet learn to write but capable of handling a pen to make a drawing. This tool was trained on a database of 305 children, including 43 with dysgraphia, who were asked to perform a graphomotor test consisting in the drawing of geometric figures (lines, circles, loops) according to a template. 10 features were extracted from the drawing tracks of the different figures and used to infer dysgraphia by a supervised classifier. The performances of different classifiers were compared and the best performing one (a Random Forest) was able to infer dysgraphia with a sensitivity of 75% and a specificity of 71% measured by cross-validation on the 305 children. These promising results highlight the relevance of graphomotor tests to diagnose dysgraphia earlier and more broadly [2].

Perspectives

These tools are currently tested by a team of clinicians at Grenoble Hospital. At short term, this will allow CEA-LETI and LPNC to get a feedback on the relevance of the model on new subjects. A long term, the increase of the number of subject in the database may lead to further Improvement of the model generalization capability. In parallel, we aim to get a better understanding of the neural processes involved in dysgraphia by adding EEG and eye tracking to handwriting tracks.

RELATED PUBLICATIONS
[1] Louis Deschamps, Louis Devillaine, Clement Gaffet, Raphaël Lambert, Saifeddine Aloui, Jérôme Boutet, Vincent Brault, Etienne Labyt, Caroline Jolly. "Development of a Pre-Diagnosis Tool Based on Machine Learning Algorithms on the BHK Test to Improve the Diagnosis of Dysgraphia", Adv. Artif. Intell. Mach. Learn., 1 (2):114-135, 2021.
[2] Devillaine L, Lambert R, Boutet J, Aloui S, Brault V, Jolly C, Labyt E. "Analysis of Graphomotor Tests with Machine Learning Algorithms for an Early and Universal Pre-Diagnosis of Dysgraphia", Sensors (Basel), 21(21):7026. doi: 10.3390/s21217026. PMID: 34770333; PMCID: PMC8588387, 2021.

Efficient planning of robotic object grasp by an under actuated multi digital manipulator

RESEARCH TOPIC:

Robotic dexterous manipulation of objects

AUTHORS:

C. Rolinat[1], M. Grossard[1], C. Godin, **S. Aloui**

Grasp planning, most specifically grasp space exploration and efficient grasp learning, is still an open issue in robotics. We present an efficient procedure for exploring the grasp space of a multi-fingered adaptive gripper for generating reliable grasps given a known object pose. This procedure relies on a limited dataset of manually specified expert grasps, and use a mixed analytic and data-driven approach based on the use of a grasp quality metric and variational autoencoders. The performances of this method are assessed by generating grasps in simulation and in real life experiments for three different objects. On this grasp planning task, this method reaches a grasp success rate of 99.91% on 7000 trials in simulation and 100% on 30 trials on the real robot.

SCIENTIFIC COLLABORATIONS: [1] CEA LIST, Saclay (FR)

Context and Challenges

Although grasping an object is a trivial human task, it involves multiple skill coordination (perception, cognition, motor skills). For robots, an understanding of object posture and shape is a requirement to grasping policy and execution, and building an analytic model that can handle all the object variability is complex.

Thanks to advances in AI and simulation tools robots learn to grasp objects by themselves better than a human would. Reinforcement learning is a promising method to develop a grasping policy that can deal with complex objects. The main challenge is the huge space to be explored especially for actuated multi-fingered grippers.

Main Results

We proposed a model that learns from a few human initiated successful grasp samples in order to explore the grasp space in a more efficient way. A high success rate was reached and new grasp samples not present in the human examples were found. A second model was then trained using the first model output along with a grasp quality assessment. It learned the successful grasp space and gave a prediction of grasp quality expected from each one. The advantage of this method is that it can suggest any required number of candidate grasp configurations along with their qualities. This allows for example to test each suggested configuration for more task constraints and choose grasps that are at the same time acceptable by the task to be performed and with high expected quality.

Simulation and experimental results show a grasp success rate of 99.91% on 7000 trials in simulation and 100% on 30 trials on the real robot (Fig. 1).

Perspectives

Other work showed that a single model can handle multiple objects provided we know each one of them. But this is still not satisfying as the objective is to be able to grasp objects that were never seen before. We worked on object perception and aimed to build a model which directly links the physical information about the object and the optimal grasp. In other words, the learning process should build a transformation function that takes the 3D camera cloud point positions as input along with a random vector for sampling and provides a grasp configuration along with grasp quality as output. Preliminary results suggest that it is possible to build a model that learns to grasp certain variations of the objects that it was trained to grasp. More power, longer simulations and bigger objects databases will enable to achieve a universal object grasping AI.

The object precise posture in hand - to perform meaningful operation such as insertion or even simple placement - and object reorientation in hand are potential perspectives for such AI given time and computing power.

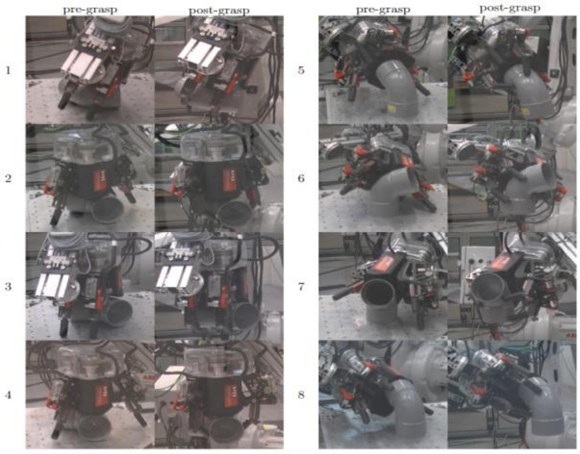

Fig. 1: Successful grasps by gripper

RELATED PUBLICATIONS:

[1] Clément Rolinat, Mathieu Grossard, Saifeddine Aloui, Christelle Godin, “Learning to Model the Grasp Space of an Underactuated Robot Gripper Using Variational Autoencoder”, SYSID, 2021.

[2] Clément Rolinat, Mathieu Grossard, Saifeddine Aloui, Christelle Godin, “Human Initiated Grasp Space Exploration Algorithm for an Underactuated Robot Gripper Using Variational Autoencoder”, ICRA, 2021.

A ^{4}He vector zero-field optically pumped magnetometer operated in the Earth-field

RESEARCH TOPIC:

Optically-pumped magnetometers, geophysics, space

AUTHORS:

T. Jager, F. Bertrand, A. Boness, W. Fourcault, G. Le Gal,
A. Palacios-Laloy, J. Paulet, JM. Léger

Low intrinsic noise, high bandwidth, and high accuracy vector magnetometers are key components for many ground or space geophysical applications. We have designed and tested a ^{4}He vector optically pumped magnetometer (OPM) specifically dedicated to these needs. It is based on a parametric resonance magnetometer architecture operated in the Earth magnetic field with closed-loop compensation of the three components of the magnetic field. It provides offset-free vector measurements in a ±70 µT range with a DC to 1 kHz bandwidth. We have demonstrated a vector sensitivity up to 130 fT/√Hz, which is about ten times better than the best available fluxgate magnetometers currently available for the same targeted applications.

SCIENTIFIC COLLABORATIONS: CNES (Toulouse), BRGM (Orléans)

Context and Challenges

High precision and high bandwidth vector magnetic measurements in the Earth field range are usually performed with fluxgate magnetometers. However this technology has an intrinsic sensitivity limited to a few pT/√Hz and exhibits offsets in the range of several nT that affect their accuracy. Zero-field vector OPMs can reach better vector sensitivities, below 100 fT/√Hz, and large bandwidths but they are usually operated in a nearly zero field magnetic environment [1]. Adapting this technology to ambient field measurements led us to design a compact, high dynamic and low noise field compensation system able to keep the zero field condition around the helium-4 gas cell without degrading the intrinsic high level of performances.

Main Results

First, we have been able to design a spherical tri-axial compensation coil with an outer maximum diameter of 5 cm, which provides a magnetic field homogeneity better than $2{\times}10^{-3}$ over the ^{4}He gas cell. With this coil geometry, the maximum magnetic field gradient generated is about 600 nT/cm @ 70 µT and we checked that it has not impact the metrological performances of the sensor [2].
Then we designed a specific electronics able to drive the sensor in a null-field closed loop operation mode over the required ±70 µT dynamic range. In our closed-loop architecture, the most critical component is the Digital to Analog Converter (DAC) of the current compensation feedback chain: a high SNR, 28 bits, 64 kSPS DAC was specifically designed and associated with a very low noise current generator. The measured noise floor of this chain was of 175 dB/√Hz. This excellent result allows equivalent vector noise measurements of 100 fT/√Hz for a full compensation range of ± 70 µT [2].
Finally the magnetometer has been operated and validated in representative ambient field conditions were it successfully demonstrated the triaxial ±70 µT measurement range in closed-loop configuration with a vector noise floor in the 130-170 fT/√Hz range over the full [DC; 1 kHz] measurement bandwidth [2]. Vector measurements were also calibrated against scalar reference sensor with a reconstruction accuracy better than 0.7 nTrms [2].

Perspectives

This ^{4}He vector magnetometer successfully demonstrated that it can be considered as an advantageous alternative to fluxgates whenever high resolution or high accuracy is required, e.g., for geophysical (magnetic observatories, groundwater prospecting, mining, and drilling), defense (zone intrusion detection with magnetometer networks), or space applications (low Earth orbit or planetary magnetic missions, including space weather activities). It is part of the magnetic payload on board the NanoMagSat satellites, a mission submitted to the ESA Scout call and that is currently under development in a Risk-Retirement phase.

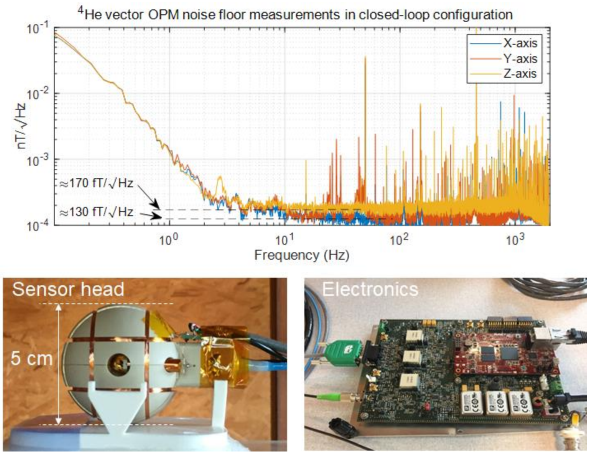

Fig. 1: ^{4}He Vector OPM and main performances

RELATED PUBLICATIONS:

[1] W. Fourcault, R. Romain, G. Le Gal, F. Bertrand, V. Josselin, M. Le Prado, E. Labyt, and A. Palacios-Laloy, "Helium-4 magnetometers for room-temperature biomedical imaging: toward collective operation and photon-noise limited sensitivity," Opt. Express 29, 14467-14475, 2021.

[2] F. Bertrand, T. Jager, A. Boness, W. Fourcault, G. Le Gal, A. Palacios-Laloy, J. Paulet and J. M. Léger, « A ^{4}He vector zero-field optically pumped magnetometer operated in the Earth-field », Review of Scientific Instruments, 92, 105005, 2021

Combining atomic orientation and alignment to attain isotropic sensitivities in magnetometry

RESEARCH TOPIC:
Optically-pumped magnetometers, medical imaging, geophysics

AUTHORS:
G. Le Gal, L.-L. Rouve[1], **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.

SCIENTIFIC COLLABORATIONS: [1] Université Grenoble Alpes, G-INP, G2eLab, Grenoble, (FR)

Context and Challenges

For medical imaging and geophysics applications, it is desirable to measure the three components with the same very good sensitivity. These last years, optically pumped magnetometers (OPM) operating in very low magnetic fields have reached excellent sensitivities, but most vector OPM can measure only two components of the magnetic field, the third component being either not accessible or suffering from a much worse sensitivity.

Main Results

The vector OPMs usually 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 varies around zero. The latter appears when, in addition to that, 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, 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, but an improvement of a factor 11 for third component. Additionally a 2 kHz bandwidth is achieved for the three components [1]. We completed this demonstration by a more fundamental study on the physics of OPMs based on elliptically-polarized pumping light [2].

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.

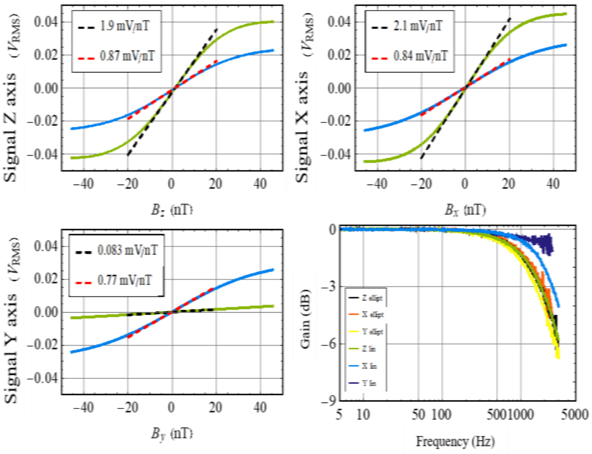

Fig.1: Comparison of both scheme sensitivities

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., 118, 254001, 2021.
[2] G. Le Gal and A. Palacios-Laloy, « Zero-field magnetometry based on the combination of atomic orientation and alignment », *To be published.*

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O6 RESEARCH DEGREES AWARDED IN 2021

- HDR: Pr Antonio CLEMENTE
- HDR: Pr Valentin SAVIN
- PhD: Dr Romain BEHEAGEL
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ANTONIO CLEMENTE, HDR

ANTENNA TECHNOLOGIES FOR BEAM-FORMING AND BEAM-STEERING FROM MICROWAVE TO SUB-THZ FREQUENCIES

CEA-Leti Systems Department, ED MathSTIC Université Rennes

The research activity presented for the defence of this Accreditation to Supervise Research (French HDR) was divided into four main axes: (1) Numerical Tools for Antenna Modelling, Synthesis and Optimization; (2) Advanced Antenna Systems for Beam-Forming and Beam-Scanning; (3) Integrated Antennas at Millimetre Wave and Near-Field Focusing Systems; (4) Antennas Measurements and Integration in Complex Systems. The proposed work included the development of numerical tools for antenna modelling, synthesis and optimization, the design and the experimental demonstration of advanced antenna systems, and its integration in complex systems for applications up to sub-THz frequencies. The research activity has been supported by 15 regional, national or European grants, and 8 industrial bilateral projects. Furthermore, Antonio Clemente has (co-)supervised or is (co-)supervising 8 PhD students, 7 collaborators or Post-Doctoral fellows, and 4 master students. In addition, the proposed results were achieved through collaborations both with several external research institutes (including University of Rennes 1, University of Bologna) and with internal CEA-Leti researchers working on antenna design and measurements, radio channel sounding and modelling, radio frequency integrated circuits (RFIC), application specific integrated circuits (ASIC) and advanced integrated components design, beam-forming, massive-input massive-output (MIMO) technologies, convex optimization algorithm design and implementation, digital electronics.

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VALENTIN SAVIN, HDR

CONTRIBUTIONS TO THE CONSTRUCTION AND DECODING OF LDPC AND POLAR CODES

CEA-Leti Systems Department, ED MSTII Université Grenoble Alpes

Consequence of the mathematical theory of information laid down by Shannon, the theory of error correcting codes aims at finding effective constructions of codes and decoding algorithms, contributing in a decisive way to an area that is vital to our modern information society. The first part of the work reported for the defence of this Accreditation to Supervise Research (HDR) provides a quick glimpse into salient aspects of coding theory, starting with the early days algebraic constructions, and culminating with Low-Density Parity-Check (LDPC) and more recent polar code constructions. The latter two constructions are recognized today as two of the most significant contributions to coding theory, due to their capacity to closely approach or achieve the theoretical Shannon limit. The second part of the report presents some of the lines of research which Valentin Savin has developed over a span of more than 15 years, in the field of advanced coding techniques for data transmission, networking, and processing. The presentation covers various topics, including decoding algorithms for LDPC and polar codes and corresponding hardware architectures, decoding under faulty hardware, the design of reliable systems built from unreliable components, as well as quantum error correction and fault-tolerant quantum computation. The last part of the thesis outlines the main research perspectives, rooted in some of his former or current research activities, and further driven by new trends in information and coding theory, from machine learning to quantum computing.

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ROMAIN BEHAEGEL, PhD

SUB 6 GHZ MIMO CHANNEL SOUNDER BASED ON SOFTWARE DEFINED RADIO BOARDS AND LTE SIGNAL

Université Gustave Eiffel / LEOST, CEA-Leti Systems Department

With the development of digital technology and the Internet of Things, there is a growing need for transmission rates per user, capacity, security and flexibility of communications systems. This trend is general in all areas of society and particularly in the field of transport and autonomous and connected mobility. V2X (vehicles for all) communication systems address these challenges. In addition, fifth generation (5G) cellular networks promise significant improvements in throughput, capacity, latency and reliability. Thus, due to the obsolescence of the current ground-train communication system used in Europe, GSM-R (Global System for Mobile Communication - Railway) will be replaced by FRMCS (Future Railway Communication System) which accounts for the parallel use of several radio access techniques including 5G. One can assess the various communication systems upstream of their deployment in railway environments (trenches, urban areas, rural areas, stations, yard areas, tunnels, etc.) by emulating these environments in channel emulators using channel templates. Representative channel models are obtained with measurements or simulations (Ray tracing/launching). This thesis work focuses on the implementation of a 4 x 4 MIMO (Multiple-input, Multiple-output) channel sounder in the sub-6 GHz range in order to characterize different railway environments for which models do not exist yet. A Software Defined Radio equipment performing channel estimation via the pilots of an LTE-OFDM symbol, was designed and tested in different mobility conditions. This research was carried out in collaboration with IFSTTAR, under FEDERER funding.

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RÉMI BERNHARD, PhD

INTRINSIC SECURITY OF NEURAL NETWORKS: ATTACKS, PROTECTIONS, EVALUATION

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There is a growing will to deploy neural network models in the everyday life, for image classification, speech recognition, autonomous driving, etc. Whether these models are used in distant APIs or embedded on devices, adversarial examples constitute a threat to this deployment, and to the integrity of machine learning (ML) models. Adversarial examples refer to attacks where an adversary maliciously modifies some input, in order to fool a model at inference time. In this thesis, we aimed at better understanding the vulnerability of neural networks to adversarial examples, and at developing efficient schemes to thwart their transferability, one of their worrisome aspect. We established links between robustness issues of different models and intrinsic frequencies properties of the data set considered and conducted a study based on cognitive psychology results showing the prevailing importance of low-frequency information in the human classification process. Moreover, we showed that quantization offers no robustness, inducing a false sense of security via the phenomenon of gradient masking, and exploited our results as a basis for the development of an ensemble-based defence scheme. We then developed an innovative way to thwart the transferability of adversarial perturbations: the luring effect, implemented on a substitute model, relatively to a target model. Finally, we highlighted a link between integrity and availability attacks and designed a new attack method against the availability of a system.

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ABDESSAMAD BOULMIRAT, PhD

HIGH-ORDER-N MULTIPLICATION-BASED MMWAVE FREQUENCY SYNTHESIZER WITH INTEGRATED LOCK DETECTOR

CEA-Leti Systems Department

Due to the limitation of sub-10GHz bands and overuse causing interferences, millimeter waves (30-300GHz) offer an interesting ground to meet the growing demand on large bandwidths and high throughputs. The use of high-order modulation schemes (256QAM, 64QAM, 16QAM…) along with channel bonding at these mmW bands enable Gbits/s data rates. To address complex modulations in those bands, very low Phase Noise (PhN) oscillators using multiplication-based frequency synthesizers were regarded. Noticeably, the smaller the frequency reference along with large multiplication ratios, the greater the spectral purity of the generated mmW frequency references. A possible implementation of high-order-N frequency multiplication is based on Pulsed-Injection Locking Oscillator and achieves multiplication factors of the order of 30 compared to "n-push" or harmonic distortion techniques which are limited to much smaller multiplication factors. Modeling these type of architectures remains challenging due to the highly nonlinear behavior of signals involved. Furthermore, the use of injection locked oscillators evidence, if not functionality issues, improvable performances. To take advantage of this high-order-N multiplication technique, accurate modelling of phase noise through the frequency multiplier chain was required. Two main contributions were achieved: the complete behavioral model description of waveforms and associated PhN figures involved in the multiplication process and the design in CMOS advanced technology of an integrated low-power and low-area functionality detector into the frequency synthesizer operating at 60GHz-band.

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HUGUES MOREAU, PhD

DEEP LEARNING FOR TEMPORAL MULTIDIMENSIONAL SIGNALS APPLIED TO TRANSPORT MODE DETECTION

CEA-Leti Systems Department

Deep neural networks have revolutionized Machine Learning, completely reshaping several domains of research in a mere decade, such as computer vision, for which deep learning outclassed the previous approaches based on handcrafted features. For instance, to the current day (end of 2021), the most baseline approach to extract features from a RGB image is to use a neural network trained on the popular Image classification task ImageNet. More generally, in the most popular domains, there is a great deal of literature, good practices, and pretrained models accessible with a few lines of Python code. However, not all problems are as crowded as computer vision. The study is placed in a laboratory work environment which deals with multiple types of sensors (accelerometers, strain sensors, GPS signals, physiological signals) to perform Machine Learning, in the span of several months. For many of these unnoticed tasks, deep neural networks require considerable work: preprocessing, hyperparameter selection, choice of an encoding, sensor prioritisation, depending on the problem. This work aimed at describing a sound scientific scheme of reviewing the most common choices to be made in order to make deep neural networks work with temporal signals, with a particular focus on Transport Mode Detection. Each study case was investigated based on experiments and/or the literature.

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MOHAMED SANA, PhD

HIGH-ORDER-N MULTIPLICATION-BASED MMWAVE FREQUENCY SYNTHESIZER WITH INTEGRATED LOCK DETECTOR

CEA-Leti Systems Department

We face an unprecedented demand for wireless communication bandwidth. Not only is the volume of data traffic exploding, but the nature of communicating objects is diversifying. New applications and use cases with stringent requirements are emerging, which complexifies the management of radio, computing and storage resources, appealing to flexible, scalable and low complexity solutions. Distributed learning approaches are a valuable solution but face several challenges, especially in dense 5G network deployments, due to an uncertain wireless environment and limited radio and computing resources. In a first approach, we proposed new distributed learning frameworks based on multi-agent reinforcement learning, where autonomous-decision-making agents collaborate with (or compete against) each other for radio and computing resources. A new architecture is proposed which conveniently combines neural attention mechanisms and multi-agent reinforcement learning to build fully transferable user association policies with "zero generalization capability". Hence, the knowledge acquired in one specific scenario is transferable to another without requiring any additional training procedure. In a second step, we addressed the problem of energy-efficient dynamic computation offloading, where multiple users compete for radio and computing resources to offload dynamically generated data. We formulated this long-term energy (and complexity) minimization problem with end-to-end delay constraints to meet user quality of service and also proposed a new architecture that enables "representation learning" of semantic symbols, evidencing the potential of semantic communications to improve future 6G network sustainability.

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GAËL VILA, PhD

WHITE-BOX MODEL FOR STRESS ASSESSMENT FROM PHYSIOLOGICAL SIGNALS AND REAL-LIFE FEASIBILITY

CEA-Leti Systems Department

Acute stress is our body's adaptive response to the challenges of daily life. Stress has well-known physiological correlates, which can be monitored through heart rate, skin conductance or respiratory activity. Over the past decade, the rise of wearable physiological sensors has provided valuable insights into the development of stress detection models that could be used in real life. Yet, physiological stress correlates are also sensitive to many confounding factors. Moreover, real-life physiological measurements involve frequent artefacts and current literature models lack an effective strategy for managing sensor data quality. Finally, current accuracy-based approaches tend to promote black-box models whose decision cannot be interpreted for therapeutic purposes. To tackle these issues, we provided white-box methods to design a stress detection model able to operate in everyday life. We first proposed a feature selection method that identifies individuals that are sensitive to stress and relatively insensitive to stress to confounding factors. We then developed a stress detection model designed to withstand artefactual data and which incorporates a modular structure to timely adapt to the quality of physiological measurements. The idea behind this model was to be able to isolate, without further training, features that are temporarily unavailable or too noisy for stress detection. To capitalize on such an adaptive ability, we finally provided an algorithm to timely estimate the quality of heart rate data. Combined with this quality index, our stress detection model is one more step towards an objective measurement of this phenomenon and its occurrence in our daily lives.

VINCENT WERNER, PhD

IDENTIFICATION AND EXPLOITATION OF FAULT INJECTION VULNERABILITIES ON MICROCONTROLLERS

CEA-Leti Systems Department

Fault injection (by focused light, electromagnetic pulse, power glitch, etc.) is an extremely powerful technique for compromising an embedded system. By physically disturbing the environment of the microcontroller, it is possible to modify its behavior to extract secret information, or to bypass security mechanisms. Although fault injection vulnerabilities are a potential threat to the security of many systems, in practice, it is often difficult to identify and exploit them, because their effects are not known in advance: they depend a lot on the target microcontroller and the fault injection equipment used. In order to analyse fault injection vulnerabilities, fault effects can be simulated using fault models. However, depending on the model fidelity and effect realism, some of the vulnerabilities identified may not be exploitable in practice. Accordingly, the main objective of this thesis was to propose new methods, techniques and tools to reduce the gap between simulation and experimentation, in order to optimize the identification and exploitation of these vulnerabilities. We proposed an end-to-end methodology, combining experimental and simulation results in order to infer the most probable fault models to improve the realism of the simulated faults. This first approach drove us towards test programs designed to maximize the fault propagation. We proposed original metrics to evaluate these tests, design more efficient ones and improve our understanding of fault effects. Finally, we used for the first time in fault injection, two recent optimization techniques to optimize the identification of the best equipment parameters, in order to speed up the exploitation of fault injection vulnerabilities.

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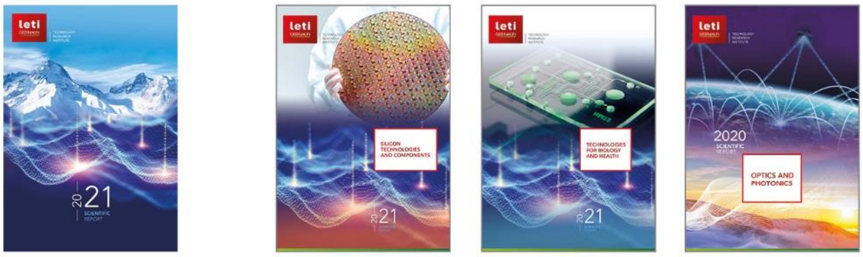

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