Research Report
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Laboratoire Traitement et Communication de l'Information - UMR 5141
Télécom ParisTech - CNRS

Research Report 2009–2011

Laboratoire Traitement et Communication de l'Information

Département COMELEC

Télécom ParisTech & CNRS

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Part I

Communications and Electronics

Communications and Electronics Department (COMELEC)

The research led in the **" Communications and Electronics "** department is devoted to the physical layer of ICT (Information and Communication technology). A useful concept for depicting the department main research concern is that of "physical information", where the information content is actually reached through some physical properties and manipulated using physical laws such as Maxwell electromagnetic equations or Quantum Hamiltonians. The department covers both the field of communication and that of information processing (electronics).

The department accounts for 39 permanent research staff and hosts over 100 non permanent researchers every year, including PhD students. The research activity is covered by four different teams. While fixed communications are dealt with by the **Optical communication team**, the **Electronics and RF systems team** concentrate on the transformation from analog to digital information and to its transmission through wireless means. The **Digital communications team** works on the digital coding of the information, and prepares for the future digital communication breakthrough in cooperative system, multi-hop communications or multi-users wireless communications. Processing information requires extremely sophisticated Silicon chips (processors, FPGAs, SOCs), the architecture of which is central to the **Complex Digital Electronics system team**. Transverse to all these activities, one may also find security as a main topic.

The department research policy claims for a research effort that spreads from fundamental physics to applied results. One may for example note our results in quantum communication (see the optical communication team) or that of metamaterials for advanced antennas (Electronics and RF Systems team). The balance between exploratory research and market oriented results is well expressed by the 1:5 ratio between our private partners funding and our total research contract income (4.7 M€ cumulated over the period). Because of an innovation minded research taking its roots in fundamental theories, the department was granted 16 patents while publishing over 450 papers in journals and conferences in the evaluation period.

The department is also strongly involved in educating students for research. This is reflected by the 51 defended PhD thesis over the period. A budget of about 40 k€ is also spent yearly for master student internships in the department research groups, with a total of about 80 man.month of internship generated every year. Besides its contribution to the "ingenieur courses" of Telecom ParisTech, the department researcher's participate to master courses with Universities Pierre et Marie Curie and Paris-Sud Orsay, as well as with the University of Nice.

The past period has been an exciting and successful period for the department. The success of our research proposals is well expressed by steady 15% growth rate per year of our lab contractual budget. As an indication of the department growing international recognition, the amount of international contract has raised from 13% in 2009 to 39% in 2011. In terms of publication, this growth reflects in as much as 99 published peer reviewed journal papers and 349 conferences accepted in the last two and a half year.

The period has also been very active for our lab facility with the launching in January 2010 of a new 130 m^2 lab area, including a 40 m^2 anechoïc chamber for our antenna tests. Another 300 m^2 of laboratory floor were entirely refurbished, giving rise to an environment entirely devoted to very high frequency experiments. These changes were strengthened by the purchase of nearly

800 k€ of new scientific equipments.

Two other major events with long lasting consequence must also be pointed out.

- A reserch team from ENSTA ParisTech merged with the Telecom ParisTech RFM team in 2010, making Telecom ParisTech an internationally recognized environment for UWB antenna design and applications.
- The joint ParisTech Morpho Lab "Identity & Security Alliance" which was inaugurated in march 2011 was created from teams in the Infres and Comelec department , a recognition of the successful research in embedded electronics security which is led in the department.

The coming period should open new opportunities for the development of our research. Discussions for joint research labs have already been open with several companies. Novel research masters will be proposed in 2012 for accreditation. And overall, a number of exciting new research projects in all of our research segments are already under consideration for fixed and wireless high bit rate communications with terabit/s communications in mind, in opportunistic radio, in secured electronics, or sustainable ICTs.

Faculty [IT, CNRS]	[32.8, 4]
PhD students	65.5
Post-docs, engineers and sabbaticals	16.1
Defended PhD thesis	51
Defended HDR	3
Journal papers [published, in press]	[99, 15]
Papers in conference proceedings	349
Chapters and books	15
Patents and software	[16, 3]
Grants [public, private, european] (k€)	[2667, 876, 1207]

Chapter 1

Digital Communications

Team leader Philippe Ciblat (P).

Faculty

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J. Vinogradova (09/11–), S. Belhadjamor (10/11–), Y. Wu (10/11–).

Post-docs and engineers

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Sabbaticals

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L. Budaghyan (04/11–10/11), C.C. Trinca (04/11–), S. Jitman (09/11–09/11),
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Faculty [IT, CNRS]	[6.8, 2]
PhD students	13
Post-docs, engineers and sabbaticals	1.8
Defended PhD thesis	15
Defended HDR	2
Journal papers [published, in press]	[25, 9]
Papers in conference proceedings	81
Chapters and books	1
Patents	6
Grants [public, private, european] (k€)	[322, 162, 163]

1.1 Objectives

For the last five years, the Digital Communication team has mainly been working on the physical layer of wireless networks. The most important results were in the context of single-user MIMO communication, cooperative communications (i.e., when a source and a destination are helped by additional nodes called relays), and finally multi-user cellular networks (when the communication is one-to-many or many-to-one). In such contexts, the team has focused on finding new:

- Coding techniques
- Resource allocation algorithms
- Estimation and synchronization methods

Nowadays, the most important topic is to design, analyze, and optimize many-to-many (wireless) communications where different flows of information are propagating through a common wireless network. Depending on the application, the network may be either centralized or ad hoc. The digital communications group has followed this important evolution by working on so-called Mobile Ad Hoc Networks (MANET). Our contributions cover different points of view: information theory, coding, resource allocation, distributed signal processing, and security (which is a major concern in such networks). Notice that the group has been enforced by hiring new Associate Professors in the area of Information Theory.

Even if our activities on wireless networking are central, we are also pursuing significant research activities on the (more traditional) physical layer of wireless or wired networks. Our main contributions here are new codes (asynchronous codes, etc.) and improved cross-layer designs (hybrid ARQ which takes into account the network layer) for wireless networks, and new signal processing algorithms and codes for next generation fiber-optical systems. This last project is a collaboration with the Optical Telecommunications team. In our research we typically present solutions on the three important facets of signal processing, coding, and information theory.

The team has important international editorial activities: we take part in the technical committee of the flagship conferences and in the editorial board of IEEE Transactions on Information Theory and IEEE Transactions on Signal Processing. All our research activities are supported by national, European, or industrial funding.

Our group is also very active in teaching for the Engineering school as well as for various Masters programmes. In particular, jointly with the Université Pierre et Marie Curie, we are leading the ”Master Recherche” called ESCO/STN.

1.2 Main Results

The main research results obtained during the period July 2009 - December 2011 are presented below.

1.2.1 Wireless Network Optimization

Faculty J.-C. Belfiore, P. Ciblat, W. Hachem, A. Tchamkerten, M. Wigger

Main events Philippe Ciblat has served as Associate Editor (resp. Area Editor) for IEEE Transactions on Signal Processing since 2008 (resp. 2010) as well as Track Chairman for the European flagship conference EUSIPCO'2001. Philippe Ciblat, Walid Hachem, and Michèle Wigger have been respectively invited professors at the International University of Rabat (Morrocco), the CTTC (Spain), and the Technion (Israel).

Projects ANR Chaire d'Excellence, "Futur & Ruptures" grants, DGA doctoral grant, Digiteo postdoctoral fellowship, ANR SESAME, Emergence Grant from the City of Paris, FP7 NoE NEWCOM++

Wireless network coding Wireless networks for high data rate transmissions are becoming more and more dominated by interference. Fundamental works in Information theory clearly shed a light by using lattices on this problem. But information theory states the fundamental limits but does not say anything about "how to achieve these fundamental limits". Thanks to our expertise concerning lattices for wireless communication, we obtained important results on lattice coding for interference channels. We are now able to propose new lattice coding schemes and analyze them. We are currently working on lattice network coding for which we were able to give a criterion of design for the lattice codes that are used. This work was a generalization of the so-called Compute-and-Forward protocol proposed by Nazer and Gastpar in 2009. In the same spirit, we started to work on the interference channel where we focus on the so-called lattice alignment for the interferers. This work had a big impact, theoretically and practically. We are developing some new tools to understand in a better way the behavior of lattices on such channels and relate it to the fundamental limits.

Fundamental Limits We studied the capacity of wireless networks where the transmitters or the receivers have some side-information, e.g., about other transmitters' messages or signals, or about the signals observed at some of the (other) receivers. Our contributions were twofold:

i) For the many-to-many interference network where the transmitters have side-information about the adjacent transmitters' messages (e.g., by prior communication over separate bluetooth links) and the receivers have side-information about the signals observed at adjacent receivers (e.g., by communication over a high-rate backhaul link) we studied the high-SNR behavior of the capacity. We mainly focused on Wyner's soft handoff model for cellular systems, for which we determined the degrees of freedom. Our result allowed us to establish a duality between the side-information at the transmitters and the side-information at the receivers in the sense that in terms of degrees of freedom they are equally valuable. We also determined the degrees of freedom when the transmitters only have partial knowledge of their adjacent transmitters' messages.

ii) For the one-to-two memoryless broadcast channels (BC) where the transmitter has feedback from both receivers (as is the case in most uplink-downlink scenarios) we studied the capacity region. This problem is unsolved for almost all memoryless BCs. In our works, we determined the capacity region of some BCs, and we proved that the capacity is increased even if the feedback is noisy. We also showed that for Gaussian broadcast channels in some cases the gain in capacity thanks to perfect feedback can be unbounded, and in most cases the high-SNR capacity is as if both receivers could perfectly cooperate. [5]

Motivated by practical communications systems, such as certain wireless sensor networks, the receiver of a communication system does not know perfectly the timing of information transmission and this leads to the so-called ”asynchronous communication”. This kind of communication has long been a neglected field in information theory. We have been investigating a new information theoretic model for asynchronous communication. Main results are the characterization of the minimum energy needed to transmit one bit of information asynchronously, and the proof of suboptimality of training in certain communication regimes. The second result says that the prevalent communication architecture where synchronization and information transmission are treated separately can be suboptimal; each transmitted bit should carry information while help the decoder locate the transmitted message [111].

Distributed computation In distributed computation/optimization/estimation communication is becoming a technological bottleneck. The problem arises both at the large and at the micro scales. Consider the task Google faces for search queries. After the query makes its way to a data center, the search task is handled to a number of servers working in cooperation. Yet, the minimum communication requirement to take advantage of multiple servers is not well understood. More traditionally in the field of wireless sensor netwokrs, resource allocation without a fusion center has to operate and can only be done in a distributive way. Similar problems occur for target location, etc.

We have focused on two types of computation: the maximum values of the sensor measurements and the average ones. Concerning the maximum computation, we have develop new algorithms well suitable for wireless communications. The main task has consisting in analyzing theoretically its performance [65]; Concerning the average computation, new powerful algorithms outperfoing exsintg ones have been introduced and analyzed also in depth. These computations are actually the first step of the distributed optimization issue which is a key point in the domain of the decentralized wireless networks. We also developed new algorithms for distributed estimation (one application could be the mobile location). These algorithms (based mainly on the so-called stochastic approximation approach) have been deeply analyzed in terms of convergence, asymptotic properties (such as asymptotic normality, asymptotic covariance). Moreover, we are moving the analysis of such algorithms in a non-stationary environment.

Finally, to better understand some of the communications tradeoffs in distributed computing, we have been investigated function computation of separate sources of information. For this setting, we provided bounds on the minimum number of bits needed to be transmitted by each source so that the receiver can reliably compute the function. For certain functions and sources these bounds are tight. [101].

Detection theory for cognitive radio The random matrix theory has received a lot of attention in probaiblity, statictics and signal processing for communications. We have focused on the applications of this theory to the statistical estimation (direction of arrival, detection at the fusion center, Shannon capacity evaluation, etc). We have especially analyzed the extremal eigenvalues of large random matrices and the corresponding subspaces. [8]

1.2.2 Coding for single-user communication

Faculty J.-C. Belfiore, P. Ciblat, G. Rekaya-Ben Othman, P. Solé, A. Tchamkerten

Main events Jean-Claude Belfiore has served as Associate Editor for IEEE Transactions on Information Theory since 2010. Jean-Claude Belfiorer and Patrick Solé are the recipient of the Best Paper Award in *IEEE Information Theory Workshop* (ITW) in 2009. Patrick Solé and Jean-Claude Belfiore organized the International Conference SETA 2010 at the school site. This conference was supported partly by Digiteo and dealt with all aspects of sequences over finite alphabets. Ghaya Rekaya-Ben Othman has been invited professor at Indian Institute of Technolgy in Bangalore in 2010. Daniela Tuninetti (Ass. Professor at Illinois Univ.

at Chicago) is in sabbatical stay in the lab in 2011. Finally Ghaya Rekaya-Ben Othman has been selected to contribute to the national event "1000 chercheurs parlent d'avenir".

Projects ANR ORIANA, CIFRE MITSUBISHI, CIFRES THALES, FP7 SMARTEN, "Futur & Ruptures" postdoctoral fellowship, Carnot Institute grant

Synchronization codes Our motivation was to study the performance of codes for joint coding and synchronization. A new class of codes intermediary between unrestricted binary codes and constant weight codes, namely bounded weight codes, and allied combinatorial functions, has been introduced. It turns out that the concept is also useful in list decoding, in bounding the list of candidate words at a given distance from the received word. In addition, but closely related, we worked on analytic number theory. We have especially connected the ideas of Alain Connes on a quantum mechanical approach to zeta functions with Jean-Louis Nicolas extremal view of arithmetic functions to derive an infinity of new criteria for Riemann Hypothesis.

Space time codes We still focused on the Space-Time codes design but in an original way. For the first time, codes over rings with non Hamming metrics are used to construct space time codes by a concatenation process similar to the so-called Construction A of lattices. We hope this work will attract the coding community attention to codes over *non commutative* rings an open territory in Coding Theory.

Cooperative communication The best known protocol for cooperative communication is the Dynamic Decode and Forward (DDF) protocol according to its Diversity-Multiplexing Tradeoff (DMT). We were interested on the practical implementation of this protocol for the relay channel with the assumption of relay unaware source. We have defined a new metric called Macro diversity (coming from long term SNRs) which represents the number of links necessary to achieve some QoS when all other links experience very low SNRs. We have proposed patching techniques in order to maximize the achievable micro and macro diversity. This technique consists of creation at the relays linear combinations of symbols already sent by the source and symbols going to be send by the source. The destination realize the same linear combinations (patching) of the received signals to build an equivalent transmission system. We have proposed different schemes using patching : patched Monostream, Patched Alamouti, Patched Golden Code and Patched Silver Code. [27]

To achieve the cooperative diversity, a synchronous communication is actually assumed. This a priori synchronization condition could be quite costly in terms of signaling and hard to handle in a relay networks. To relax this constraint, we have constructed $M \times M$ delay-tolerant codes based on cyclic division algebras of the $M \times M$ perfect codes. For $M = 2, 3, 4$ and 5, the new codes maintain the same properties (full rate, full diversity and non-vanishing determinants) as perfect codes in synchronous case. These codes are useful in a network without a direct link between the source and the destination. We have also proposed "bounded delay-tolerant STBC" which ensures optimal performances when the cooperative nodes are synchronous an a full diversity and optimal rates for a certain set of delay profiles that depends on the code length.

Hybrid ARQ schemes analysis In modern wireless networks, the physical layer is combined with Automatic ReQuest (ARQ) technique to improve the reliability of the whole system. Moreover the ARQ (or more generally, the Hybrid-ARQ (HARQ) which "belongs" to the MAC layer) can be greatly improved by taking into account the upper Network layer. Our first contribution has consisted in analysing deeply the theoretical performance (packet error rate, delay, jitter and efficiency) of any HARQ scheme at any layer for any channel model (the Gaussian one, the Rayleigh one, ...). We have also taken into account imperfect feedback conditions. We have also proposed new HARQ techniques more robust to imperfect feedback.

1.2.3 Optical communications

Faculty P. Ciblat, G. Rekaya-Ben Othman, O. Rioul

Projects FUI 100GFLEX, "Futur & Ruptures" Grants, ANR TCHATER, CIFRE MITSUBISHI

Due to the new applications (video streaming, cloud computing, ...), the amount of data in the optical core networks have strongly increased. To handle the saturation of the core network, advanced digital communications tools have to be applied to the optical communications field. Indeed, the information (passing through the optical fiber) now relies on the wave intensity but also on the wave phase. Therefore standard wireless digital communications can be now advocated for optical communications.

In this new paradigm, we have focused on various facets:

i) Usually adaptive approaches have been carried out to mitigate the inter-symbol interference (generated by the dispersion of the fiber and also the polarization mixing) and the carrier frequency offset. but as the channel is very slowly time-varying, we have proposed to counter-act these impairements by using block-wise methods. Thanks to simulations and experimental measurements, we have proven that this block-wise approach enables us to speed up significantly the convergence by the expense of moderate extra computational load, and thus is well adapted to burst mode transmission [457]. In addition, we have studied some near maximum a posteriori probability low-complexity phase estimators under phase uncertain channel for BPSK and QAM signals and prove their convergence, via a conditional gradient descent algorithm, towards the Bayesian Cramer-Rao lower bound for which we also found simple expressions depending on the modulation used and other assumption (off line / online, data aided / non data aided scenarios). This in particular explained anatically why such low-complexity estimators perform so well over a wide range of SNRs.

ii) In order to evaluate the ultimate performance of optical communications, we have also considered a information-theoretic point-of-view. We especially derive Shannon-like channel capacities when nonlinear impairments occur.

iii) The polarization multiplexed optical systems can be seen as multi-input multi-output (MIMO) systems, and so space-time coding techniques could be applied in this case. The implementation of such codes requires the use of OFDM systems. We have showed that the space-time coding can efficiently mitigate polarization dependent loss (PDL) impairments, and that their performance are very different from those obtained in wireless communication. The Silver Code performs better than the Golden code. This results was explained by an analysis of the error probability. We have also showed that the gain provided by Space-time coding is added to the gain provided by error correcting codes.

1.2.4 Security issues

Faculty J.-C. Belfiore, O. Rioul

Main events Jean-Claude Belfiore has been invited professor at NTU (Singapore).

Physical Layer Security Due the broadcast nature of the wireless channel, the security has also to be takein into acocunt by the physical layer (and not only but the cryptographic point of view). The most famous example is the so-called wiretap channel where one eavedrooper can listen to the message too. Our contribution dealt with the analysis of the nested lattice codes for the Gaussian wiretap channel as well as for the MIMO wiretap channel. The proposed closed-form expressions for the system performance were related to the theta series of the lattice (Gaussian case) and to some zeta function (which can be Epstein or Solomon) in the MIMO case. These results gave a design criterion for the lattice codes which have to be used. We are continuing with the proposition of practical lattice codes now.

Hidden channels for electronic devices Side-channel analysis (SCA) aims at extracting cryptographic keys from a device by analyzing its leakage, knowing its input or output. The general formalisation of SCA models the leakage as well as the data that causes it (called the sensitive variable), from an information theoretic standpoint. The traditional approach consists in distinguishing the correct key from the bad key hypotheses by selecting the key guess that maximizes the mutual information between the leakage and the sensitive variable. Now, it is well known that this mutual information is equal to the Kullback- Leibler divergence between the leakage and the leakage conditioned by the sensitive variable. In this work, we have suggested another distinguisher consisting in the divergence between pairs of conditional leakage. Our goal were twofold: to compare it theoretically with the mutual information, and to study its efficiency for certain types of leakage (especially in the presence of countermeasures to SCA, like masking).

1.2.5 Tools for Information Theory and Statistics

Faculty O. Rioul, A. Tchamkerten

Projects ANR Chaire d'Excellence

About Fitt's law Whether Fitts' law (a well-known model of human pointing movement in experimental psychology) is a logarithmic law or a power law has remained unclear so far. Papers have claimed that the power model they derived from their celebrated stochastic optimized-submovement theory encompasses the logarithmic model as a limiting case. We have shown that this claim is questionable mathematically. Our analysis revealed that these papers implie in fact a quasi-logarithmic (Shannon-like), rather than quasi-power model, the two models being not equivalent. Also, testing the prediction that throughput (TP) is conserved accross variations of speed/accuracy, we found it to be affected by the strategy, which pleads against a currently popular definition of TP which is incompatible with the Shannon equation. We also have shown that the statistical elaboration of the TP suffers from a problematic amount of random variability due to the inadvertent but multiple impact of Jensen's inequality.

About entropy power inequalities While most useful information theoretic inequalities can be deduced from the basic properties of entropy or mutual information, up to now Shannon's entropy power inequality (EPI) is an exception: Existing information theoretic proofs of the EPI hinge on representations of differential entropy using either Fisher information or minimum mean-square error (MMSE), which are derived from de Bruijn's identity. I have derived a unified view of these proofs, showing that they share two essential ingredients: 1) a data processing argument applied to a covariance-preserving linear transformation; 2) an integration over a path of a continuous Gaussian perturbation. Using these ingredients, I developped a new and brief proof of the EPI through a mutual information inequality. The result has the advantage of being very simple in that it relies only on the basic properties of mutual information.

Theory of Optimal Stopping Given sequential observations of a stochastic process, we consider the problem of estimating a stopping time defined with respect to an unobserved process which is correlated to the observation process. This problem, called the tracking stopping time (TST) problem, applies in a number of areas, including communications, monitoring, and forecasting. In spite of its simple formulation, the TST problem is hard as it also generalizes the well-known Bayesian change-point detection problem whose solutions have been reported only for specific (mostly asymptotic) settings. In spite of this apparent difficulty, we obtained interesting results for the natural settings where both the observed and unobserved processes are Gaussian random walks (possibly with drift), with the observed process being either a noisy version of the unobserved process, or a delayed version of the unobserved process. The stopping time to be estimated is some first-passage time of a given threshold. For this setting we characterized the best estimator with respect to arbitrary moment loss functions in the limit of large thresholds.

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Chapter 2

Complex Digital Electronic Systems

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Sabbaticals

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Faculty [IT, CNRS]	[10 , 2]
PhD students	20.4
Post-docs, engineers and sabbaticals	5.5
Defended PhD thesis	10
Journal papers [published, in press]	[15, 1]
Papers in conference proceedings	113
Chapters and books	2
Patents and software	[3, 3]
Grants [public, private, european] (k€)	[1016, 359, 389]

2.1 Objectives

The “Complex Digital Electronic System” team research topics are about the architectures and methods to design efficiently digital electronic systems under harsh requirements. The objectives are closely linked to the study of cutting edge techniques which allow electronic designers to meet ever growing constraints of complexity management, reliability, power consumption, speed, security and flexibility. The team has research collaborations with well known companies of the area such has STMicroelectronics, NXP, Freescale, ST-Ericsson, CEA, Orange or TexasInstruments. Among the academic laboratories the most representative are the CNRS laboratories LIP6 (UMR7606), LIRMM (UMR5506), GIPSA-Lab (UMR5216) or TIMA (UMR51599). We are also highly involved in the CIM (Centre Intégré de Microélectronique) PACA regional framework and the SAME (Sophia Antipolis MicroElectronics) association, two very important academic-industrials French consortiums. In order to balance industrials concerns and advanced academic research, we increased during the two past years our effort for PhD supervision. We focused our research towards three main themes:

- Design methodologies are coverered by the **Design Space exploration and assisted refinement of integrated systems** theme.
- Architectures with security constraints are dealt in the **Trusted computed hardware** theme.
- Architectures with a high constraint in Reliability are in the theme **Analysis and Design of Reliable Processors Based on Unreliable Technologies**
- Architectures with constraints of complexity and Power Consumption are in the **Optimal architectures for complex algorithms implementations** theme. Architectures for “Software defined radio” and multimedia applications are covered in this theme.

Team members, located in the sites of Paris and Sophia-Antipolis (LabSoC), have a strong teaching activity in the undergraduate and master level at Telecom ParisTech and at Eurecom. Lectures are in the fields of digital electronic design, embedded systems design, SoC (Systems-on-Chip) design and embedded systems security. An important part is given to practical aspects which are covered by supervisions of numerous student projects. The latest research results feed our teaching activity, for example, ANR SoCLib project methods are directly used in the ”System-On-Chip Design” track of our master of engineering. Team members have teaching activities and responsibilities at master level in several others institutions such as Paris-6 University.

2.2 Main Results

The main research results obtained during the period mid-2009 - end-2011 are presented below for the research areas of the Complex Digital Electronic System team.

2.2.1 Design Space Exploration and Assisted Refinement of Integrated Systems

Faculty L. Apvrille, R. Pacalet, S. Coudert, R. Boulifa

Main events Release of the free toolkit TTool[1], steering of the SAFA (Sophia-Antipolis Formal Analysis Group) workshop

Projects Cifre Ph.D. with Freescale, FP7 european project EVITA, LIP6-Telecom ParisTech project *Robustar*, Institut Telecom Futur/rupture Ph.D. on power-consumption aware design space exploration

The increasing complexity of Systems-on-Chip requires new design and verification methodologies. The approach developed at LabSoC relies on modeling at a very high level and on early verifications in the design cycle. A strong separation between control and data processing is introduced. At the highest levels data processing is completely abstracted away. Control–oriented tasks exchange abstract and valueless samples, allowing ultra-fast simulations and static formal verification. This approach is supported by a dedicated UML profile (DIPLODOCUS) and a free software toolkit (TTool). For the period 2009–2011 the main achievements are:

System-level Design Space Exploration (DSE): definition of a four-step methodology, comprising requirement / property capture, application modeling, architecture modeling and mapping [152] [287]. Simulation and formal verification are used in the first and second steps [152]. The current focus is on the property modeling step that still needs to be enhanced [152], and the modeling of advanced communication schemes and hierarchical scheduling [287].

Very fast simulation techniques: Design of a new speculative and transaction-based simulator. [172].The current focus is on adding power consumption estimation during simulation.

Formal verification: formal definition of the sets of primitives used in application and architecture modelling. Formal description and implementation of the mapping phase [219].

Coverage-enhanced simulation: To offer an intermediate scheme between a on-trace simulation, and an exhaustive computation of all system traces, definition of a coverage-enhanced simulation engine that can explore a given percentage of a mapping model [288]. To achieve this, definition and implementation of a new model-checker with possible variability in the system coverage.

The TTool toolkit: design and open–source release of a toolkit. This toolkit shares several features with related works of the team, on embedded systems modeling [168], embedded system dimensioning [276] and methodological assistant [275]. TTool is supported by Freescale. The whole framework is currently used in the context of the European project EVITA for security modelling and analysis on automotive security [245]. It has also been selected for the design of future aeronautics platforms (CORAC project).

Automated and Proved Refinement A new approach based on abstraction refinement [235, 283] intends to automate the refinement validation of high-level models into lower-level ones. That process shall as well guarantee the consistency between two abstraction levels.

Component-based design Whereas refinement approaches decompose complexity of systems ”vertically”, by splitting the design into multiple design levels, component-based approaches reduce complexity ”horizontally” whereby designs are obtained by assembling existing components. The global correctness of a design is based on the correctness of components and their assembly. Using that approach, we have defined a semantic model for the analysis and verification of safety and security properties of component-based applications [146, 165].

[1] http://labsoc.comelec.enst.fr/turtle/ttool.html

2.2.2 Trusted Computing Hardware

Faculty J-L Danger, G. Duc, T. Graba, S. Guilley, P. Hoogvorst, Y. Mathieu, R. Pacalet

Main events International DPA Contest V2 & V3, creation of the spin-off "Secure-IC", winner of the CNCE'2010 contest, in "création-développement" section, organization of CryptArchi'2010, chair of IEEE FDTC'2011, sabbaticals of Prof. Naofumi Homma (Tohoku U., Japan) and Prof. Sorin A. Huss (Darmstadt U., Germany).

Projects ANR SeFPGA, ANR SECRESOC, System@tic Pôle "Secure Algorithm", DGA RAPID "BCDL", ANR-JST "SPACES", ENIAC "TOISE", PhD CIFRE BULL, PhD CIFRE OBERTHUR, PhD CIFRE Secure-IC.

Cryptoprocessor implementations can be attacked by taking advantage of the physical behaviour of the VLSI circuit. The passive attacks also called "Side Channel Attacks" are based on the analyzis of the activity which can be made either by observing the power lines or the electromagnetic field radiation. The active attacks consist in injecting faults to modify the circuit's behaviour. The attack goal is to recover the secret key of the known algorithm, or to modify the code stored in external memories. The Trusted Computing Activity of the "Complex Digital Electronic Systems" research group is to understand the attack mechanism and provide prouvable efficient countermeasures.

The attacks and therefore their protections are done at circuit level or board level. At circuit level they aim at recovering the ciphering key or even the algorithm. They can be performed on any circuit from the smartcard to bigger VLSI devices.
Board-level probing attacks use external memories and memory buses as natural targets.

Protection at logical and physical level: During the mid-2009 end-2011 period, the research about the **protection at logical and physical level** has advanced on many point:

The **Electromagnetic Analysis** has been investigated. It has been shown that the attack can be enhanced by using precharacterized models [230] or by performing a pre-stage of cartography which allows to locate accurately the spatial position of interests for the analysis [249, 291, 248, 250]. The observation traces represented in the frequency domain have also been studied and can greatly enhance the attack [231, 229, 233]. The **Template Attack**, a powerful attack which does not need any detail about the implementation but a profiling stage, has been investigated. It has been shown that it is possible to improve this attack by reducing the noise and by using good models [158]. Also the technique of Principal Component Analysis has been studied to find and combine the best points of interest [259]. The combination of different parameters of the attack, like the model and the points of interest has also been tried to enhance the attack [203]. The use of **digital signal processing** techniques, like the Kalman filtering, allowed to reduce the noise of the acquired traces and thus the power of the attack [256, 257]. These techniques can also be used to attack protected implementation where a jitter has been added on traces to avoid a synchronization operation [208]. The attack used for reverse engineering has started by using either the side-channels [207] or the fault injection technique [246]. Some protections have been proposed [184].

The **countermeasures with Dual Rail with Precharge Logic (DPL)** have been intensively used. It has been shown that the DPL logic which is a good protection against Side-Channel Attack has also good properties against fault attack [253, 178, 292]. Moreover techniques to show the impact and enhance the place and route stages of DPL implementations has been carried out [150, 247, 155]. A powerful DPL logic "BCDL" as Balanced Cell Differential Logic, has been devised to avoid the flaws of the traditionnal WDDL logic [193, 237, 179]. However special care has to be taken to implement a cryptoprocessor in BCDL , as explained in [181]. The technique of **countermeasures by masking** has been succesfully analysed and formalized by using second order attacks [224, 225, 226]. Therefore powerful countermeasure by masking have been devised in order to thwart high-order attacks [227, 238, 271].

Protections at protocol level by using resilience properties have been studied [210]. They greatly reduce the needs to protect the implementations at physical level.

The randomness generation being a key operator for cryptographic systems, a True Random Number Generator has been studied to provide both speed and high level of robustness [148]. A study of Physically Unclonable Function (PUF) has started [186] to characterize the PUF at the design stage.

Protection at board level:

At board level, a complete architecture, called SecBus, has been proposed to protect the confidentiality and the integrity of code and data on the memory bus and on external memories [294]. This architecture has been combined with an internal protection mechanism to build a completely secure MPSoC [187].

The impact of fault injection attacks on smartcards that implement the JavaCard standard has been studied. New combined hardware/software attacks and new attack paths that highlight flaws in the JavaCard standard and on some implementations, have been discovered and some counter-measures have been proposed [175, 176].

Hardware security module: In the scope of the European project EVITA for security modelling and analysis on automotive security, we have participated to the definition and implementation of a secure architecture for automotive embedded system. A new global methodology has been settled, from requirement and attack tree captures, to the definition of the architecture [252] - including a hardware security module, and cryptographic protocols relying on this hardware security module - and the formal verification of this architecture [245] [244], and until its implementation and tests (on-going work). Future work will consist in applying techniques and architecture we have defined in EVITA for other kinds of systems, e.g. for future aeronautics platforms (CORAC project).

2.2.3 Analysis and Design of Reliable Processors Based on Unreliable Technologies

Faculty L. Alves de Barros Naviner, P. Matherat, A. Polti , J-L Danger, G. Duc

Main events Invited seminar on DSM Reliability Issues at Universida Federal do Ceara (Fortaleza, Brazil/August 2011). Organization of STIC-AmSud workshop on Design for reliability and portability of RF Interfaces based on Nanoscale CMOS technology (Paris, French/May 2010). Invited conference at the Schloss Dagstuhl for Informatik GmbH (Dahstuhl, Germany/September 2008).

Projects STIC-AmSud NanoRadio, CATRENE Rely, ANR RobustFPGA, CIFRE STMicroeletronics, CIFRE EDF, CIFRE THALES.

Fault-tolerant architectures have been historically targeted to mission critical applications, but the current research shows that with the expected reduction in the reliability of nanoscale CMOS, even ordinary circuits will need fault protection. On these cases, the associated overheads must be minimized to guarantee some gain in the scaling process. Indeed, deep submicron technologies (DSM) process is reaching some important limits that reflect negatively in the reliability of the integrated circuits. Some of these are manufacturing imprecision, increased susceptibility to environmental factors and physical parameters variability. This results in accelerated aging of components and increased number of faults in the system. Our work deals with the challenges related to reliability analysis and reliability improvement of digital circuits. The objective is to propose efficient methods and tools for, on the one hand, accurate reliability analysis and, on the other hand, design of economically viable reliable complexe processors. Initial results have led to the establishment of cooperation with renowned academic laboratories (Delft University, IMEC, Fraunhofer Institutes, CEA, LIP6, TIMA, UDR, UFRJ, UFRGS...) and with suppliers/end-users industrials (ATMEL, EADS, NXP, ARM, THALES, STMicroelectronics, ...) in the context of cooperative or billateral contracts.

Reliability Assessment: Our initial studies focused on estimating the reliability of logic circuits and we proposed two new approaches (Probabilistic Binomial Reliability-PBR- and Signal

Probability Reliability- SPR-) as mentioned in previous report. Both proposed approaches deal with different fault models and allow several trade-offs between accuracy and computation complexity for reliability assessment that outcome state of the art solutions. During the period concerned by this report, we have explored new approaches to the analysis of reliability, such as the use of Petri nets [223] and progressive analysis [198]. Our search for even more effective approaches lead to two new methods (CPA and H-CPA) [284, 157, 270] based on SPR. These solutions use conditional probabilities and clustering approach to produce accurate estimation with linear complexity. We also proposed a smart IP for generating fault vectors[191]. This IP has been embedded in a FPGA based solution to accelerate reliability analysis of digital circuits. This fully parameterizable platform, named FIFA and based on PBR model, deals with several fault models as well as multiple faults are supported [142]. Furthermore, we studied the problem of defining appropriate metrics for reliability assessment taking into account the processor target application [342] and in order to compare some fault tolerance approaches [398]. Work in progress include reliability analysis of probabilistic circuits and bottom-up reliability prediction of SoCs.

Reliability Improvement: Studies on improving the reliability voluntarily began after those on the analysis of reliability. This is because the development of efficient algorithms and tools for reliability assessment is crucial to establish effective cost-quality trade-offs related to different reliability improvement schemes. Among the produced results, we can mention a simple fault-tolerant voter for TMR schemas [173], a tool for automatic reliability improvement based on TMR [147], a progressive module redundancy approach [145]. We have defined the concept of significance as an indicator of the relative importance of a sub-system with respect to reliability properties of the system which it is part of [159]. This powerful approach allows to guide efficient redundancy insertion and constitutes the basis of our actual work on selective hardening. Work in progress include design of defect-tolerant FPGA, design of cost-effective self-controlled digital arithmetic operators, hardening/test of embedded processors.

2.2.4 Optimal architectures for complex algorithms implementations

Faculty P. Matherat, Y. Mathieu, L. Naviner, R. Pacalet, A. Polti

Main events

Projects Telma(ANR) Calder(ANR), IDROMel (ANR), PFMM (French cluster SCS, DGE), SYMPA (French cluster SCS, DGCIS), SACRA (FP7 European project), SPECTRA (CELTIC European project, DGCIS)

Architectures for image and multimedia processing: Studies on n-dimensional generic cache architectures for FPGA-based image processing systems gave promising results. We have demonstrated the efficiency of a low-cost cache solution exploiting spatial and temporal locality in a smarter manner than classical associative caches [153, 228, 289]. This work was carried out in collaboration with the Gipsa-Lab laboratory with the support of the ANR project TELMA. This work will continue in the framework of a new collaboration with the TIMA labs and control theory specialists from LAAS.

Energy consumption of digital circuits and clockless systems:

We continue the study of the origin of the dissipation of digital circuits, by focusing on the logical origins rather than the technological ones of this dissipation. The thesis beign carried by Mariem Slimani is an overview of these issues, and tries to understand how aspects that appear to be technological are in fact related to architectural issues. In particular, the leakage currents of modern technologies have to be balanced with the switching energy, and this balance is clearly related to the choice of architecture implementations [255, 254]. In addition, we continue the study of more fundamental sources of dissipation related to synchronization issues, and this leads us to explore the logical foundations of clockless circuits [154, 282]. Regarding education, we published a book on the history of microelectronics [272].

Flexible architecture for the Software Defined Radio (SDR)

Nowadays mobile communication systems operate in different radio spectrum, radio access technologies, and protocol stacks depending on the network being utilized. Moreover, new services and applications, like Cognitive Radio (CR), require new digital signal processing capabilities (sensing, etc.) This gives rise to the need of a flexible hardware platform that would be capable of supporting the baseband processing for all the different standards in the entire wireless communication frequency range. This platform shall of course be extremely power efficient.

In a large multi-projects context we propose a generic baseband prototype architecture for SDR applications[215, 240]. This architecture embeds a general purpose micro-controller and a collection of specialized Digital Signal Processors (DSP), each dedicated to a class of algorithms like, for instance, interleaving - de-interleaving of sequences of data samples[242], sample rate conversion[151, 251] or channel decoding[285, 144, 143]. Most existing works in the field are based on specialized micro-processors (vector processors, VLIW, ASIP, etc.) and on advanced interconnects (Networks on Chip). Unfortunately these solutions are still usually above the maximum power budget for such applications. Our approach mainly consists in identifying a small set of very complex hardwired processing blocks that will take in charge 90 to 95% of the total baseband processing power in a very power-efficient way. Each block is highly parametrizable and is assisted by a minimal 8 bits micro-controller allowing it to run sequences of operations (e.g. channel estimation) from basic commands (Fourier transforms, component-wise products, etc.) The platform is open and the whole project will be distributed under the French equivalent of the GPL-LGPL open source licenses, both for hardware models and embedded software.

The baseband processor is complemented by an open source software development kit comprising a high level Application Programming Interface (API), an embedded Operating System (OS), cross-compilers, linkers, debuggers and several simulation environments. It is currently used in several national and European projects (SYMPA, SACRA, SPECTRA); depending on the projects' specificities, several target technologies are considered, from high end, FPGA-based, prototyping boards to System-on-Chip integrated circuits.

2.3 References

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2.3.5 APTH: Phd thesis

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Chapter 3

Electronics and RF systems (ELECRF)

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M. Sacko (10/10–), Y. Wei (10/10–), M.A. Yousuf (10/10–10/11),
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C. Ouffoue (11/10–), J. Sarrazin (02/11–).

Sabbaticals

A. D'assuncao (10/09–10/09), J.P. Barbot (11/11–), F. Rangel De Souza (12/11–).

Faculty IT	10
PhD students	18.4
Post-docs, engineers and sabbaticals	4.1
Defended PhD thesis	11
Defended HDR	1
Journal papers [published, in press]	[30, 3]
Papers in conference proceedings	77
Chapters and books	9
Patents	6
Grants [public, private, european] (k€)	[674, 244, 498]

3.1 Objectives

Future “ambient intelligence“ systems strongly depends on the emergence of a new type of embedded and mobile wireless RF systems that can sense their local environment and react to it by switching to some environment taylored configuration. The primary bottlenecks to address before the widespread use of ambient intelligence are related to communication requirements, energy sobriety, and security. Our research has developped along these lines innovating concepts at several levels of the physical layer: components (antenna), characterization and modeling (Power Amplifier, radio channel), system architectures (cognitive radio) and communication schemes (modulation) for wireless communication systems.

The need for terminals that provide their users ubiquitous access to a multitude of services calls for frequency-agile, multi-standard and multi-band terminals integrating the cellular standards GSM/EDGE, UMTS, LTE, LTE-Advanced as well as any additional wireless communication standards. Driven by these future wireless communications systems , our micro-electronics research has focused on agile deep-submicron CMOS circuit designs and architecture, and on the associated signal processing to correct errors, non-linearity and mismatch calibration. Our work on microwave technology concentrates on the so-called ”RF front-end” which is one of the most sensitive parts of communicating objects. It involves improved RF modulation/demodulations schemes as well as the study of novel antenna technologies applied to several wireless communication standards from 450 MHz to 40 GHz. Another research topic has focused on wideband and low-profile antennas and arrays using artificial materials for the antenna’s reflector.

Other relevant challenges to the ELEF RF group are designing ultra-low power solutions for future generation ICs. We have targetted circuits with the largest energy consumption, such as PAs in the RF transmitters. To enhance the performances of RF power amplifiers, nonlinear power components operating in the Q band (33-50 GHz) have been characterized with advanced RF metrology. For integrated components, we have developped optimized low voltage micro-architectures.

Electronics and RF Systems designers have also to face many challenges to handle nanoscale technology: variability, new CMOS technology for the AMS parts, integration of novel technologies for the RF parts. In this context, our main research objectives were to design reliable and robust mixed-signal circuits in response to limited technological accuracy and repeatibility, and to use design techniques impervious to technology suited to performance, cost and reliability compromises.

Finally, there is a great benefit in considering radio channel physical properties in conjunction with RF transceivers design. In this context, the sounding of RF propagation channels using relay between transmitter and receiver in a LTE communications scenario has been performed,in order

to provide an adequate propagation model with well matched parameters. The radio channel has been modeled by taking into account jointly the local propagation environment and the antennas. The method is based on a new statistical approach which has been applied to various use cases such as BAN networks, multiple antennas on terminals and UWB RFID tags. In particular, parametric models of UWB antennas have been developed, allowing a strong compression rate of the radiation data and lending themselves to statistical modeling of the antenna electromagnetic behavior.

3.2 Main Results

The main research results obtained during the period mid 2009 to end 2011 are presented below for the research areas of the "Electronics and RF systems" team.

3.2.1 From frequency-agile and reconfigurable transceiver to cognitive radio systems:

Faculty V.T.Nguyen, P.Loumeau, H. Fakhoury, P.Desgreys, H.Petit, J.F.Naviner

Main events Coordinator of the TEROPP project between 6 Carnot Institutes and 3 Fraunhofer institutes, 3 new European projects, leader of the task on multi-standard and multiband transceiver for cellular applications in ENIAC ARTEMOS project.

Projects FP7 SACRA, ENIAC ARTEMOS, CATRENE PANAMA, ANR-07-P2IC TEROPP, ANR-06-TCOM HyperSCAN.

Frequency-agile and reconfigurable receiver: The focus is on frequency agile high dynamic range digital friendly RF architectures suitable for nanoscale CMOS. The properties such as the RF carrier frequency, channel bandwidth, noise figure, linearity and selectivity characteristics can be adapted to the requirements of the communication standard. This work which is a close collaboration with ST-Ericsson, is a part from European ENIAC ARTEMOS project starting on April 2011 where we are the leader of the task on multi-standard and multiband transceiver for cellular applications.

High performances, reconfigurable ADCs: One of our main research topics for years is high performances, reconfigurable ADCs for various applications. It is one of the key building components of the receiver. Our main expertise is on innovative delta sigma modulator architecture and the design in advanced CMOS technology. We has proposed innovative architecture for high-pass delta sigma modulator [309, 310], reconfigurability with high-pass and low-pass [366], unity signal transfer function with global feedback loop [381] and high performance ADC designed in 65nm CMOS technology [348]. We have been also working on continuous-time modulator in order to improve the performance in terms of low power consumption and higher bandwidth. A very high performance ADC designed in 65 CMOS technology with 40MHz of bandwidth, 76dB of SNR, 88dB of SFDR and with less than 100 mW of power consumption using an innovative continuous-time modulator is recently sent to foundry. This work is a part of FP7 SACRA project and ENIAC ARTEMOS project. This ADC will be part of a demonstrator on cognitive radio systems in FP7 SACRA project.

The development of the software radio is still very much limited by the available resolution and speed of the ADC stage. Parallel ADCs seem to be the best suited way of increasing analog-to-digital conversion rates. After the study of time-interleaved (TI) Sigma Delta ADC with a four-channel [331, 297, 298], we studying TI architecture employing Nyquist pipeline ADCs. The objective is to compensate the frequency response error between the different channels. This work is ongoing in a bilateral project with an industry. An alternative solution for parallel architecture is to employ hybrid filter banks. The advantage of this approach compared to TI architecture is the robustness against channel mismatch at the cost of more complex analog and

digital parts. An innovative solution has been proposed [356, 357] using time multiplexing and frequency multiplexing at the same time in order to retain the advantages of both architectures (TI and hybrid filter banks). This work is a part of ANR-07-P2IC TEROPP focusing on opportunistic and cognitive radio, but this approach can be used for other applications as well.

Non-uniform sampling: To deal with the suppression of RF anti-alias filtering, Non Uniform Sampling (NUS) based receiver architectures have been studied in a collaborative project with SUP'COM Tunis. We have demonstrated relaxed constraints on both RF filter and ADC dynamic power consumption using appropriate NUS architecture. The results have been published recently [296]

Disruptive technologies Disruptive technologies offer new ways to accomplish breakthroughs in cognitive and opportunistic radio. Based on superconductivity physics, the RSFQ (Rapid Single Flux Quantum) logic is a very low power consumption and ultra-fast electronic logic which is considered as the best alternative to CMOS in the ITRS for ultra high frequency applications. The team has proposed an RFSQ Analog to Digital architecture in a work conducted within the ANR Hyperscan project. The goal is a 2x8 bits and 500 MHz BW Sigma-Delta analog-to-digital converter (ADC or CAN) circuit with performance specifications to achieve space telecoms at 30 GHz carrier frequency. To verify the project feasibility, we have developed a model that implements superconductivity physics into the RFSQ ADC circuit simulation [350].

ADC design in the non linearity correction path of base station PA Power amplifiers (PA) are inherently non-linear and even more if we aim to reduce its power consumption, therefore they introduce unbearable distortions for new modes of communication. The digital predistortion (DPD) is a very effective linearization technique due to the increasing use of digital modulations and progress in digital signal processing. This technique requires digitizing at least five times the input PA signal bandwidth as the distorted output PA is spectrally made up of a high power signal band and of lower power adjacent signal bands resulting from intermodulation. To digitize this signal we need an Analog to Digital Converter (ADC). The design of one single ADC meeting the requirements of high dynamic range ($>$60 dB) and wide bandwidth ($>$75 MHz) would produce an oversized solution consuming much power than using several parallel converters with adapted specifications. We suggest using one primary A/D converter to convert the high power signal band (15 MHz) and two secondary converters for the adjacent bands (30 MHz each) with lower signal powers. The problem is that the secondary converters may be saturated by high power signal band so this band has to be attenuated. We propose to use the inherent signal shaping achieved in Delta Sigma modulators to do this attenuation. A patent is pending for this innovative solution.

Cognitive Radio Systems: CRS is a disruptive technology targeting very high spectral efficiency. In CRS, cognition and intelligence are introduced in the terminal and cognitive network to take benefit of the high number of interacting devices to increase the spectral efficiency. Even interference is considered as an opportunity rather than a drawback by exploiting intelligently the degrees of freedom in CRS. CRS covers multidisciplinary areas attracting a large number of researches with many interesting obtained results. The challenges remain numerous, namely intelligence distribution and implementation, security, delay/protocol overhead, cross-layer design, flexible hardware design, etc. In this topic, we are working on high level concept of CRS [384], convincing use cases, RF receiver for spectrum sensing [356, 357, 418] and sensing algorithms talking into account the implementation constraints. We will study also cognitive radio resource management and smart spectrum management, all these taking into account the implementation constraints and perspectives. The work on CRS is part of ANR-07-P2IC TEROPP, FP7 SACRA project and ENIAC ARTEMOS project.

3.2.2 Nanoelectronics architectures and circuits

Faculty P.Desgreys, J.F.Naviner, H.Petit

Projects CATRENE RELY

Reliability of mixed-signal architectures and circuits: Works on reliability of analog or mixed-signal architectures were initiated in Oct. 2008 with a PhD thesis. Considering that many circuits are today Systems-on-Chip (SoC), that they include often various analog or mixed-signal sub-circuits and that the reliability level of a SoC results from both the reliability of each sub-parts and the connections/interactions between them, our main objectives are:

- to assess the reliability of basic functions considering the physical causes of failures (ageing effects or other causes),
- to assess the reliability of an architecture working at an abstracted behavioural level,
- to compare basic functions circuitries and architectures on both performance and reliability criteria,
- to define methods of architecture/circuit design that includes the reliability in the design criteria.

The present work is focusing on the reliability of A/D converters [299]. After studying the causes of degradation and failures in nanoscale integrated circuits with ageing [313], we are working on the prediction (early in the design process) of circuit lifetime facing process variability and devices aging (European project: RELY). This prediction will be based on physical models provided by physical design kits.

3.2.3 RF metrology

Faculty X.Begaud, E.Bergeault, J.C. Cousin, B.Huyart

Projects Bilateral project with LNE and Orange Labs, French ANR Smartvision (Système multi senseur de détection d´objets cachés)

Power probes and PAs: Our research in fundamental metrology with the LNE have yielded significant results on the RF power sensors (1-18 GHz) [307, 324, 368, 420] and the probe measurements of MMIC components (Monolithic Microwave Integrated circuits) over a wide frequency band (few kHz-40 GHz) [327, 326, 413]. Our efforts have focused since 2009 on the design and implementation of a load & source Pull measurement setup in the Q-band. The nonlinearities of the components of the RF front-end (PAs) causes spectral spreading over adjacent channels and distort the base band data. Numerical predistortion techniques have been used to fight the degradation of the RF signal [295]. The originality of our setup is that the excitation signals of the device under test have modulation bandwidths of gigabits/s [379].

Radio communications channel sounding: 2 sounders have been designed and realized for non stationary MIMO channel in the Wifi & UWB frequency bands. Our studies have been focused on the simultaneous determination of the angles of departure and arrival of transmitted and received signals [314] and the measurement of arrival time [345, 346]. Comparisons between measurement and models were made from a 3D ray tracing [378]. Another aspect of channel sounding has been led with Orange Labs to estimate the contribution of relays in a multi link propagation channel modeling for the 4G systems. To this end, a multi link measurement campaign with relays has been carried out in realistic urban environments. These have allowed to assess the relaying aspects and to focus on the path loss models developed for the 4G systems [337], the shadow fading correlation [339, 338] and the impact of the relay antenna height [335]. A particular attention has been paid for the Base station-Relay Station link which had not been studied yet.

Smart vision project: An ANR project with Thales Service as the main leader has been developed since two years. This project has dealt with the realization of a smart corridor dedicated to an electronic body scanner to check people without a body search in airports for example. In this project, we have participated in the realization of the active body scanner based on a 77 GHz radar structure initially developed for the help drivers [385].

3.2.4 Wireless communication systems technology

Faculty X.Begaud, B. Huyart, A.C.Lepage

Main events Publication of the book "UWB antennas" (Wiley), co-edited by X. Begaud, GDR ONDES, CNRS (X.Begaud)

Projects European projects FP7 SACRA (Spectrum and Energy Efficiency through multi-band Cognitive Radio) and Celtic SPECTRA (Spectrum and energy efficiency in 4G and beyond communication systems), EDA project MIMiCRA (Metamaterial Inspired Microwave Conformal Radar Antenna), projects from the French Cluster SYSTEM@TIC PARIS-REGION : CONRAHD/OPTIMUM (CONnexion Radio sans fil Haut Débit) and PUMA (Produit Ultra haut débit sur bande millimétrique), bilateral projects with Thales Airborne Systems (2), Thales Air Systems (1), CNES, Innovation project "DEMODU" from Institut Telecom

MMIC design for RF "front-end": Our research activity has been focused on the design of demodulator dedicated to software defined radio applications. 2 three-phase demodulators using MMIC technology have been designed in the 1-24 GHz bandwidth [369] and Q band (33- 45 GHz). This demodulator architecture shows a better rejection of adjacent channels [312].

Metamaterial inspired wideband antennas: The RF team's research is devoted to the design of wideband antennas and arrays. We initially focused our work on UWB (UltraWideBand) applications [323, 322, 408, 403] and add today the design of novel artificial materials to reduce the size/thickness of wideband antennas [406]. On one hand, the developed materials use periodic structures in order to exhibit the behaviour of an Artificial Magnetic Conductor (AMC) as well as that of an electromagnetic band-gap (EBG) structure [427, 426]. On the other hand, the extraordinary properties of Left Handed materials are exploited to develop miniaturized filters and directive antennas [423, 332] and Leaky-wave antennas [399]. We are developing a new methodology that takes into account the interaction between the radiating element and its artificial ground plane [304, 354, 347, 302]. We are also considering refined characterizations of the artificial material itself, a necessary step for improving our control on the phenomena occurring in these metamaterials [305, 343]. Finally, we are applying our artificial materials to the problem of reducing the coupling between elements in a wideband antennas array, with a focus on analytical models [426].

Antennas for cognitive radio: One of the main challenge of cognitive radio is to improve the efficiency of the system, ie. energy efficiency, spectrum efficiency and also reduction of the number of components. The following topics aim to propose solutions to these needs. In the framework of the European project SACRA, our research is focused on compact dual band dual polarized antennas for the terminal side dedicated to future systems using LTE and having also cognitive radio capabilities in the TVWS band (TeleVision White Space) [380]. Diversity performances studies are also performed for different environments. We are also studying co-design between antenna and filters: the objective of this topic is to develop an ultra wideband dual polarized antenna associated to a filter with non standard features in order to suppress any matching circuit. In the framework of the European project SPECTRA, we propose to design a compact wideband antenna associated with an automatic matching circuit. In fact, over a wide band, the input impedance of the antenna varies due to intrinsic properties, but also due to the environment.

3.2.5 Antennas and radio channel modelling

Faculty (from September 2009) C. Roblin, A. Sibille

Main events Publication of the book "MIMO: From Theory to Implementation" (Elsevier), co-edited by A. Sibille.

Projects European FP7 SELECT project on UWB RFID system, French FUI URC project on urban planning for radiocommunications, French ANR BANET on body area networks, French

FUI RECOSS project on high data rate communications for security services, European COST 2100 Action and COST IC 1004 Action on mobile networks.

Parametric models for ultra wide band antennas: The full characterisation of the radiation of UWB antennas requires a significant amount of data arising from either measurement or electromagnetic simulations. It is therefore desirable to use ”data compression” methods to handle them more easily. A complete (parametric) modeling of both frequency and time domain far field antenna responses (for any direction of radiation) with extremely high order reduction (”ultra compression”) has been developped [408]. It is based on both the singularity expansion and the spherical mode expansion methods. Theoretical properties of the model parameters and relationships with global indicators of performance of UWB antennas have been derived. The modeling has been applied to full 3D measurements of omni-directional or moderately directive UWB antennas with a good accuracy and high data compression rates of more than 97% (and up to more than 99.9% for some cases) [391, 391]. These models can be efficiently used in simulations of the physical or link layers, or in deterministic propagation simulators based on asymptotic methods (UTD/GTD “ray tracing”, etc.).

Joint antennas and channels statistical modelling: Wireless networks need channel models in order to be able to test competing physical/link layer schemes and perform network level simulations. However there is an increasing complexity in the current and future communications standards, which are multiantennas, multifrequency and where the behaviour of terminals in a use context is highly variable. The group has initiated and developed since a few years a statistical approach of this behaviour [321], taking into account the variability of the terminals characteristics in their close environment. The method combines full antenna performance data to local propagation characteristics in order to arrive a an effective gain concept, seen as a stochastic quantity. It has been applied to the efficiency and effective gains of handsets in proximity to a user head and hand [395, 316] and to multiple antenna systems [392]. In body area networks, the influence of the human body on the behaviour of antennas is often of prime importance; the properties of the on-body propagation channel are very specific, and are notably sensitive to the subject movement for most scenarios. Both aspects, which are intricately related, have been studied with a statistical approach [390, 318, 319]. Joint space and frequency correlated path loss data have also been modelled through a simple semi-Kronecker approximation [320]. The latest works address the statistical analysis and modelling of UWB tag antennas employed in a backscattering based RFID system [396, 300, 301, 377]. A patent has benn issued on non regenerative relays [414].

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Chapter 4

Optical Telecommunications (GTO)

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Faculty IT	6
PhD students	13.75
Post-docs, engineers and sabbaticals	4.7
Defended PhD thesis	15
Journal papers [published, in press]	[32, 2]
Papers in conference proceedings	91
Chapters and books	3
Patents	2
Grants [public, private, european] (k€)	[654, 111, 157]

4.1 Objectives

The evolution of optical communication systems represents a particularly challenging guideline for the research activities taking place in the Optical Communications group of Télécom ParisTech. In addition to the topics directly relevant to the upgrading of optical networking techniques, architectures, devices, components, etc., our field of activity expands both to subjects that use similar methods and technologies and to characterization systems for telecommunication devices.

Following a meditated focus on access network technical solutions (FTTx) bridging the "last mile" by means of optical support, the new evolution step in the field of optical communications is related to a merging with digital communications and fast digital electronics and affects all the levels of the optical network. Technical forecasts predict a constant increase of bit-rate demand for networks with a steady rising factor of 40 to 60% per year (according the Systematic Paris-region Telecom roadmap). This tendency is supported presently by video-related application associated with new terminal facilities. Presently, the three traditional fixed-network segments are all going through a strong evolution process:

- with the deployment of FTTH (Fibre-to-the-home), the optical access network has relied first on rather traditional solutions while advanced optical technologies are still under strong competitive development (WDM PON, OCDMA, ...). New generation PON (NG-PON) investigating 10Gbit/s solutions are being normalized. A strong requirement on components able to fit the constraint of access network (technical specification, cost, consumption, foot-print) leads to some renewed question on sources and receivers;
- the metropolitan network has to cope with an enhanced connectivity and some constraints related to equipment cost which requires new technical solutions. New end-to-end network architecture are investigated;
- in the core network, traditional individual channel bit-rates enhancement up to 40 Gbit/s is progressively replaced by new paradigms making use of the digital communication knowledge that was the development key of RF mobile communication. Multi-levels or multi-carriers modulations associated with digital signal processing thanks to high rate digital circuits, brings the required spectral efficiency enhancement.

In this wide panorama, the GTO group relies on its theoretical competence and its modelling and experimental know-how for developing new concepts and for participating in advanced collaborative research on optical systems.

A first research axis concerns the development of new optical signal processing techniques and functional analysis of new components for communication systems. This field covers several related studies concerning light emission, light amplification, light transmission and new reception

techniques. Although a number of applications lie in the field of telecommunication, the activity expands to other application areas such as energy, industrial process and defense.

The second research axis lies closer to the actual networks and transmission systems structures, approaching multiplexing techniques, high bit rate communication, new optical network architectural topics.

Finally, a specific research axis is related to quantum communications in particular to quantum key distribution for cryptography systems.

These research axes usually associate theoretical investigation and modelling activities, simulation using internal or commercial software and experimental activities. The latter rely on a rather well-equiped optical laboratory which includes a 4*10Gbit/s transmission platform, picosecond optical facilities allowing some 40Gbit/s experiments, very high sample rate arbitrary waveform generator associated to a real time oscilloscope and dedicated characterisation and sensor set-ups. The equipment for the assessment of coherent transmission systems and algorithm experimental testing, internally named “plateforme Penser 100Giga” has received a Region Ile-de-France SESAME-programme sponsorship.

The reporting period has been characterized by many national initiative interactions, (ANR, Cifre) and a strong activity on the European landscape. Through FP7-BONE and FP7-EUROFOS Networks of Excellence our international activity has been pushed to a high level. In addition to project review papers involving many teams, we can count journal publications with laboratories representing many different countries (Denmark, Japan, USA, Germany, Mexico, China, Greece, Tunisia, China, Sweden).

4.2 Main Results

The main research results obtained during the period mid-2009 to 2011 are presented below for the research areas of the GTO team.

4.2.1 Optical functionalities and novel devices for communication systems and networks

Faculty G. Debarge, D. Erasme, R. Gabet, P. Gallion, Y. Jaouën, C. Ware, F. Grillot (CNRS-Photon)

Projects PôleSystem@tic-CARRIOCAS(10/06—09/09),ANR AROME (01/07—12/09), ANR L2CP, ANR MODULE (11/09-11/12), FUI TRILOB(09/09-09-12), FP7-EUROFOS (05/08—04/12), trilateral projet with EDF and LCPC, Bilateral project with ONERA and with CEA, 3 cifre Thesis, collaboration with Shanghaï Jiao Tong and Tondjï universities.

The widespread introduction of broadband at all levels of communication networks, the ubiquity of data exchange, the wired network infrastructure increasingly using the optical medium, and its being extended over the last mile all the way to the end-users, are changing the deal on signal processing functions implemented directly in the optical domain, giving them a foremost place in system design. These optical functionalities aim at keeping, as best can be done, the optical signal’s integrity, avoiding optical-to-electrical conversions. The intrinsically high speed of the physical phenomena to be used allows them to take over processes, which were traditionally implemented in the electrical domain, and the development of devices adapted to these applications.

Clock recovery

After yielding record results during the previous reporting period, our clock recovery activity was rewarded by an invited paper in the Journal of Lightwave Technology. It was built upon,

mostly through collaborations with international partners, especially in the framework of FP7-EUROFOS[1]. Bit rate was pushed up to 0.87 Tbit/s [536], including phase modulation.

Now that this level of performance and versatility has been shown, this activity is now reduced in favor of network-oriented functionalities.

Integrated semiconductor optical sources and receivers

The recent evolution of the optical communication network led to a large demand for new low-cost and high-performance components. Following a proposal and some initial results obtained at the end of the CARRIOCAS project [524], the concept of "dual modulation", consisting in modulating simultaneously the laser and the modulator of an EML source leads to the proposal of the new ANR project MODULE[2], which we are leading. Condition for optimum modulation procedure for access—type distance range up to over 140km and rates up to 20Gbit/s. Single sideband modulation dedicated to radio-over-fibre and OFDM transmission have been demonstrated also [544, 504]. Simulation software has been used to confirm and explore transmission effect in dispersive fibres with dual-modulation. We also participated in the design of new "colourless" (wavelength-independent) devices for WDM-PONs and RoF applications, notably through a Cifre Thesis with Alcatel-Lucent III-V Lab, which more than doubled the state of the art for systems based on RSOAs (Reflective Semiconductor Optical Amplifiers) both in distance (100 km over standard fibre) and (separately) in bit rate (10 Gbps without any electronic processing). [433, 480, 562]. Additionally, another project FUI-TRILOB[3] studies the integration of ELM with a SOA in order to enhanced the budget of downstream access transmission in PONs. We have recently demonstrated the effect of chirp compression induced by the SOA, which allows the transmission distance to be augmented strongly [521, 522]. The group has been involved in other devices development through 2 more Cifre theses with III-V lab (on 100G receivers and reflective SOA modules for access networks). The former resulted in the development of state-of-the-art integrated very-high rate SOA-PIN receivers [560]. Modelling of semiconductor lasers have been push forward; Some new understanding on chirping effect and reduction in various configuration, especially in the case of feedback has been accessed [447],[503].

Optical Code-division access coders-decoders

For OCDMA implementation (see next chapter), the most commonly used optical component is fiber Bragg grating (FBG). Part of the ANR-SUPERCODE[4] project was focused on FBGs both for direct-sequence codes (DS-OCDMA) and spectral phase encoding (SPE-OCDMA).

The FBG-based coding method has the disadvantage that each FBG-based component can only generate one code word while as much as 64 may be required. We have proposed to realize the coding devices by using the Hadamard transform on a 2 dimensional multimode interference couplers (2DMMIC). The approach demonstrates the possibility to achieve the higher order Hadamard transform using simple 2D structures and provides a possible solution for all optical CDMA systems. It is worth mentioning that although the discussion is based on the MMI structure, the method of extension of 1D structure to 2D can be generalized for other devices, such as the LPFGs based Hadamard transform devices. The simulation results match the theoretical prediction precisely. [463]. In addition, we have analyzed the optical switch based on the MMI couplers and proposed the operation principles for this device based on an analytical transfer matrix theory. The device can be controlled by proportionally adjusting the inter-stage variable phase

[1] FP7-EUROFOS (: Institute of Communication & Computer Systems/ National Technical University of Athens (leader), Heinrich-Hertz Institute, University of Essex, Universitat Politecnica de Catalunya, ACREO AB, Technical University of Eindhoven, Research and Educational Laboratory in Information Technology, Chalmers University of Technology, University of Karlsruhe, Politechnico di Torino, University College Cork, Scuola Superiore Sant'Anna, Universidad Polytecnica de Valencia, Interuniversitair Micro-Elektronica Centrum IMEC, Instituto de Telecomunicaoes, Technical University of Denmark

[2] Partners: GIE Alcatel-Thalès III-V lab, CNRS-LPN, IRCOM, Orange labs

[3] Partners: 3S-Photobics (leader), GIE Alcatel-Thalès III-V lab, Egide, ESPCI, Orange labs

[4] Partners: Institut Carnot de Bourgogne (leader), CNRS PhLAM, XLIM

shifter array. An 8*8 MMI coupler based switch is analyzed in detail, which demonstrates the feasibility of the proposed operation principles he theoretical prediction is verified by the numerical simulations. Fabrication error tolerance analysis is provided afterwards. The design principles presented here can be used for the design of the integrated MMI coupler based switches with either thermal-optical or electro-optical index tuning. [464]

Distributed Raman amplification

The distributed amplification based on the Raman effect, appears as an alternative or an additional technique to the doped fiber amplifier (EDFA) widely used in today optical communications systems. It offers the benefits of low noise due to gain distribution over large span and of the potentiality of pump polarization attraction. However noise transfer from the pump noise to the signal, the pump polarization fluctuations and the double Rayleigh scattering (DRB) strongly impact the noise figure and the single pump configuration is bandwidth limited.

Raman amplifiers (RAs) with time-division-multiplexed (TDM) pumps have been analyzed using a computational cost-effective Fourier series approach. It gives deeper insight into the pump modulation induced noise (PMIN) in TDM pumped RAs. Moreover, the approach allows the analytical analysis of the TDM pumped RAs with multiple pumps. By optimizing the pumping order of the multiple pumps, more than 3-dB reduction of the PMIN can be achieved. For short fibres, by properly choosing the modulation frequency, more than 3-dB reduction of the PMIN can be realized. [465]

We have analyzed the Raman amplifiers (RAs) with time division multiplexed (TDM) pumps via analytical approaches for the forward and backward propagating configurations. The gain and the optimal analytical formulas of the pump power configuration have been derived, by using the least mean square (LMS) method. Explicit analytically formulas have been derived for double Rayleigh scattering (DRB) and ASE noises as well as the impact of the pump modulation. They provide a performing tool for the design, the analysis and the optimization of multi pump amplification. [462]

Brillouin-based optical sensors

Given its low required power threshold, the Brillouin effect in optical fibre is one of the most promising nonlinear effect to design new all-optical processing or optical sensors. A self-referenced technique for measuring the Brillouin gain in an optical fibre has been recently proposed, and the importance of acousto-optic effective area in place of optical effective area on the Brillouin efficiency has been confirmed for the first time [446]. The analysis of optical and acoustic properties of optical fibers is required for accurate Brillouin gain spectrum (BGS) determination. Under collaboration with EDF, a 2 D FEM model has been proposed for BGS calculation in acoustic guiding and anti-guiding singlemode optical fibres [533, 532]. The intrinsic residual draw-induced stresses during the cooling from fusion to temperature to room temperature can impact significantly optical and acoustic mechanical properties, and should be taken into account in the calculation of BGS. Different fibres all coming from a same perform but with different conditions have been realized by Draka. The predicted theoretical BGS show very good agreement with corresponding measurement [534]. The following step in the EDF collaboration should be the analysis of Brillouin frequency shift dependence with strain and temperature and finally propose a fibre design specially devoted to optical sensing.

High-power fiber lasers

The technology of rare-earth doped optical fibres - Ytterbium (Yb3+) for amplification at 1µm and Erbium/Ytterbium (Er3+/Yb3+) at 1.55µm - represents a strong contender for applications requiring high optical power. Our contribution is carried out mainly through collaborations with external laboratories (ONERA, CEA) and Keopsys Company. With ONERA we have participated in the

design of LMA fibre amplifiers, in the analysis of Brillouin spectrum of doped fibres in connection with doping, and more recently the combination of coherent fibre amplifiers in continuous regime [471, 466] and pulsed regime respectively [448, 508, 509, 473]. Spectral broadening is required on high power lasers to avoid Brillouin scattering in high power laser chains such as Laser Mégajoule. The collaboration with CEA concerns the spectral broadening properties on FM-AM conversion induced by non-sinusoidal phase modulation in comparison to the sinusoidal phase modulation case [442, 441, 523]. Taking into account recent developments in Thulium and Holmium fibres technology, more than 100W output powers with very good beam quality have been achieved at 2µm and are an alternative to actual laser solutions. In collaboration with Keopsys Company and ONERA, we develop currently advanced architectures of pulsed fibre Thulium laser for LIDAR or remote sensing.

Optical Low Coherence reflectometry

The optical low-coherence reflectometer (OLCR) developed in our laboratory has been upgraded over the years and has proven to be a unique investigation tool for the study and the characterization of new photonic components. Through collaboration with component makers, we have been able to measure some otherwise inaccessible parameters in optical wavelength mux-demux, speciality optical fibers, fiber Bragg gratings, semiconductor devices, including semiconductor optical amplifiers... Our state-of-the-art phase-sensitive OLCR spatially resolves internal reflections of the device under test, and allows measurement of different polynomial terms of dispersion, birefringence, loss / gain material coefficient, phase/amplitude coupling coefficients. It has attracted many national and international collaborations, industrial and academic. The latest results concern the study of photonic bandgap semiconductor waveguides under the ANR-L2CP[5] project [477, 478, 482, 535, 458, 439] in collaboration with Thalès R&T and specialty fibers characterization [468, 469] for which the OLCR provides incomparable elements of analysis.

4.2.2 Optical network evolutions

Faculty D. Erasme, P. Gallion, C. Gosset, Y. Jaouën, C. Ware.

Projects ANR-SUPERCODE (11/06—11/09), ANR ECOFRAME (-12/09), ANR-TCHATER (10/07—12/10), ANR OCELOT(01/11-01/14)[6], FUI 100G-Flex(06/10-05/13), FP7-BONE (1/08—12/10), FP7-EUROFOS (05/08—04/12), research project Orange labs, 3 Cifre PhD.

Fast development of bandwidth consuming services like high-definition/on-demand television, network gaming, cloud computing, makes stringent the need to further network capacity. The objective to provide broadband to a maximum of users (“broadband-for-all”) has been leading research and development in the field of fibre-to-the-home (FTTH) technology for the deployment of high bit-rate access networks. Deployment of FTTH, on one hand, of Cloud-computing on the other, will significantly impact the capacity requirement carried by metro and core transport networks in a medium-term future. The fibre capacity must also be maximized through the deployment of new techniques such as new multi-level modulation formats eventually combined with coherent detection, new techniques for multiplexing and routing (packet switching). Finally, a strong driver concerning the design of the physical layer or optical networks today is energy consumption.

Optical access (PON) and code-division multiple access

Today, passive optical network (PON) have been largely accepted as a robust technique for the last mile bottleneck. TDM PON is the commonly accepted technique for resource sharing. For

[5] Partners: Thalès R&T (leader), CNRS-LPN, IEMN, Télécom SudParis, Télécom ParisTech
[6] Partners:Apex(Leader),Université de Rennes, GIE Alcatel-Thalès III-V lab

the next generation PON, hybrid-multiplexing solutions (WDM/TDM, WDM/OCDMA...), will be considered as well as source-less of color-less ONUs, long reach PON, and private networking. Our research in PON architecture and components is facilitated through collaboration and 2 successive Thesis with FT-Orange labs on new generation PON including extended PON, WDM PON, etc [570, 467]. The former thesis presents a complete study of expended PON solution and established design rules for such networks. Although large amount of the research field of WDM-PON is presently concerned with the matching of proper components or devices structure for obtaining the performance in terms of budget and splitting ratio, distance (see previous part)... specific techniques can be accessed embracing the overall architecture.

The ANR-SUPERCODE[7] project started off combining WDM and OCDMA by designing a supercontinuum pulsed source which can be shared among many users by being sliced into WDM channels, each of which supports multiple users through all-optical encoding and decoding. It also demonstrated the use of spectral phase encoding (SPE-OCDMA), which makes a better use of the bandwidth of the optical fiber, as in the long-haul context, by using the phase of the optical field instead of just the amplitude. Enhanced FBG-based encoders developed for this project were shown in a proof-of-concept SPE-OCDMA demonstration [539], which also used an all-optical power thresholder at the receiver. The latter is the last non-cost-effective piece of the puzzle, which will require higher-nonlinearity materials to fully enable this technique in the access network.

In addition we propose a novel decentralized scheme supporting multiple optical private networking (PNs) over ring-based PON taking benefit of asynchronous OCDMA technique. This technique leads to interconnect optical network units (ONUs) in the same PN sharing the same codeword while other PNs benefiting from different code words. We have experimentally demonstrated the feasibility of 2-active PNs over ring at 625 Mbps. [494].

The network scalability and throughput performance of the proposed scheme have been analyzed and its bit error rate (BER) performance have been experimentally demonstrated. Finally, the network scalability and throughput performance of the proposed scheme are analyzed. Impact of time and wavelength domain crosstalk on capacity performance of a WDM/Optical CDMA have been investigated [436]

Optical Digital communications techniques for next generations of Metropolitan and Core networks

Today's processing capability allows performing digital signal processing for optical communication systems at high bit rates. In close collaboration with the Digital Communications group, the potential and future trends of electrical signal processing techniques to mitigate e.g. noise accumulation, linear and nonlinear distortions are beginning to be investigated.

Under the project ANR-ECOFRAME[8] we have modelled and simulated the physical channel of an optical ring WDM network architecture. We provide the parameters of the statistical distribution χ^2 and estimate the performance in collaboration with XLIM working on FEC implementation. An extension of the concept to mesh networks has been proposed.

Optical signal propagation simulations performed in the case of a new concept of packet ring network reveals that the Gaussian model is not sufficiently accurate to constitute a valuable model of noise-corrupted optical systems. We have proposed an alternative Chi-square model, which is more accurate and corrects deficiencies of the Gaussian model. In such specific channel, we design a FEC scheme based on Low Density Parity Check (LDPC) codes in the case of soft decoding. The performance of a Chi-square-based LDPC soft decoder and a Gaussian-based one are compared, both applied to a real Chi-square optical channel. We point out that the design can be done assuming an AWGN statistic but that considering the real channel statistics is essential to achieve optimal performance. [456, 563]

[7] Partners: Institut Carnot de Bourgogne (leader), CNRS PhLAM, XLIM
[8] Partners: ALU (leader), Orange, Prism Laboratories, XLIM

The convergence of digital communications and optical transmission is a key enabling factor to increase the capacity and flexibility of optical networks. Progresses in digital signal processing and optical integration have enabled a new generation of optical transmission systems using complex modulation formats, coherent detection and digital algorithms to compensate for transmission impairments.

The project ANR-TCHATER[9] concerns the design of a real-time coherent receiver at 40Gbit/s using a FPGA implementation. Our contribution concerns the design of hard and soft FEC solutions adapted to optical coherent systems. We have proposed an original construction of low-density parity-check (LDPC) code suitable for high bit-rate implementations and that have good performance compared to the codes proposed in the literature [517]. To improve the performances of the FEC, it is very important to consider the specificities of the channel. In particular, coherent and direct detection systems both require differential modulation and this degrades the performance. We have proposed a new structured interleaving of the FEC codewords with a corresponding decoding scheme, in order to reduce the penalties introduced by differential modulation [513]. Moreover, the proposed scheme allows decoding complexity reduction and redundancy decrease without any performance loss [454].

We have investigated the interest of space-time codes for optical transmission systems. They have been developed for MIMO wireless channels but can be employed in polarization multiplexed optical systems. However their implementation requires the use of optical orthogonal frequency multiplexing (OFDM). For the first time, we have shown that space-time coding can efficiently mitigate polarization dependent loss impairments. We have also shown that their performance is very different than in wireless transmission and explained the reason [515, 514]. In collaboration with Karlsruhe Institute of Technology, we have proposed for the first time an experimental implementation of Polarization-Time code for optical communications [518, 516]. The performance of Silver, Golden and Alamouti PT codes for PDL mitigation are compared to the uncoded case.

Taking into account recent advances in ADC and DSP circuits, real-time implementation of polarization multiplexing coherent receiver is currently available at 40Gb/s and 100Gb/s. The implemented algorithms in circuits running are well adapted for QPSK formats. As higher modulation formats are more sensitive to signal distortions, accurate estimators and more robust equalizers are still required for QAM formats. Our contribution concerns the development of robust Digital Signal Processing (DSP) tools specific to the optical channel. A new adaptive blind and decision-directed equalizers based on Pseudo-Newton gradient-descent algorithm that are well adapted to QAM and that offers a better convergence speed with only a little extra computational load has been introduced [529]. According to the fact that the channel is very slowly time varying (compared to the data rate), we have proposed block-wise implementation of the blind-time CMA equalizers [528]. We have shown that block-wise version outperform the sample-per-sample adaptative CMA approach in term of convergence speed only at a moderate expense of computational load [531]. Moreover, a new CFO estimator very adapted to QAM modulation yields remarkable performance and enables the system to work without penalty [527]. Our proposed algorithms should be tested using a simulation setup of an optical transmission system using coherent detection and validated with off-line processing of real measurements in collaboration with HHI in the framework of the European NoE EURO-FOS and Orange Labs respectively. We are currently investigated in the project FUI9 100GFlex[10], dedicated to metropolitan and core transmissions systems based on multi-band OFDM approach for 100Gb/s in 50GHz. Particularly, the concept of optical sub-band switching can be use advantageously to realize a multi-band OFDM-based reconfigurable optical add-drop multiplexer (ROADM). A very high-baud transmission platform is currently in developing, including a 100Gb/s transmitter/receiver and a 400 km recirculating loop. This versatility and upgradability will enable us to investigate different aspects of digital optical communications: Tx/Rx characterization, propagation techniques, new detection schemes, digital processing and coding techniques dedicated to the optical channel.

[9] Partners: ALU (leader), E2V semiconductors, INRIA Lyon, ENS Lyon

[10] Partners: Mitsubishi Electric(leader), ENSAAT, Orange Labs, Télécom-Bretagne, Ekinops, Yenista

Analysis of High Bit Rate Optical Signals in amplitude and phase

The asynchronous optical linear sampling of very high rate (>100Gbps) optical signals with advanced modulation formats, especially in phase (x-PSK), by short laser pulses source (<1ps) is a low cost technique, very competitive constellation oscilloscope market. It allows extracting amplitude and phasing information and displaying it in a constellation diagram, for system design characterization and survey. In the frame of the OCELOT project, aiming the development and the technology the transfer from a research industry, we have start to perform the identifications of the basics limit and the utilization range for this technique, as well as the associated signal processing. [487]. Classical real time phase and frequency signal measurement schemes have been revisited [455] following renew demand for signal assessment in new specific application in particular access networking components in collaborative project (MODULE, TRILOB)

Optical switching

The evolution of optical networks toward more efficient and more flexible architectures leads to tasking optical systems with more work than just what the physical layer requires, tending towards a "cross-layer" approach. The prime research axis in this direction is to route data packets or bursts directly on the optical layer.

In collaboration with Columbia University, we demonstrated a fast-failure-recovery-enabled architecture in an optical packet switching matrix based on a bandwidth-flexible wavelength-striping packet format and semiconductor optical amplifiers used as gates [445]. Other avenues for cutting across the classical network layers are being pursued.

Also, following previous work on packet switching architecture, a whole addressing architecture based on the OCDMA technique and a flip-flop operation has been proposed and has been tested within a co-tutelle thesis in collaboration with Sup'Com Tunis. Within the frame of FP7-EUROFOS full scale experiments have been performed] leading to a demonstration of the feasibility of the architecture including flip-flop operation [474] and OCDMA addressing [476, 475].

4.2.3 Quantum Optics and application in Communications and Cryptography

Faculty P. Gallion.

Project ANR-HQNet (12/06—11/09)[11], collaboration CICISE-Mexico-BC

Balanced homodyne detection (BHD) system implementation

We have implemented an all fiber one-way QPSK quantum key distribution system at 1550nm using both photon counting and balanced homodyne detection (BHD) configurations. It includes an automatic optoelectronic feedback loop for the interferometric phase drift compensation and a dual-threshold decision scheme for the BHD signal post-detection. Experimental comparison points out that BHD is potentially more effective in terms of quantum key generation rate and system flexibility.

We have also investigated the security issues of the BHD QKD system under two main individual attacks: intercept-resend attack and intermediate-base attacks. A mixed attack strategy of signal power modification has also been analyzed [460]. As the use of decoy states improves the security, facing the photon number splitting (PNS) attacks, we have generalized the standard QKD security analysis to the proposed systems based on coherent detection [453].

[11] Partners: GEORGIA TECH, FEMTO, PHOTLINE

Optical carrier recovery for weak optical signals (WCS)

Access to the optical carrier phase is important in a diversity of applications, not only in coherent telecommunications but also in other fields such a coherent optical sensor and instrumentation, coherent Lidar, etc., that require the measurement of the two field quadratures. Costas loops or decision driven loops that detect both field quadratures simultaneously, require 2 BHD receivers at the expense of additional measurement uncertainty which is introduced due to the vacuum fields that leak through the unused ports.

We implemented a receiver structure in which a sequential measurement scheme alternatively switches the local oscillator phase between 0° and 90° to sequentially beat with the signal. We implemented our digital Costas loop in the signal processor block, and we obtained good long-term stability. The measurements on the post-detection statistics were close to the uncertainty limit, especially for small values of the photon number. Similarly our measurements of BER were close to the standard quantum limit for low photon numbers [459, 461, 511].

Space quantum communications

Optical communications with in low photon number for each transmitted symbol constitutes an expanding field in a diversity of applications. Beyond cryptography, many applications requiring power economy frequently deal with these quantum level signals, such as quantum communications for airborne, space to ground and inter satellite scenarios.

By using the quantum coherent state model of the radiation field, we have compared the different quantum receiver implementations and derived the minimum signal energy required to achieve a given bit error rate, or a given bit erasure rate in high bit rate, quantum level communications [542]. We have implemented an optical Costas loop at 1550 nm based on polarization splitting of the laser field to detect I and Q quadratures simultaneously. We have obtained results on the performance in phase error and bit error rate and compare with corresponding quantum limit [543].

Holistic quantum security approach

The security of quantum communications is traditionally considered as limited only by the basic principles of physics and not, as in merely conventional safety, in terms of resources that Eve could realistically have. However the needs of a time independent truly unconditional security will be very limited and it is not proven that its cost will be finite, making the widely used unconditional security limitation discussion under risk of confining into academics or thought experiments, with weak economics or societal interest. Furthermore an unconditional security of the quantum layer is not sufficient to achieve an end-to-end security up to the application layer. The only way for quantum security to keep a credible role and to create a wide industrial application range is a progressive infiltration into the classically secured system technologies and culture, including an end-to-end security approach and to clarify its compatibility with optical fiber technologies and systems. In collaboration with local Electronics group and the Computer Science Department we have developed a holistic approach of quantum security [512, 490].

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