A year of research at Télécom Paris

Un an de recherche
à Télécom Paris

2019 - 2020
Annual report
Rapport annuel

2019
2020

Annual report
Rapport annuel

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Editorial
Édito

Nicolas Glady Dean and President, Directeur

EN Télécom Paris has inherited its research model from the model of French-style engineering schools. Our school covers all the layers of the digital world, from hardware to the economics and sociology of digital technologies, including networks, algorithmic, and big data. This transdisciplinary approach, requiring bridges to be built across disciplines to find solutions that best meet today's challenges, is highly relevant to the economy and to society. Our relationship with our supervisory ministry naturally prompts us to address questions of digital sovereignty in particular, but not exclusively. Very large networks and systems, data science, artificial intelligence, digital trust and so on are all becoming increasingly important topics.

Which is why Télécom Paris has recently redefined its raison d'être and enshrined it in its rules and regulations.

It consists in training, imagination and entrepreneurship, to design the models, technologies and digital solutions serving society and an economy that are mindful of humans and their environment.

We have therefore reaffirmed our original approach to address these major social issues head on, based on an approach that is the embodiment of our DNA.

One of the challenges our school will face in tackling these issues is the ability to mirror changes in the economy and in society, to meet the need for entrepreneurship innovation and support. Our strategic assets in this field (researchers, laboratories, alumni, etc.) will be crucial in helping us assert our expertise in the deep tech required by technological and economic development. Excellence in our areas of research enables us, among our organizational and academic partners, to drive the momentum for our school to become a true open-air laboratory, accessible to our entire ecosystem.

In reading this document we put together for you, you will learn about the many aspects of our research activity, which feeds into our training programs, from the engineering cycle to doctorates, including post master's degrees.

Excellence in our areas of research enables us to drive the momentum for our school to become a true open-air laboratory.

FR Télécom Paris a un modèle de recherche original hérité du modèle d'école d'ingénieur à la française. Notre école couvre toute la verticale du numérique : des couches matérielles à l'économie et la sociologie du numérique, en passant par les réseaux, l'algorithmique et le big data. Cette approche transdisciplinaire est particulièrement pertinente pour l'économie et la société qui ont besoin de faire des ponts entre les disciplines pour trouver des solutions en réponse aux enjeux d'aujourd'hui. Nos relations avec notre ministère de tutelle nous orientent naturellement en particulier, mais pas uniquement, vers les sujets de souveraineté numérique qui sont de plus en plus importants étant donné les évolutions du monde actuel : très grands réseaux et systèmes, science des données, intelligence artificielle, confiance numérique, etc.

Dans ce contexte, Télécom Paris a redéfini récemment sa raison d'être et l'a inscrit à son règlement intérieur.

Celle-ci est de former, imaginer et entreprendre pour concevoir des modèles, des technologies et des solutions numériques, au service d'une société et d'une économie respectueuses de l'humain et de son environnement.

Nous avons donc réaffirmé notre approche originale pour nous emparer de ces grandes questions de société selon une approche qui est celle de notre ADN.

L'un des enjeux pour répondre à ces challenges sera la capacité de notre école à accompagner les évolutions de l'économie et de la société pour répondre aux besoins d'innovation et de soutien à l'entrepreneuriat. Nos atouts stratégiques en la matière (chercheurs, laboratoires, réseaux d'anciens, etc.) seront clés dans ce cadre et nous permettront d'affirmer notre expertise *deep tech* nécessaire aux développements technologiques et économiques. C'est fort de cette excellence dans nos domaines de recherche que nous pourrons être, parmi nos partenaires institutionnels et académiques, à l'initiative d'une dynamique pour faire de notre école un véritable laboratoire à ciel ouvert, accessible à tout notre écosystème.

En parcourant ce document que nous avons élaboré pour vous, vous pourrez appréhender les multiples aspects de notre activité de recherche qui nourrit nos enseignements, du cycle ingénieur au doctorat en passant par les Mastères Spécialisés.

Key figures
Télécom Paris en chiffres

Disclaimer
EN This document concerns the research activity of our teams between 2019 and 2020. In order to obtain the most representative figures possible, unless otherwise stated the indicators on these pages and on the Team pages are taken over the calendar year 2019.

Avertissement
FR Ce document concerne l'activité de recherche de nos équipes entre 2019 et 2020. Afin d'obtenir des chiffres les plus représentatifs possibles, les indicateurs sur cette page et sur les pages Equipes sont pris sur l'année civile 2019, sauf indication contraire.

Staff
Personnel

Figures as of December 31, 2019
Chiffres arrêtés au 31 décembre 2019

161
Permanent Researchers and Faculty members
Chercheurs et enseignants-chercheurs permanents

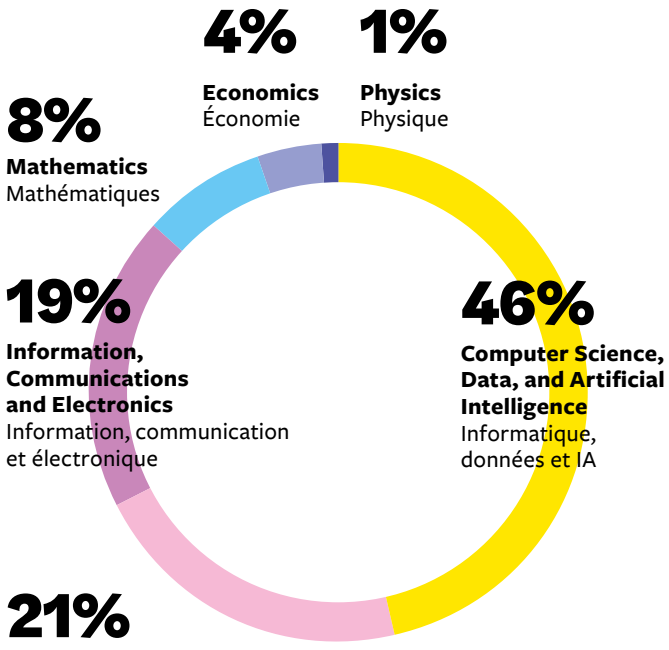
265
PhD Students and postdocs
Doctorants et post-doctorants

75
R&D Engineers
Ingénieurs recherche et développement

19
Administrative staff
Personnel administratif

520
Total Research Staff
Personnel total de la recherche

19
Research Teams
Equipes de recherche



Breakdown by Institut Polytechnique de Paris Research and Education Departments / Répartition par Départements d'enseignement et recherche de l'Institut Polytechnique de Paris

ERC Grants
Bourses ERC

→ telecom-paris.fr/erc

Since the beggining of the ERC Program /
Depuis la création du programme ERC

Mansoor Yousefi
ERC Starting Grant 2018

Michèle Wigger
ERC Starting Grant 2016

Yanlei Diao
ERC Consolidator Grant 2016

Alexandre Gramfort
ERC Starting Grant 2015

Innovation and transfer
Innovation et transfert

5-year consolidated figures / Chiffres consolidés sur 5 ans

Pending patents / Brevets déposés — **78**

Registered software / Logiciels déposés — **18**

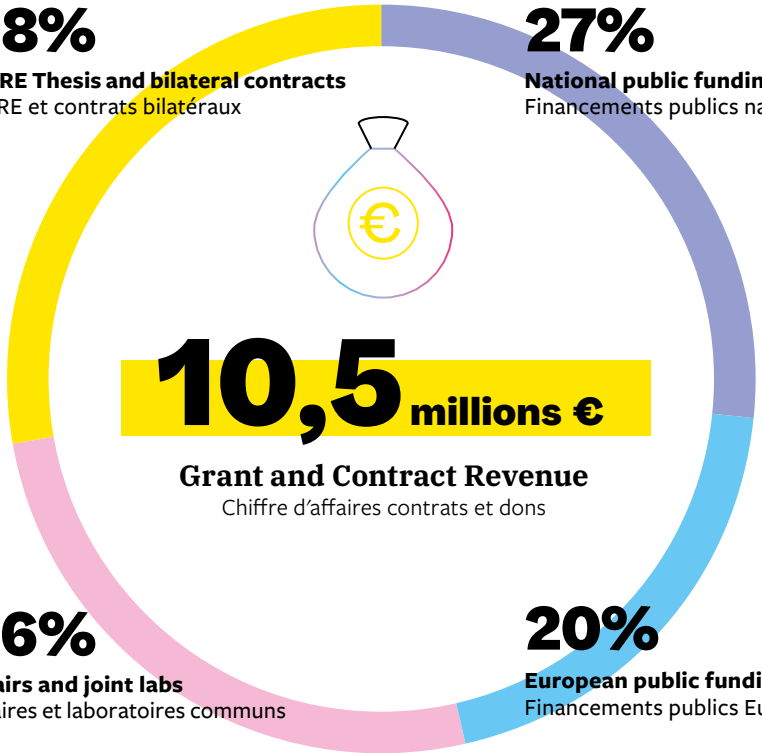
Registered technical know-how / Savoir-faire protégé — **1**

Maturing projects / Projets en maturation — **39**

Spinoff creation / Spinoff créées — **2**

Research Funding
Financement de la recherche

Figures as of December 31, 2019
Chiffres arrêtés au 31 décembre 2019



Scientific results
Résultats scientifiques

175
Journal Articles
Articles dans des journaux

319
Conference Papers
Articles dans des conférences internationales

44
Book Chapters and Proceedings Directions
Livres et chapitres de livres

62
PhD Defenses
Thèses soutenues

January 19
Janvier 19

→ telecom-paris.fr/erc

Launch of the ERC research program on optical fiber network limits

EN Optical fiber forms the backbone of communication systems. The exponential increase in data traffic is placing increasing pressure on fiber-optic networks. Optical fiber is a nonlinear medium because its properties change with signal intensity. It is well known that the fiber nonlinearity limits the achievable information rates of the conventional transmission methods in optical communication.
The objective of the ERC Starting Grant "Optical communication using the nonlinear Fourier transform," led by Mansoor Yousefi (GTO), is to develop signal processing and communication algorithms suitable for the nonlinear optical fiber. The project applies information theory, nonlinear Fourier transforms (NFTs) and machine learning to address the limitation that the fiber nonlinearity sets on the transmission rates.
The European Research Council grants support ground-breaking high-risk high-gain projects that go substantially beyond the state-of-the-art, awarded solely on the basis of scientific excellence.

Lancement du programme de recherche ERC sur les limites des réseaux de fibres optiques

FR Les liens optiques constituent l'épine dorsale des systèmes de communication. L'augmentation exponentielle du trafic de données exerce une pression croissante sur les réseaux à fibres optiques. La fibre optique est un support non-linéaire car ses propriétés changent en fonction de l'intensité du signal. Il est bien connu que la non-linéarité de la fibre limite les débits atteignables des méthodes de transmission conventionnelles.
L'objectif de l'ERC Starting Grant « Communication optique utilisant la transformée de Fourier non linéaire », dirigée par Mansoor Yousefi (GTO), est de développer des algorithmes de traitement du signal et de communication adaptés à la fibre optique en régime non-linéaire. Le projet applique la théorie de l'information, la transformée de Fourier non-linéaire (NFT) et l'apprentissage statistique pour traiter la limitation imposée par la non-linéarité de la fibre sur les débits de transmission.
Le Conseil européen de la recherche soutient des projets novateurs à haut risque et à gain élevé qui vont bien au-delà de l'état de l'art. Les bourses ERC sont attribués uniquement sur la base de l'excellence scientifique.

Highlights

Temps forts

05

March 19
Mars 19

→ telecom-paris.fr/un-autre-regard-sur-lintelligence-artificielle

Another take on artificial intelligence

EN The publication of books by Antonio Casilli (SID) Jean-Louis Dessalles (DIG) - respectively, *En attendant les robots, enquête sur le travail du clic* (Waiting for Robots: An inquiry into click work, Seuil) and *Des intelligences très artificielles* (Very Artificial Intelligence, Odile Jacob) - was an opportunity for the authors to discuss the true nature of artificial intelligence. For Casilli, the AI generated by our clicks is in fact very human, whereas Dessalles believes that AI is incapable of understanding what it manipulates.

Un autre regard sur l'intelligence artificielle

FR À l'occasion de la sortie de leurs livres, Antonio Casilli (SID) *En attendant les robots, enquête sur le travail du clic*, Seuil et Jean-Louis Dessalles (DIG) *Des intelligences très artificielles*, Odile Jacob, ont débattu sur la véritable nature de l'intelligence artificielle, celle qui se nourrit de nos clics et est finalement très humaine selon le premier, ou celle qui n'est pas capable de comprendre ce qu'elle manipule pour le second.

12 March 19
Mars 19

→ digit-finance.com

Creation of the Digital Finance Research Chair

EN Télécom Paris, Université Paris II Panthéon-Assas, Institut Louis Bachelier, Groupement des Cartes Bancaires (CB) and La Banque Postale joined forces to create the Digital Finance Chair. The chair is led by David Bounie (ECOGE), and Marianne Verdier at Université Paris II Panthéon-Assas.

Création de la chaire de recherche Finance Digitale

FR Télécom Paris, l'université Paris II Panthéon-Assas, l'Institut Louis Bachelier, le Groupement des Cartes Bancaires et La Banque Postale se sont associés pour créer la chaire de recherche Finance Digitale. Elle est portée par David Bounie (ECOGE) et Marianne Verdier de l'Université Paris II Panthéon-Assas.

03 April 19
Avril 19

→ telecom-paris.fr/dsaidis

Inauguration of the DSAIDIS Research Chair

EN Airbus, ENGIE, IDEMIA, Safran and Valeo are the corporate partners of the Data Science and Artificial Intelligence for Digitalized Industry and Services Chair. The chair led by Florence d'Alché-Buc (S²A) focuses on the study of temporal data, the large-scale use of heterogeneous data and the way in which guarantees can be offered on the reliability and robustness of algorithms and learning, while interacting with the environment.

Inauguration de la chaire de recherche DSAIDIS

FR Les entreprises Airbus, ENGIE, IDEMIA, Safran et Valeo sont les partenaires de la chaire Data Science and Artificial Intelligence for Digitalized Industry and Services. Portée par Florence d'Alché-Buc (S²A), elle met l'accent sur l'étude des données temporelles, l'exploitation à grande échelle des données hétérogènes, sur la façon d'offrir des garanties sur la fiabilité et la robustesse des algorithmes et sur l'apprentissage en interaction avec l'environnement.

20/21 June 19
Juin 19

→ telecom-paris.fr/entreprise

Corporate Partner Days

EN More than 40 companies have been partnering Télécom Paris since 2000: they recruit graduates, benefit from continuous learning programs and engage in many collaborative research programs. Corporate Partner Days (JPE) are a forum in which to interact and share experiences, in order to define and understand the needs of Télécom Paris's partners, as part of the latter's activities. In 2019, the spotlight was on two major science topics: blockchain and artificial intelligence.

Journées Partenaires Entreprises

FR Depuis 2000, Télécom Paris réunit plus d'une quarantaine d'entreprises qui recrutent ses diplômés, bénéficient de ses prestations de formation continue et avec lesquelles elle poursuit de nombreuses collaborations de recherche. Ces JPE sont l'occasion d'échanges, de transferts d'expérience et de réflexion pour définir et appréhender les besoins des partenaires de l'École au sein de ses missions. La blockchain et l'intelligence artificielle étaient les deux grandes thématiques scientifiques mises en avant lors de l'édition 2019.

20 October 19
Octobre 19

→ perso.telecom-paristech.fr/maitre/francis

Tribute to Francis Schmitt

EN The international workshop, a satellite event at the CIC-2019 conference, was dedicated to Francis Schmitt, professor of image processing at Télécom Paris from 1974 to 2008 and a pioneer of 3D image synthesis and colorimetry.

Hommage à Francis Schmitt

FR Ce workshop international, en marge de la conférence CIC-2019, était dédié à Francis Schmitt, professeur en traitement d'image à Télécom Paris de 1974 à 2008 et pionnier de synthèse graphique tridimensionnelle et de colorimétrie.

04 November 19
Novembre 19

Moving to the new campus

EN Télécom Paris is moving closer to its Institut Polytechnique de Paris partners, including Télécom SudParis, part of which is moving to the same building, with École Polytechnique, ENSAE Paris and ENSTA Paris located a few hundred meters away. Special partner HEC Paris is just a few kilometers away. Proximity will promote collaborations in this new science and technology institute with global scope.

Emménagement sur le nouveau campus

FR Télécom Paris se rapproche notamment de ses partenaires de l'Institut Polytechnique de Paris : Télécom SudParis qui rejoint en partie le même bâtiment, l'École polytechnique, ENSAE Paris et ENSTA Paris situées à quelques centaines de mètres. HEC Paris, partenaire privilégié, est situé à quelques kilomètres. Cette proximité favorise les collaborations dans le cadre de ce nouvel institut scientifique et technologique d'ampleur mondiale.

25/26 January 20
Janvier 20

→ swerc.eu/2019

Southwestern Europe Regional Contest SWERC

EN After two editions co-organized with Ecole Normale Supérieure, Télécom Paris welcomed the final of SWERC, the world's largest competitive programming competition, to its news premises in Palaiseau. It was organized by the Institut Polytechnique de Paris for the first time. This year, a record number of 98 teams of three students competed in SWERC, 95 of which were ranked. All told, the event gathered around 400 people.

SWERC

FR Après deux années de co-organisation avec l'Ecole Normale Supérieure, Télécom Paris a accueilli dans ses nouveaux locaux de Palaiseau la finale du SWERC, le plus grand concours mondial de programmation compétitive. Il était pour la première fois organisé dans le cadre de l'Institut Polyethnique de Paris. Cette année, un nombre record de 98 équipes de trois étudiants se sont affrontées dont 95 ont été classées. Près de 400 personnes au total ont participé à l'événement.

26/27

February 20
Février 20

First meeting of the Institut Polytechnique de Paris ISAB

EN Télécom Paris welcomed the International Scientific Advisory Board (ISAB) who had come to assess the scientific project of Institut Polytechnique de Paris and visits its labs, including LTCI at Télécom Paris. Some twelve top scientists from universities and research centers all over the world expressed a very positive opinion of the new Institute's project.

Première réunion de l'ISAB de l'Institut Polytechnique de Paris

FR Télécom Paris a accueilli le Comité scientifique international (ISAB) venu évaluer le projet scientifique de l'Institut Polytechnique de Paris et visiter ses laboratoires, dont le LTCI de Télécom Paris. La douzaine de scientifiques de haut niveau issus d'universités et de centres de recherche à travers le monde a rendu un avis très favorable sur le projet du nouvel Institut.

27

April 20
Avril 20

Two chairs selected by the National Program for AI

EN The National Research Program in AI aims to place France firmly in the top five countries in the world in the field of AI and to make it the European leader. Two of the forty projects selected by the French National Research Agency are led by Télécom Paris.

XAI4AML, Explainability of artificial intelligence for anti-money laundering, in partnership with PwC and ACPR, aims to design the optimal environment for the employment of AI to combat money laundering and terrorist financing. This project is led by David Bounie and Winston Maxwell (ECOGE) together with Stephan Clémençon (S²A).

NoRDF Project, in collaboration with EDF, BPCE, Schlumberger and Converteo, aims to model and extract complex data from natural language texts. This project is led by Fabian Suchanek (DIG).

Deux chaires retenues par le Programme National pour l'IA

FR Le Programme National de recherche en IA a pour objectif de propulser durablement la France dans le top 5 des pays experts en IA à l'échelle mondiale et faire de la France le leader européen. Parmi les quarante projets retenus par l'Agence Nationale pour la Recherche, deux sont portés par Télécom Paris.

XAI4AML, Explicabilité de l'intelligence artificielle pour la lutte contre le blanchiment d'argent, en partenariat avec PwC et l'ACPR, a pour objectif de développer un cadre optimal pour le déploiement de l'IA dans la lutte contre le blanchiment d'argent et le financement du terrorisme. Elle est portée par David Bounie et Winston Maxwell (ECOGE) ainsi que Stephan Clémençon (S²A).

NoRDF Project, en collaboration avec EDF, BPCE, Schlumberger et Converteo, vise à modéliser et à extraire des informations complexes à partir de textes en langage naturel. Cette chaire est portée par Fabian Suchanek (DIG).

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June 20
Juin 20

Institut Polytechnique de Paris Science Day

EN The aim of the first Institut Polytechnique de Paris Science Day for researchers and PhD students was to bring together the Institute's ten disciplinary communities, in order to present an overview of the research that best illustrates the range of topics in the various labs. Filippo Miatto (IQA) presented his work on the design of photonic circuits for quantum computers and Winston Maxwell (ECOGE) gave a talk on ethics, fundamental rights and AI.

Journée Scientifique Institut Polytechnique de Paris

FR La première journée scientifique de l'Institut Polytechnique de Paris, à destination des chercheurs et des doctorants, avait pour objectif de réunir les dix communautés disciplinaires de l'institut afin de présenter un panorama des recherches reflétant au mieux la variété des thèmes des différents laboratoires. Filippo Miatto (IQA) a présenté ses travaux sur le design de circuits photoniques pour l'ordinateur quantique et Winston Maxwell (ECOGE) a fait un exposé sur l'éthique, les droits fondamentaux et l'IA.

Among our young talents

Parmi nos jeunes talents

Hadi Ghauch

ComNum

EN Hadi Ghauch's research lies at the intersection of optimization theory, learning, signal processing, and wireless communications. In particular, Hadi's research focuses on optimization for large-scale learning, **interpretable models for machine learning**, machine learning for resource allocation, optimization for millimeter-wave communication, and distributed optimization of wireless networks. Among the projects Hadi is working on in this context are applications in recommendation systems, bioinformatics (DNA analysis), and beamforming for large mmWave MIMO.

FR Les recherches de Hadi Ghauch se situent à la croisée de la théorie de l'optimisation, de l'apprentissage, du traitement du signal et des communications sans fil. Cinq axes sont plus particulièrement étudiés : l'optimisation pour l'apprentissage à grande échelle, **les modèles interprétables pour l'apprentissage machine**, l'apprentissage machine pour l'allocation des ressources, l'optimisation dans les communications par ondes millimétriques et l'optimisation distribuée des réseaux sans fil. Parmi les travaux que Hadi mène dans ce cadre se trouvent les applications pour les systèmes de recommandation, la bioinformatique (analyse de l'ADN) et le filtrage spatial pour les ondes millimétriques des systèmes MIMO.

PUBLICATIONS

▸ **H. Ghauch**, H. Shokri, M. Skoglund, C. Fischione, "Learning Kolmogorov Models for Binary Random Variables", accepted to ASILOMAR 2020

▸ H. Shokri, **H. Ghauch**, C. Fischione, M. Skoglund, "Learning and Compression in Large Datasets", ICML' 19

CV

► MSc in Information Networking, Carnegie Mellon University (CMU), USA (2011)

► PhD in Electrical Engineering and postdoc at Royal Institute of Technology, KTH, Stockholm (2016)

► Joined Télécom Paris (ComNum) in November 2018

► Received several scholarships for studies/research visits: University of California at Berkeley (UCB), KTH excellence scholarship, full scholarship from Carnegie Mellon University (CMU)

Web
sites.google.com/site/ghauchhadi/

Jan Gugenheimer

DIVA

EN Jan Gugenheimer specializes in Human-Machine Interaction, a multidisciplinary field that lies at the intersection of computer science, psychology and sociology. More specifically, his research focuses on the way in which humans and technology can interact effectively. He also examines the consequences of mastering technology, both for individuals and for society. He carries out his research in the field of **spatial computing**—the underlying model for mixed reality. The fact that it can offer digital contents with which we can interact in our own 3D environment, and the manner in which this is done, strongly influence the way in which our society is changing.
Jan's work in this very active field was recognized during the 2020 ACM CHI, four of his articles having been selected, as well as one workshop.

FR Jan Gugenheimer est spécialisé dans l'Interaction Humain-Machine, un domaine multi-disciplinaire à la croisée de l'informatique, de la psychologie et de la sociologie. Il s'intéresse plus spécifiquement à la manière dont les humains et les technologies peuvent interagir de façon efficace, et quelles conséquences la maîtrise de ces technologies a pour les individus et pour la société. Il mène ses travaux dans le domaine de l'**informatique spatiale** – le modèle sous-jacent de la réalité mixte. La possibilité qui y réside de proposer des contenus numériques et d'interagir avec eux dans l'espace en trois dimensions qui nous est propre et la manière de le faire, ont une influence toute particulière sur l'évolution de notre société.
Dans ce domaine en pleine effervescence, les travaux de Jan ont été reconnus lors de l'édition 2020 de ACM CHI avec 4 de ses articles et un atelier retenus.

PUBLICATIONS

▸ M. Colley, M.Walch, **J. Gugenheimer**, A. Askari, and E. Rukzio 2020. "Towards inclusive external communication of autonomous vehicles for pedestrians with vision impairments". In Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20 Best Paper Honorable Mention)

▸ T. Drey, **J. Gugenheimer**, J. Karlbauer, M. Milo, and E. Rukzio. 2020. "Vrsketchin: Exploring the design space of pen and tablet interaction for 3d sketching in virtual reality". In Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20).

CV

► Visiting Researcher at MIT Media Lab Fluid Interfaces Group (2015)

► Research Intern at Microsoft Research Redmond (2017)

► PhD Computer Science (Human-Computer Interaction) at Ulm University (2019)

► Joined Télécom Paris (DIVA) in January 2020

Web
telecom-paris.fr/jan-gugenheimer

Pavlo Mozharovskyi

S²A

EN Pavlo Mozharovskyi's research interests lie in the areas of data depth, machine learning, computational statistics, missing values, robust statistics, multivariate data analysis, **functional data analysis**, data envelopment analysis.
As part of the Data Science and Artificial Intelligence for Digitalized Industry and Services Chair, his focus is on the functional data he processes in their own functional space, to which he applies new methods, with many advantages (in favorable cases: better detection rate, better sensitivity to abnormality, reduced execution time). For example, Pavlo has recently extended the forest isolation approach to functional data, and has also proposed an approach based on data depth (ranking of observations by their probability of arrival).

FR Les travaux de recherche de Pavlo Mozharovskyi couvrent les domaines de la profondeur des données, de l'apprentissage machine, des statistiques computationnelles, des valeurs manquantes, des statistiques robustes, de l'analyse des données multivariées, de l'**analyse des données fonctionnelles** et de l'analyse des enveloppes de données.
Dans le cadre de la chaire Data Science and Artificial Intelligence for Digitalized Industry and Services, il s'intéresse aux données fonctionnelles qu'il traite dans leur propre espace fonctionnel et leur applique des méthodes nouvelles, avec des avantages qui s'avèrent nombreux (dans les cas favorables : meilleur taux de détection, meilleure sensibilité à l'anormalité, temps d'exécution réduit). Pavlo a ainsi récemment étendu l'approche isolation forest aux données fonctionnelles et également proposé une approche fondée sur la profondeur de données (data depth ; rangement des observations par leur probabilité d'arrivée).

PUBLICATIONS

▸ G. Staerman, **P. Mozharovskyi**, S. Clémençon, and F. d'Alché-Buc, (2019) "Functional isolation forest." In: Proceedings of Machine Learning Research (ACML 2019), 101, 332-347.

▸ G. Staerman, **P. Mozharovskyi**, and S. Clémençon, (2020): "The area of the convex hull of sampled curves: a robust functional statistical depth measure." AISTATS 2020

▸ P. Lafaye De Micheaux, **P. Mozharovskyi**, and M. Vimond, (2020) "Depth for curve data and applications." Journal of the American Statistical Association, in press.

CV

► PhD Computer Science at University of Cologne (2014)

► Joined Télécom Paris (S²A) in September 2018

Web
telecom-paris.fr/pavlo-mozharovskyi

Laurie Ciaramella

ECOGE

EN In her research, Laurie Ciaramella conducts studies in **economics and management of innovation and in intellectual property**. Her research focuses on companies' strategies in markets for technology, as well as on the impact tax policies have on the way these markets operate. She also studies the relationship between markets for technology and the innovation trajectories of economic players. To do so, she uses large patent databases, which she merges with detailed company-level data. One of her projects was awarded the Best Paper award at the Druid Academy 17 conference, and her PhD dissertation received the Best Dissertation Finalist award in the TIM division of the 2018 Academy of Management.

FR Laurie Ciaramella réalise des travaux en **économie et management de l'innovation et de la propriété intellectuelle**. Sa recherche porte sur les stratégies d'entreprises sur les marchés de technologies, ainsi que sur l'impact des politiques fiscales sur le fonctionnement de ces derniers. Elle étudie également le lien entre marchés de technologies et trajectoires d'innovation des acteurs économiques. Pour ce faire, elle exploite de larges bases de données sur les brevets, qu'elle croise avec des données d'entreprises. L'un de ses projets a reçu le Best Paper award de la conférence Druid Academy 17, et sa thèse de doctorat a été récompensée du Best Dissertation Award, finaliste, de la division TIM de l'Academy of Management 2018.

PUBLICATIONS

▸ **L. Ciaramella**, (2019) "Taxation and the Transfer of Patents: Evidence from European Patent Boxes", SSRN working paper.

▸ **L. Ciaramella**, G. de Rassenfosse, (2019) "Geography and the Markets for Technology", mimeo.

▸ **L. Ciaramella**, F. Gaessler, B.H. Hall, D. Harhoff, (2020) "International Patent Transfers and Knowledge Spillovers", mimeo.

CV

► PhD in Economics at Mines ParisTech (2017)

► Senior Research Fellow at the Max Planck Institute for Innovation and Competition in Munich, affiliated with the Innovation and Entrepreneurship research group (2017-2019)

► Visiting Researcher at the Searle Center of the Northwestern University in Chicago, and at the College of Management of the École polytechnique fédérale de Lausanne (2017)

► Joined Télécom Paris (ECOGE) in January 2019

Web
telecom-paris.fr/laurie-ciaramella

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Some of our most prestigious international partnerships

Quelques-unes de nos coopérations internationales emblématiques

EN Researchers have always ignored borders, ever since European universities first emerged in Oxford, Bologna and Paris. The academic vision of a truly world-wide community makes for extraordinary interactions, fueling the creation and dissemination of knowledge. As a key player in the design and promotion of communication and information technologies, Télécom Paris naturally subscribes to this vision. Since it was created, its researchers have established relations with universities and research centers all over the world. Cooperation takes many forms, including research partnerships, study visits and sabbatical exchanges, workshops and conferences and also joint PhD supervision, leading to a diploma that is recognized in both countries. Cooperation also leads to the publication of many articles.

FR Depuis la naissance des grandes universités européennes comme Oxford, Bologne ou Paris, les chercheurs se sont toujours affranchis des frontières. La vision académique d'un monde distribué sur l'ensemble du globe permet de formidables échanges qui touchent à la création et au partage des connaissances. Télécom Paris, au cœur de la conception et de la promotion des technologies de la communication et de l'information, s'inscrit naturellement dans cette vision. Depuis sa création, ses chercheurs ont noué des relations avec des universités et des centres de recherche dans le monde entier. Ces coopérations peuvent prendre la forme de partenariats de recherche, de séjours d'études et d'échanges sabbatiques, de workshops et de conférences ou encore de co-encadrements de thèses aboutissant à une diplomation reconnue par les deux pays. Elles donnent naissance à de nombreuses publications d'articles.

Canada

Institute for Quantum Computing, Waterloo, IQA
University of Toronto, Toronto, IQA

USA

Cisco, Mountain View, California, CCN
Columbia University, New York, GTO
HP Labs, Palo Alto, GTO
Qualcomm, Massachusetts, CCN
University of California, Los Angeles, GTO
University of Florida, Gainesville, CCN

Brazil

Instituto Tecnológico de Aeronáutica, São José dos Campos, LabSoC
Universidade de Brasilia, Brasilia, SSH
Universidade de Sao Paulo, Sao Paulo, IMAGES

Uruguay

ICT4V, Montevideo, SSH

Sweden
KTH, Stockholm, MM

Switzerland
ETH Zurich, Zurich, ComNum

Belgium
Université Catholique de Louvain, Louvain, ECOGE
Université de Liège, Liège, ECOGE

UK
Imperial College of London, London, RMS

Germany
Infinera Corporation, Munich, GTO
Max-Planck-Institut für Informatik, Saarbrücken, DIG
Nokia Bell Labs, Stuttgart, GTO
Technische Universität Chemnitz, Chemnitz, LabSoC
Technische Universität München, Munich, ACES

Romania
Universitatea Politehnica din București, Bucharest, MM

Poland
Warsaw University of Technology, Warsaw, ACES

Spain
ICFO, Barcelona, IQA

China
Chinese Academy of Science, Beijing, SSH
ShanghaiTech, Shanghai, GTO
Tsinghua University, Beijing, RMS
Shanghai Jiao Tong University, Shanghai, ACES
Wuhan University, Wuhan, IMAGES

Hong Kong
HKUST, Hong Kong, CCN

Japan
Kobe University, Kobe, SSH
Tōhoku University, Sendai, SSH

India
Indian Institute of Science, Bangalore, ComNum

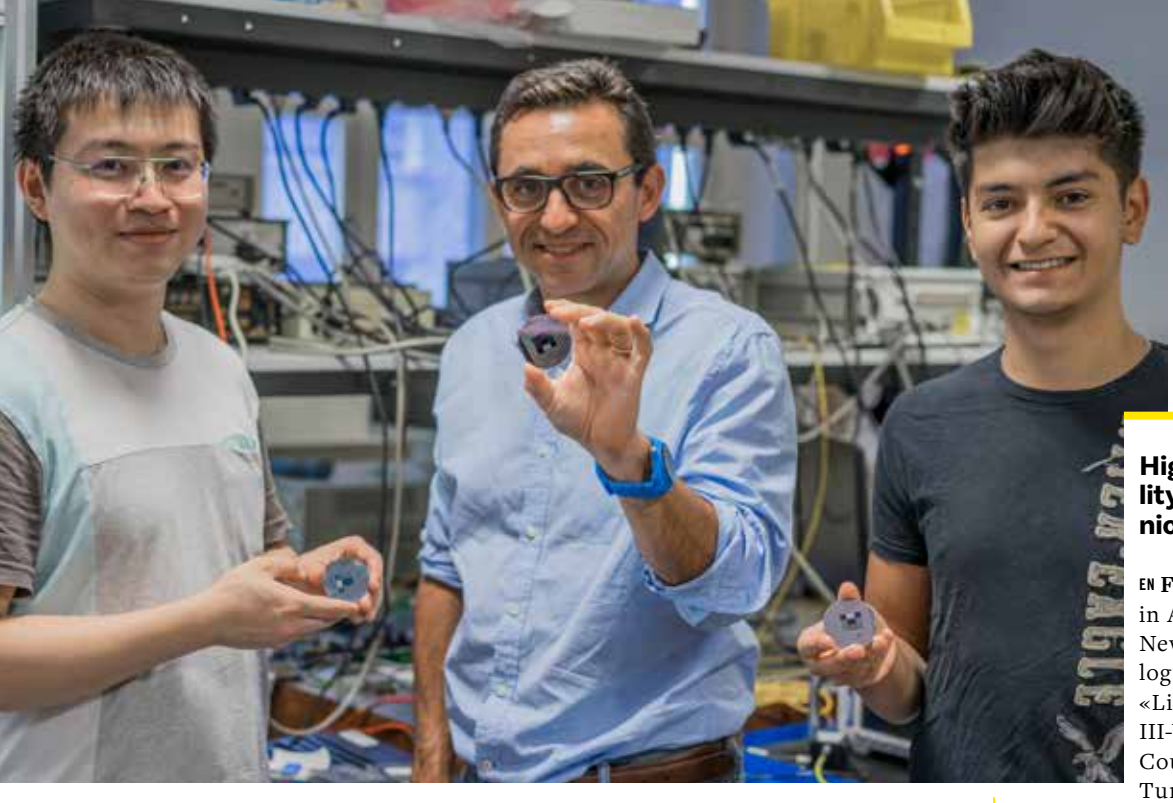
Singapore
Nanyang Technological University, Singapore, RFM²
National University of Singapore, Singapore, DIG

Algeria
Université de Boumerdes, Boumerdes, LabSoC

Morocco
Université Internationale de Rabat, Rabat, ComNum

Australia
Université de Canberra, Canberra, ECOGE

New Zealand
University of Waikato, Waikato, DIG



High international visibility for integrated photonics on silicon

EN **Frédéric Grillot** (GTO) earned in April 2020, the University of New Mexico Science & Technology Innovation Award for the «Light-Emitting Device Having III-V Semiconductor Gain Section Coupled to Whistle-Geometry Tunable Filter» patent, filed in June 2019 jointly with Marek Osiński, Professor at the University of New Mexico (UNM).

UNM, which has a long recognized tradition of excellence in optics, thus shone a spotlight on a new type of laser module—based on micro-resonators coupled to silicon waveguides—that paves the way for low-cost, mass-producible transmitters, targeting applications such as metropolitan and access networks, servers and data centers, high-performance computers and optical interconnections.

Frédéric Grillot and **Jianan Duan**'s work on silicon photonics to develop ultra-stable optical emitters is particularly noteworthy. It consists in creating quantum dots within semiconductor nanostructures directly on silicon, which makes the light emitter insensitive to light feedback and avoids the cost and complexity of an optical isolator.

▸ **J. Duan**, **H. Huang**, B. Dong, J. C. Norman, Z. Zhang, J. E. Bowers, and **F. Grillot**. "Dynamic and nonlinear properties of epitaxial quantum dot lasers on silicon for isolator-free integration", Photonics Research, vol. 7, p. 1222, 2019.

▸ **J. Duan**, **H. Huang**, B. Dong, D. Jung, J. C. Norman, J. E. Bowers, and **F. Grillot**. "1.3 micron reflection insensitive InAs/GaAs quantum dot lasers directly grown on silicon", IEEE Photonics Technology Letters, vol. 31, p. 345, 2019.

Mapping the coproduction of digital infrastructure by firms and peer projects

EN At the 10th edition of the Open CIO Summit, held in Paris on December 11, 2019, **Laure Muselli** (ECOGE), a specialist in the process of emergence and institutionalization of Open Source, presented the first results of a French-Australian research project funded by the Sloan/Ford Foundation and led by Mathieu O'Neil (University of Canberra and Visiting Professor at Télécom Paris in September and October 2019), with Xiaolan Can and Mahin Raissi (University of Canberra) and Stefano Zacchiroli (Université Paris Diderot / Inria). The study, «Mapping the co-production of digital infrastructure by firms and peer projects», shows that major Internet companies such as Microsoft, Google, Apple and Facebook rank highest (1st, 3rd, 5th and 7th respectively) among the largest contributors on GitHub. This international analysis, which resulted from data collection covering the period from January 1, 2015 to May 31, 2019, aimed to map the global network of connections between contributing firms and projects, to understand the impact of paid work on the autonomy and sustainability of projects, and to identify the implications in terms of public policy.

▸ www.openciosummit.org

Florence d'Alché-Buc, Co-Chair of the NeurIPS 2019 Program Committee

EN The NeurIPS conference held in Vancouver from December 8 to 14, 2019 has, over the years, become the largest international meeting in machine learning and artificial intelligence. Three women were chosen this year as co-chairs of the scientific program, including **Florence d'Alché-Buc** (S²A), who took on this responsibility after two years as senior area chair and longstanding and constant commitment. Holder of the Data Science and Artificial Intelligence for Digitalized Industry and Services Chair, Florence d'Alché-Buc is also very committed to ethical issues and the representation of diversity in this field of research.

Stephan Clémençon (S²A) was also part of the program committee as area chair. Six papers from Télécom Paris were accepted at NeurIPS 2019, with contributions from Roland Badeau, Olivier Fercoq, Robert Gower, Gaël Richard, Othmane Sebbouh and Umut Şimşekli.

▸ www.telecom-paris.fr/neurips-2019-telecom-paris-comite-programme

Editorial

Édito

See also
- LTCI Lab p. 20
- i3 Lab p. 64
- Partners p. 84

Talel Abdessalem
Dean of Research - Director of the LTCI
Directeur de la recherche - Directeur du LTCI

EN The research carried out at Télécom Paris is recognized to be of an excellent level, even exceptional for the principal themes of the school's scientific activity. These results were made possible by the particular environment of the school, which brings together a high-quality faculty, students of an excellent level and state-of-the-art equipment, and by the strength of its relations with its many partners, from both academia and industry.

In its two research laboratories, the LTCI (Information Processing and Communications Laboratory) and i3 (Interdisciplinary Institute on Innovation), more than 160 faculty and more than 210 PhD students contribute to extending the limits of knowledge in the field of digital science and technology, and their societal and economic impacts.

Their work is now being developed within Institut Polytechnique de Paris, whose ambition is to develop excellent training programs and cutting-edge research. It does so in a particularly rich and dynamic ecosystem that constitutes the Orsay-Palaiseau-Saclay area, where Télécom Paris moved to at the end of 2019.

"Just as fundamental research is essential for the advancement of knowledge, so are partnership-based and applied research, proposing effective solutions to the challenges and issues of tomorrow. This often requires the confrontation of expert views from different disciplines."

The next pages will give you an overview of the research activity of our nineteen teams. A more detailed description of their projects and further information can be found on their websites.

Cutting-edge research is now being developed within the Institut Polytechnique de Paris.

FR La recherche conduite à Télécom Paris est reconnue d'un excellent niveau, voire exceptionnelle pour les thématiques au cœur de l'activité scientifique de l'école. Ces résultats ont été rendus possibles par l'environnement particulier de l'école qui réunit un corps professoral de grande qualité, des étudiants d'un excellent niveau et des équipements de pointe, et par la solidité de ses relations avec ses nombreux partenaires académiques et industriels.

Au sein de deux laboratoires de recherche, le LTCI (Laboratoire Traitement et Communication de l'Information) et i3 (Institut Interdisciplinaire de l'Innovation), ce sont plus de 160 chercheurs et enseignants-chercheurs permanents et plus de 210 doctorants qui contribuent à repousser les limites des connaissances dans le domaine des sciences et technologies du numérique et de leurs impacts sociétaux et économiques.

Leurs travaux se développent désormais dans le cadre de l'Institut Polytechnique de Paris, avec l'ambition de construire une recherche de rang mondial et des programmes de formation d'excellence, dans un écosystème particulièrement riche et dynamique constitué par le plateau Orsay-Palaiseau-Saclay, où l'école a emménagé fin 2019.

"Si la recherche fondamentale est capitale pour l'avancement du savoir, la recherche partenariale ou appliquée l'est autant pour proposer des solutions efficaces aux défis et enjeux de demain. Cela nécessite souvent le croisement de regards d'experts de différentes disciplines."

Ce que vous lirez dans les pages suivantes est un aperçu des projets actuels de nos dix-neuf équipes de recherche. N'hésitez pas à consulter leurs sites Web et les rapports d'évaluation de nos laboratoires pour une vision plus approfondie de leur activité.

Strategic focuses

Axes stratégiques

(54-55)

Very Large Networks & Systems

Très grands réseaux et systèmes

55 Permanent members
Membres permanents

206 Publications
Publications

23 Thesis
Thèses soutenues

(46-47)

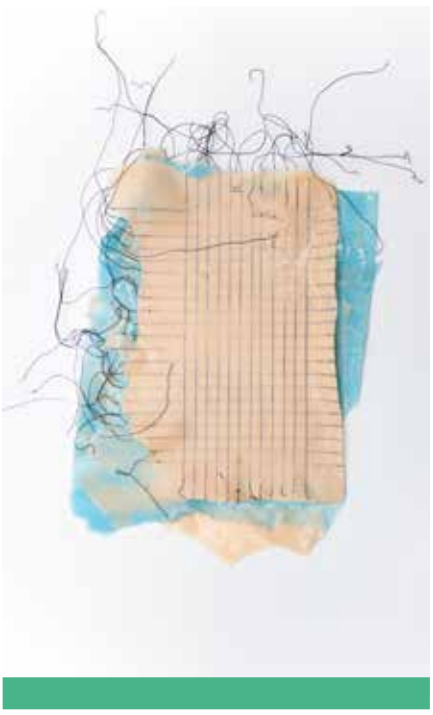
Design, Interaction, Perception

Design, Interaction, Perception

17 Permanent members
Membres permanents

56 Publications
Publications

10 Thesis
Thèses soutenues



(34-35)

Digital Trust

Confiance numérique

27 Permanent members
Membres permanents

71 Publications
Publications

9 Thesis
Thèses soutenues

EN The institute's six strategic focuses allow Télécom Paris to promote cross-disciplinary and interdisciplinary research on major issues related to the digital revolution across all industry sectors.

FR Six axes stratégiques d'établissement concrétisent le potentiel de mobilisation transversale et interdisciplinaire de la recherche de Télécom Paris sur les enjeux majeurs de la révolution numérique communs à tous les domaines sectoriels.

(62-63)

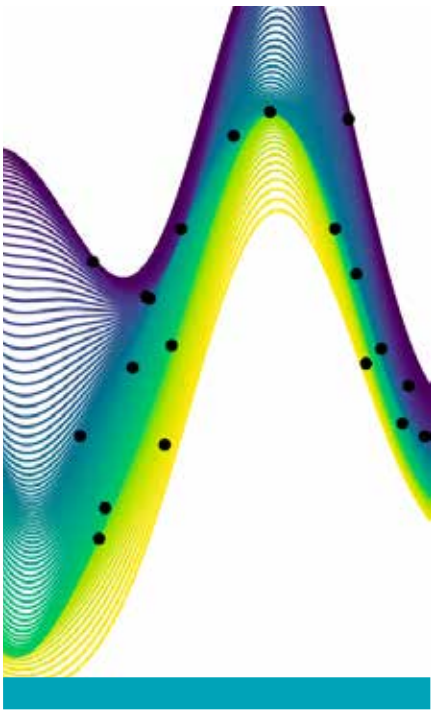
Data Science & Artificial Intelligence

Sciences des données et intelligence artificielle

44 Permanent members
Membres permanents

227 Publications
Publications

24 Thesis
Thèses soutenues



(28-29)

Transversal focus

Mathematical Modeling

3 areas

> Content, knowledge and interactions
> Networks and systems
> Information and its ecosystems

Axe transversale

Modélisation mathématique

3 domaines

> Contenus, connaissances et interactions
> Réseaux et systèmes
> L'information et ses écosystèmes

(76)

Transversal focus

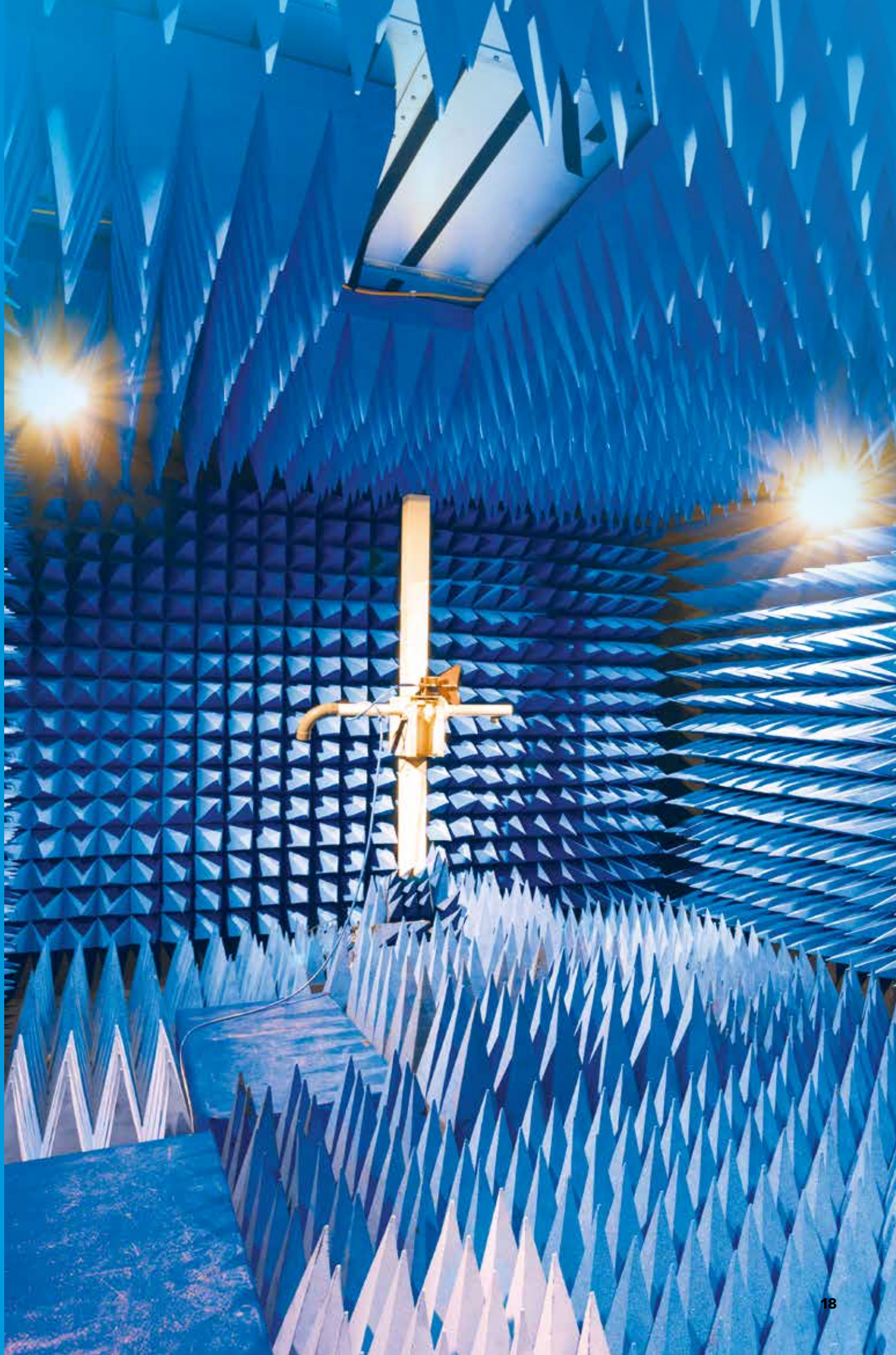
Digital Innovation

4 Joint laboratories
2 Research chairs
1 Startup incubator
1 SME Builder

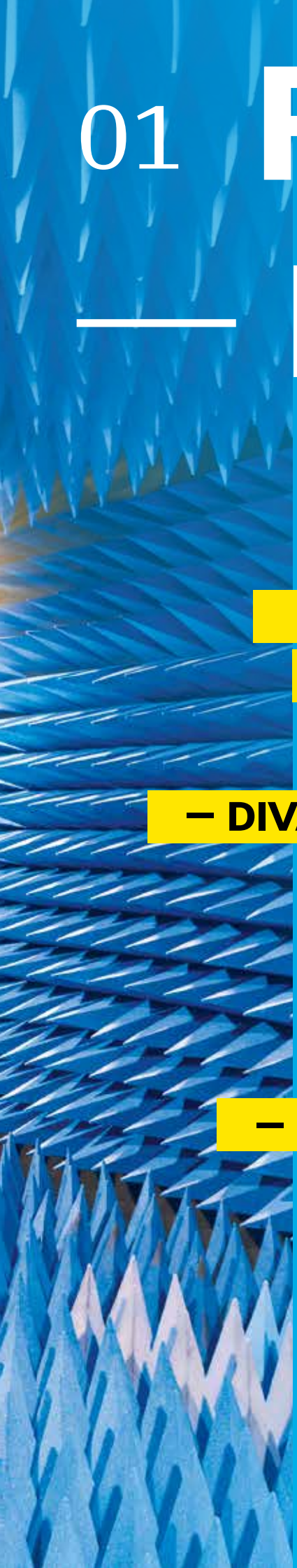
Axe transversale

Innovation numérique

4 Laboratoires communs
2 Chaires de recherche
1 Incubateur de startup
1 accélérateur de startup



Anechoic chamber
Chambre Anéchoique



01 Research — Recherche

Indicators

EN Permanent members include researchers, faculty members, associate researchers, emeritus researchers and engineers. Publications include, over one year: books and book chapters, publications in international conferences with program committees and proceedings, articles in scientific journals. Thesis defenses are agreed upon over one year. Patents are accounted for 5 years.
The following pages present only a selection of the research currently being conducted within the various teams. Visit their websites for more information.

Indicateurs

FR les membres permanents comprennent les chercheurs, enseignants-chercheurs, chercheurs associés, chercheurs émérites et ingénieurs. Les publications comprennent, sur un an : les livres et chapitres de livres, les publications en conférences internationales avec comité de programme et actes, les articles de journaux scientifiques. Les soutenances de thèse s'entendent sur un an. Les brevets sont comptabilisés sur 5 ans.
Les pages suivantes ne présentent qu'une sélection des recherches actuellement menées au sein des différentes équipes. Consultez leurs site Web pour en savoir plus.

TELECOM Paris

IP PARIS

LTCI

Laboratoire Traitement et Communication de l'Information

“In 2018, the French High Council for Evaluation of Research and Higher Education (HCERES) evaluated the scientific results of LTCI as “being exceptional in quality with publications in the best journals and conferences”.”

EN The LTCI brings together more than 370 employees, including nearly 130 permanent research professors and more than 190 doctoral students. Organized into 16 research teams, it produces around 650 annual international publications (in scientific journals and books, or in leading international conferences). At the Institut Polytechnique de Paris, the LTCI works regularly with teams from the i3 laboratory (pages 64-65), LIX, CMAP and Samovar. It also maintains strong links with a vast Ile-de-France ecosystem, presented on pages 80-81.

Members of the laboratory have obtained four ERC grants (since the creation of the program), including two ongoing ERC Starting Grants: Michèle Wigger (ERC 2016; theoretical aspects of information transmission, flow management and distributed storage) and Mansoor Yousefi (ERC 2018; mathematical methods based on nonlinear Fourier theory).

The LTCI, which has been certified for the quality of its industrial research partnerships, is a member of the Carnot Télécom & Société Numérique (p. 84).

Web
www.telecom-paris.fr/ltci

EN The **Information Processing and Communications Laboratory** (LTCI) is a research laboratory of Télécom Paris. It succeeds, since January 2017, to the UMR CNRS of the same name. The LTCI was created in 1982 and is characterized by its extensive coverage of topics in the field of information and communication sciences and technology. The laboratory is also active in issues related to systems engineering and applied mathematics.

Information and communication technology becomes more firmly embedded in our society and fundamentally affects the way it operates. The objects which instantiate their highly multidisciplinary character require, in order to be developed, the understanding and exploitation of physical phenomena, the algorithmic processing of signals and data passing through them, and the way they efficiently slot into a global information system. They are socio-technical objects and as such, represent some of today's major challenges, including access to information networks and knowledge, energy efficiency and environmental constraints, privacy, security and health, as well as cooperation with artificial intelligence systems.

Research at the LTCI addresses three transversal themes: **Digital Communications and Electronics** – physical and hardware basis of processing and design/modeling/integration of objects in an information system; **Computer Science and Networks** – infrastructure, systems and digital networks, with a special focus on mathematical modeling, protocols and functions of next generation networks, computing architecture of systems and services, in their algorithmic and software aspects; **Images, Data and Signal Processing** - study and analysis of signals and images in all their forms, study and development of algorithms and statistical processing methods for learning, optimization and data analysis.

This cutting edge research is also carried out in industrial chairs and in several joint laboratories with our partners from academia and/or industry. The laboratory regularly organizes multidisciplinary research seminars on critical embedded systems, data science and artificial intelligence, communication systems and networks and, jointly with the i3 laboratory, on innovation issues and the socio-economic aspects of digital technologies. LTCI researchers also offer their expertise in governmental bodies, regulation authorities and in telecommunications standard-setting organizations.

FR Le **Laboratoire de Traitement et Communication de l'Information** (LTCI) est un laboratoire de recherche de Télécom Paris. Il succède et prolonge, depuis janvier 2017, le travail effectué au sein de l'UMR CNRS du même nom. Créé en 1982, le LTCI est caractérisé par sa couverture large du domaine des sciences et technologies de l'information et de la communication. Le laboratoire est également actif sur des thèmes relevant des sciences de l'ingénierie et des systèmes et des mathématiques appliquées.

Les technologies de l'information et de la communication accentuent chaque jour leur pénétration dans la société dont elles révolutionnent les modes de fonctionnement. Les objets qui en instancient le caractère très multidisciplinaire nécessitent, pour être développés, la compréhension et l'exploitation des phénomènes physiques, le traitement algorithmique des signaux et des données qui les traversent et leur insertion efficiente dans un système d'information global. Objets socio-techniques, ils sont au cœur des grands enjeux contemporains comme l'accès aux réseaux d'information et de connaissance, la maîtrise des énergies et des contraintes environnementales, la sécurité et le respect de la vie privée, la santé et la sécurité sanitaire, ou la coopération avec les systèmes d'intelligence artificielle.

Dans ce contexte, la recherche au LTCI est organisée en trois thématiques transverses : **les Communications numériques et l'Électronique** - assise physique et matérielle des traitements et conception/modélisation/intégration des objets au sein du système d'information -, **l'Informatique et les Réseaux** - infrastructures, systèmes et réseaux numériques, en insistant notamment sur les modélisations mathématiques, sur les fonctions de communication pour les futurs réseaux de toute nature et sur les architectures informatiques des systèmes et des services, dans leurs aspects logiciels -, **le traitement des Images, des Données et du Signal** - étude et analyse des signaux et images sous toutes leurs formes, étude et développement d'algorithmes et méthodes de traitements statistique pour l'apprentissage, l'optimisation et l'analyse de données.

Cette recherche de pointe s'effectue également au sein de plus d'une dizaine de chaires d'enseignement / recherche ou de recherche et de plusieurs laboratoires communs avec d'autres équipes académiques et/ou industrielles. Le laboratoire organise régulièrement des séminaires de recherche pluridisciplinaires, sur les systèmes embarqués critiques, sur les sciences de données et l'intelligence artificielle, sur les systèmes et réseaux de communication ou, en commun avec le laboratoire i3, sur les questions d'innovation et des dimensions socio-économiques des technologies du numérique. L'expertise des chercheurs du LTCI s'exerce aussi auprès des pouvoirs publics, des autorités de régulation et dans les instances d'élaboration des normes et standards de télécommunication.

C2S

Circuits & Communications Systems
Circuits et Systèmes de Communication

Group leader
— Responsable d'équipe

Patricia Desgreys

Keywords
Smart AMS systems, Frugal signal processing, Smart radio, Cyber-physical system interfaces

Mots-clés
Systèmes AMS intelligents, Traitement parcimonieux de signaux, Radio intelligente, Interfaces des systèmes cyberphysiques

EN C2S designs Radio-Frequency communication chips and is specialized in **analog and-mixed-signal** (**AMS**) **interfaces** for 5G and IoT Systems. It concentrates specifically on the critical interface between radio communication and digital processing, combining analog electronics efficiency with digital flexibility in optimal trade-offs.

Its historical expertise in AMS circuit design spans analog-to-digital Converters (ADCs), receivers and samplers. For these sub-systems, C2S have designed solutions to meet the ever-increasing demand for data rate while limiting power consumption. ASICs have been implemented in CMOS technology to demonstrate the efficiency of the solutions. C2S then broadened its theoretical approach with the development of new algorithms and digital processing dedicated to AMS systems performance. The added-value lies in specific pre- and post-processing algorithms dedicated to the linearity improvement of AMS communication interfaces.

The concept towards "smart" AMS Systems has been pushed further recently by developing **compressed sensing** (**CS**) algorithms and **cognitive radio** (**CR**) algorithms, which are useful in drastically reducing the power consumption and increasing CR security.

Historical expertise in AMS circuit design

FR C2S conçoit des puces de communication par radiofréquence et est spécialisé dans les **interfaces AMS** (*Analog-and-Mixed-Signal*) pour les systèmes 5G et l'Internet des objets. C2S s'intéresse spécifiquement à l'interface critique entre les communications radio et le traitement numérique, en combinant par des compromis optimaux l'efficacité énergétique de l'électronique analogique et la flexibilité du numérique.

Son expertise historique dans la conception de circuits AMS couvre les convertisseurs analogique-numérique, les récepteurs et les échantillonneurs. Pour ces sous-systèmes, C2S a conçu des solutions répondant à la demande croissante de débit de données tout en limitant la consommation d'énergie. Les ASIC conçus sont implémentés en technologie CMOS avancée. C2S a ensuite élargi son approche théorique avec le développement de nouveaux algorithmes et de nouveaux traitements numériques dédiés aux performances des systèmes AMS. La valeur ajoutée réside dans des algorithmes spécifiques de pré- et de post-traitement dédiés à l'amélioration de la linéarité de l'interface de communication AMS.

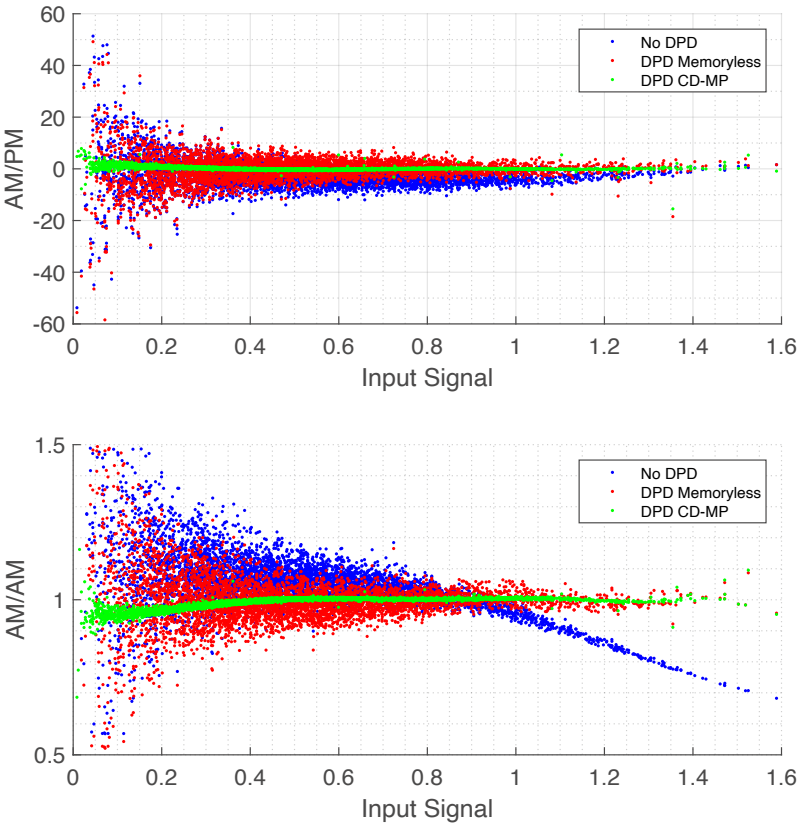
Le concept de systèmes AMS «intelligents» a été poussé récemment plus avant en développant des algorithmes d'**acquisition comprimée** et des algorithmes de **radio cognitive** utiles pour réduire considérablement la consommation d'énergie et augmenter la sécurité de ces communications.

Web
telecom-paris.fr/c2s

See also
▸ Our spinoff SCALINX, p. 78

Mise en œuvre de Composants Montés en Surface CMS

AM/AM and AM/PM of the PA output before and after DPD



Smart chips for Digitally Enhanced Mixed Signal Systems

EN As a result of an international cooperation of experts working together for several years in workshops and conferences, the book **"Digitally Enhanced Mixed Signal Systems"**, dedicated to digital enhancement techniques addressing key challenges relevant to analog, RF and mixed signal components, was published in June 2019. This topic has emerged in the context of steadily shrinking CMOS technology, users' increasing demand for higher flexibility and higher data traffic in communications networks. Organized around nine chapters, the book provides an overview of how to design, size and implement a digital assistance system to compensate for a given non-ideality. All the main steps are covered from the modeling approach to implementation, and the advantages, drawbacks and limits of the methods and models presented are discussed.

▸ **C. Jabbour**, **P. Desgreys** and D. Dallet, "Digitally Enhanced Mixed Signal Systems", IET The Institution of Engineering and Technology, June 2019.

Energy efficient RF communications

EN New modulation techniques introduced in current and future mobile communication standards have the drawbacks of requiring a higher signal-to-noise distortion ratio (SNDR) and increasing the signal-peak-to-average power ratio (PAPR) compared with former modulation schemes. The latter leads to higher non-linear terms which are the main contributors to SNDR degradation on the transmitter side.

The transmitter output is mainly distorted by the power amplifier (PA) non-linearity, operating close to its saturation point for power efficiency. A new behavioral model named **memory aware physically enhanced polynomial** (MAPEP) is proposed. This modeling approach is based on using a physical analysis of how the PA operates and takes into account the electro-thermal and electrical memory effects as the main sources of long-term memory for narrowband and wideband signals, respectively.

▸ E. Soleiman, **D.-K. Pham**, **C. Jabbour**, **P. Desgreys** and M. Kamarei, "Memory Aware Physically Enhanced Polynomial Model for Power Amplifiers", IET Microwaves, Antennas & Propagation, IET Digital Library, Jan. 2019

Permanent members / Membres permanents **4**

Thesis / Thèse soutenue **1** | Patent / Brevet **1** | Publications / Publications **10**

ComNum

Digital Communications
Communications Numériques

Group leader
— Responsable d'équipe

Philippe Ciblat

Better understand and reach the fundamental limits of communication networks

Keywords
Information theory, Network data processing, Channel coding, Distributed optimization, Security, Distributed coding and scheduling for caching

Mots-clés
Théorie de l'information, Traitement de l'information sur réseau, Codage correcteur d'erreur, Optimisation distribuée, Sécurité, Codage distribué et ordonnancement pour le stockage

Web
telecom-paris.fr/comnum

See also
▸ Hadi Ghauch, p. 10

EN Communication networks rely on a range of communication media that can be wireless, wired, optical etc., to transmit, retrieve and process data. Constraints are generally placed on the tasks that need to be carried out. These constraints take into account a number of performance metrics, such as complexity, reliability, energy efficiency, latency and secrecy. Depending on the nature of the network, they can be addressed in a centralized or in a decentralized way.

ComNum research efforts provide a better understanding of the fundamental limits of communication networks and means to reach these limits. Contributions span the areas of **information theory, coding, optimization, and signal processing**. The main results are obtained in the context of multi-user cellular networks (one-to-many or many-to-one communication), wireless ad hoc networks (many-to-many communication), and optical communications (one-to-one communication). For these settings, ComNum has developed insights on fundamental limits and related coding techniques for information transmission and storage over networks, on resource optimization for wireless networks, and on fundamental limits and related estimation techniques for centralized or distributed contexts.

FR Les réseaux de communication impliquent une variété de supports de communication – sans fil, câblés, optiques, etc. – pour transmettre, récupérer et traiter les données. Les tâches à accomplir sont généralement soumises à des contraintes qui prennent en compte un ensemble de métriques de performance, telles que la complexité, la fiabilité, l'efficacité énergétique, la latence et le secret. Selon la nature du réseau, elles peuvent être traitées de manière centralisée ou décentralisée.

Les efforts de recherche de ComNum permettent de mieux comprendre les limites fondamentales des réseaux de communication et les moyens d'atteindre ces limites. Les contributions couvrent les **domaines de la théorie de l'information, du codage, de l'optimisation et du traitement du signal.** Les principaux résultats sont obtenus dans le cadre des réseaux cellulaires multi-utilisateurs (1-N ou N-1), des réseaux ad hoc sans fil (N-N) et des communications optiques (1-1). ComNum a développé des compétences et des savoirs sur les limites fondamentales et sur les techniques de codage associées concernant la transmission et le stockage d'informations sur les réseaux, sur l'optimisation des ressources pour les réseaux sans fil, et sur les limites fondamentales et les techniques d'estimation associées pour les contextes centralisés ou distribués.

Permanent members Membres permanents	6	Thesis Thèses soutenues	5
Patents Brevets	21	Publications Publications	37

Age of Information aware cache updating

EN Prestoring popular contents in cache memories close to end users has become a popular tool to reduce congestion and latency in communication networks. For those files that are both time-varying and time-sensitive, regular updates are required. The size of an update thereby may depend on the file's **Age of Information** (AoI)—the original size of the file and the time elapsed since the latest version in the cache was created.

In [1], an **update policy** is designed that minimizes the average AoI over files with respect to a given popularity distribution. Actually a relaxed problem, close to the original optimization problem, is solved and a practical update policy is derived. The update policy is based on **file popularity** and the functions that characterize the **update durations** of the files depending on their AoI. Numerical simulations show a significant improvement of this new update policy compared to the square-root policy that is optimal under file-independent and constant update durations as found in the seeding paper [2].

▸ [1] H. Tang, **P. Ciblat**, J. Wang, **M. Wigger** and R. Yates, "Age of Information Aware Cache Updating with File- and Age-Dependent Update Durations", 2020 18th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOPT), Volos, Greece, 2020, pp. 1-6.

▸ [2] R. D. Yates, **P. Ciblat**, A. Yener, and **M. Wigger**, "Age-optimal constrained cache updating", in 2017 IEEE International Symposium on Information Theory (ISIT), June 2017, pp. 141–145.

Research in education

EN **Research in teaching** has still got much to offer **the teaching of mathematics**, say Olivier Rioul, a lecturer researcher in ComNum, and invited professor, Karim Zayana, an inspector for education, sport and research. Whereas teaching aims to acquire, then pass on knowledge developed over decades, research takes the opposite route as it broadens and extends the scope of discovery. This duality produces a promising and stimulating hybrid system which the two researchers are exploring, against the context of educational science being recognized in the Shanghai ranking.

In [3], they revisit the set of real numbers, turning their back on more traditional approaches. In [4], they review the more functional and "odd(s)" version of Bayes' rule, taught in English-speaking countries, applied to medical screening and anti-spam filters.

▸ [3] K. Zayana, **O. Rioul**. Imagine $\mathbb{R}$, Bulletin de l'Union des Professeurs de classes préparatoires Scientifiques n°267, Septembre 2019, pp. 30-47

▸ [4] K. Zayana, **O. Rioul**. Les probabilités ont la cote. Juin 2020 https://culturemath.ens.fr/thematiques/concours-d-enseignement/les-probabilites-ont-la-cote

GTO

Optical Telecommunications
Télécommunications Optiques

Group leader
— Responsable d'équipe

Yves Jaouën

From theory to practice

EN GTO conducts advanced research in high-rate fiber-optic transmission, optical network architectures, advanced lasers for communications, integrated photonics and distributed optical fiber sensors. In a context where optical communications and processing rely increasingly on digital technologies, GTO works closely with ComNum (see previous pages), as well as with world-renown international research groups in photonics and communications, placing the group in a strong position in multidisciplinary research.

Experimental demonstration of novel **concepts in optical communication** is of strategic importance. Thanks to a state-of-the-art experimental test bed (see opposite), GTO have performed high-speed transmission experiments using sophisticated digital signal processors and advanced mathematical algorithms for the compensation of channel impairments.

GTO is particularly active in the following areas: high-rate communications in short-reach and long-haul transmission systems; optical networks architecture and cross-layer optimization; performance improvement in optical devices and systems for context-driven applications; quantum optics, non-linear photonics and laser dynamics.

FR Les recherches menées par GTO couvrent la transmission à haut débit par fibre optique, les architectures de réseaux optiques, les nouvelles solutions lasers semiconducteurs et les dispositifs en optique intégrée pour les communications et les capteurs à fibre optique distribués. Dans un contexte où les communications optiques intègrent de plus en plus du traitement numérique des signaux, GTO collabore étroitement avec ComNum (voir pages précédentes), ainsi qu'avec des groupes de recherche de renommée mondiale en photonique et en communications, ce qui lui confère une position forte dans une recherche interdisciplinaire.

Faire la démonstration expérimentale de **nouveaux concepts de communication optique** est d'une importance stratégique. Grâce à une plateforme de test (voir page ci-contre), GTO réalise des expériences de transmission à grande vitesse en utilisant des processeurs de signaux numériques sophistiqués et des algorithmes mathématiques avancés pour la compensation des phénomènes physiques liés à la propagation des canaux.

GTO est ainsi particulièrement actif dans les domaines suivants : communications à haut débit dans les systèmes de transmission à courte et longue distance ; architecture des réseaux optiques et optimisation *cross-layer* ; amélioration des performances des dispositifs et systèmes optiques pour les applications appropriées aux contextes ; optique quantique, photonique non linéaire et dynamique des lasers.

Keywords
Optical fiber communication, Optical networks, Nonlinear effects in optical fibers, Nonlinear Fourier transform, Advanced photonics components, Optoelectronics, Semiconductor laser dynamics, Optical fiber sensors

Mots-clés
Systèmes de communication optiques sur fibre, Réseaux optiques, Effets non-linéaires dans les fibres optiques, Transformée de Fourier non linéaire, Composants optiques innovants, Optoélectronique, Dynamiques des lasers à semi-conducteur, Capteurs à fibres optiques

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See also
▸ Frédéric Grillot and Jianan Duan, p. 14
▸ Mansoor Yousefi ERC Starting Grant, p. 6

High-rate fiber-optic transmission platform

EN GTO and ComNum operate an experimental platform for the study and validation of hardware and/or algorithmic solutions. The setup enables new high-rate fiber-optic systems to be studied, using coherent optical reception combined with sophisticated electronic and digital signal processing methods. It is being adapted to accommodate the increase in fiber-optic transmission rates (Nyquist-WDM format up to 32 Gbaud).

This platform, which was used in collaboration with corporate and academic partners, led to the breakthroughs shown here. In 2018-20, it also served to carry out experiments on the use of machine learning techniques to mitigate non-linear effects (ITN FONTE and REAL-NET European projects).

Equipment

- Keysight DSOZ504A oscilloscope (80 GSa/s, 33 GHz, 4 channels)
- Arbitrary waveform generator (AWG): Keysight M8195A (64GSa/s, 25 GHz)
- APEX P2050A ultra high resolution optical spectrum analyzer
- 4*100km recirculating loop
- Yenista XTA-50 (4 - 625 GHz) tunable optical filter with slopes up to 800 dB/nm
- Ultra high spectral purity lasers (1 KHz)
- Various tunable laser sources with high spectral purity (< 100 KHz)

Nonlinear Fourier Transform Achievements

EN It is of first importance to combat fiber non-linearities on long haul optical communication systems and recent mitigation techniques such as nonlinear frequency-division multiplexing (NFDM), with information encoded via Nonlinear Fourier Transform (NFT), are being studied. Following a previous demonstration where GTO demonstrated dual-polarization NFDM using the continuous spectrum in 1680 km of normal dispersion fiber [1], we designed a two-dimensional signal constellation based on the exact inverse **periodic nonlinear Fourier transform** (PNFT). The feasibility of continuous transmission with periodic signals was experimentally demonstrated over more than 2,000 km [2].

Work has been carried out as part of cooperation with [1] Brescia University (Italy) and [1], [2], [3] Huawei France.

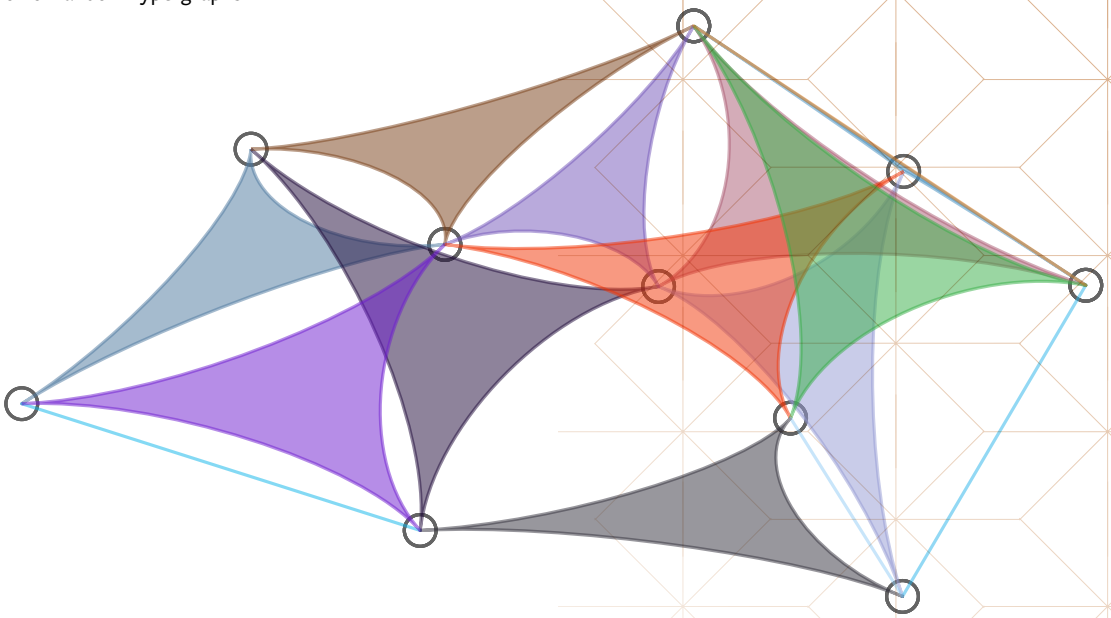
Permanent members Membres permanents	**8**
Thesis Thèses soutenues	**8**
Patents Brevets	**10**
Publications Publications	**43**

2018
First dual-polarization NFDM transmission

2019
First PNFT transmission

- [1] W. A. Gemechu, T. Gui, **J. W. Goossens**, **M. Song**, S. Wabnitz, H. Hafermann, A. Pak Tao Lau, **M. I. Yousefi**, and **Y. Jaouën**. "Dual Polarization Nonlinear Frequency Division Multiplexing Transmission". IEEE Photonics Technology Letters, Vol. 30, No. 18, September 15, 2018
- [2] **J. W. Goossens**, **Y. Jaouën** and H. Hafermann. "Experimental Demonstration of Data Transmission Based on the Exact Inverse Periodic Nonlinear Fourier Transform". OFC 2019. Paper M1I.6, March 2019
- [3] **J. W. Goossens**, H. Hafermann and **Y. Jaouën**. "Experimental realization of Fermi-Pasta-Ulam-Tsingou recurrence in a long-haul optical fiber transmission system". Nature. Scientific Reports Sci Rep, 9, 18467, December 2019

Laurent Decreusefond (RMS),
Representation of random hypergraphs



Mathematics, from chalkboard to applications

EN The Mathematical Modeling theme, which cuts across all other research areas and calls for multidisciplinary cooperation, represents one of the key strengths of Télécom Paris research. It focuses on both the theoretical and practical aspects of the Information and Communication Science and Technology field, with modeling methods and tools applied to three sets of objects: content, data, knowledge and interactions; networks and systems; information and its ecosystems.

From fundamental mathematics (algebraic geometry, number theory, combinatorics...), applied mathematics (graph theory, optimization, probabilities, statistics, mathematics of imaging...) to areas at the frontier between mathematics and computer science (automata, coding theory, cryptography, computational complexity, logics...) but still with a predominantly mathematical perspective, the spectrum of research work is broad and applications are varied. Indeed, researchers are as likely to work on modeling communication systems, sensor networks, visual signals (image, video, 3D) or interactions between electromagnetic waves and the human body, as they are to work on modeling emotions or social phenomena.
Moreover, all these advanced mathematical models are developed at Télécom Paris to represent the complex reality of the world in an effective way, to reduce this complexity to something that can be traced, and to make the best use of it. Emphasis is given to understanding and facilitating simplification, representation, visualization and mediation between people and devices. This can include the modeling of distributed systems, interactions between humans, agents and computers, probabilistic modeling, logically structured modeling of knowledge, geometric or topological modeling of complex objects. Mathematical modeling is also an intrinsic part of the Data Science and Artificial Intelligence focus area (see page 62), covering aspects such as statistics, variational approaches, machine learning, algebraic and symbolic artificial intelligence approaches, and sparse, adaptive representations of information.

There are two main challenges: finding the right compromise between remaining faithful to reality and the effectiveness of the model – usability, computability, suitability for needs – and the ability to address problems with a high level of complexity, involving heterogeneous data, which may be massive or have gaps, involve poorly understood uncertainties, explosive computing or complex reasoning.

As an example, the global climate challenge in the years to come combines all these considerations. The use of mathematical modeling, neural network algorithms and its internal data representations can be used, among other tools, to model, visualize and better understand and explain fluid dynamics. Télécom Paris is dedicated to this overall challenge through its participation in the Energy4Climate (E4C) Interdisciplinary Center at the Institut Polytechnique de Paris.

Representing the complex reality of the world in an effective way

EN LTCI is an active member of the LMH (Labex Mathématique Hadamard), a Laboratory of Excellence which covers the full spectrum of research in mathematics, from pure and fundamental studies to applied mathematics. A small proportion of LTCI PhD students are registered in the associated doctoral school "Mathematics-Hadamard" of Université Paris-Saclay.

Background picture from the work of Kiwon Um (IMAGES) on physics-based simulations and data-driven approaches with deep learning.

Getting young people interested in mathematical research

EN For the past few years, faculty members have been contributing to the work of Math en Jeans (www.mathenjeans.fr), which organizes maths workshops for middle and high school students who then present their work at an annual conference. The conference, which included presentations from our faculty members, took place at Télécom Paris in 2016 and 2017.

LabSoC

System on Chip

Group leader
— Responsable d'équipe

Ludovic Apvrille

EN LabSoC research activities focus on the **design**, **modeling** and **validation** and also analyzes and proposes **new architectures for embedded systems**. The main objective is to develop models and methods to—better—formally verify and—automatically—program safe and secure embedded systems.

More precisely, LabSoC focuses on several research topics. Firstly, new methods, techniques, languages and tools for complex integrated and embedded systems are developed. This includes abstraction, formal methods, very fast simulation, design space exploration, handling of both safety and security aspects, and code generation from abstract models. Secondly, work is conducted on hardware security, and paranoid Systems on Chip with zero trust in their hardware and software environment. Emphasis is also placed on the confidentiality and the integrity of external communications and storage.

A last research topic concerns the digital signal processors for the software-defined radio. This includes the study of the trade-off between flexibility and energy efficiency, the associated software design environments, the abstract modeling of waveforms and hardware architecture, and the automatic generation of control software.

LabSoC contributions, based on **five platforms** (TTool, Alligator, Embb, SecBus, Rover) have first been defined internally before being applied in academic, collaborative projects (FUI Netcom, H2020 AQUAS) and industrial collaborations (Freescale, VEDECOM, Nokia, Engie). LabSoC is hosted by EURECOM at Sophia-Antipolis.

Definition of methods, techniques, languages and tools for complex integrated and embedded systems

Keywords
Architecture exploration, Formal validation, Model engineering, Safety, Security and performance, Security of electronic circuits, Software/hardware architecture for signal processing applications

Mots-clés
Exploration d'architecture, Vérification formelle, Ingénierie des modèles, Sûreté de fonctionnement, Sécurité des systèmes informatiques, Sécurité des circuits électronique, Architecture logicielle / matérielle pour les applications de traitement du signal

Web
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See also

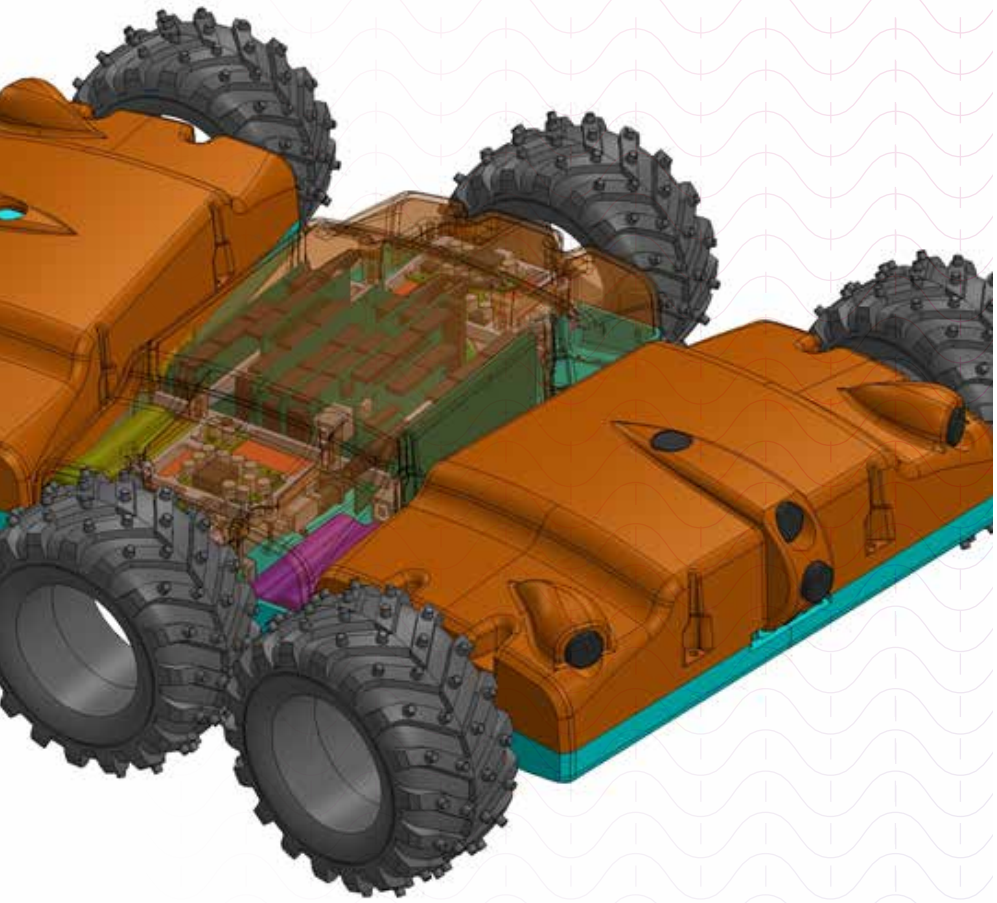
▸ Connected Cars and Cyber Security (C3S) Chair, p. 35
▸ POM joint lab, p. 79

FR Les activités de recherche du LabSoC portent sur la **conception**, la **modélisation** et la **validation,** ainsi que sur l'analyse et la proposition de **nouvelles architectures pour les systèmes embarqués**. L'objectif principal est de développer des modèles et des méthodes pour mieux vérifier formellement et programmer automatiquement des systèmes embarqués sûrs et sécurisés.

Plus précisément, le LabSoC se concentre sur plusieurs thèmes de recherche. Tout d'abord, de nouvelles méthodes, techniques, langages et outils pour les systèmes intégrés et embarqués complexes sont développés. Ceci inclut l'abstraction, les méthodes formelles, la simulation très rapide, l'exploration de l'espace de conception, la gestion des aspects de sûreté et de sécurité et la génération de code à partir de modèles abstraits. Ensuite, des travaux sont menés sur la sécurité matérielle et les systèmes paranoïaques sur puce avec une confiance nulle dans leur environnement matériel et logiciel. L'accent est également mis sur la confidentialité et l'intégrité des communications externes et du stockage.

Un dernier sujet de recherche concerne les processeurs de signaux numériques pour la radio logicielle. Il comprend l'étude du compromis entre flexibilité et efficacité énergétique, les environnements de conception logicielle associés, la modélisation abstraite des formes d'onde et de l'architecture matérielle, et la génération automatique de logiciels de contrôle.

Les contributions, basées sur **cinq plateformes** (TTool, Alligator, Embb, SecBus, Rover) ont d'abord été définies en interne avant d'être appliquées dans le cadre de projets universitaires, collaboratifs (FUI Netcom, H2020 AQUAS) et industriels (Freescale, VEDECOM, Nokia, Engie). Le LabSoC est hébergé par EURECOM à Sophia-Antipolis.



Tools for safe & secure modeling and verification

EN LabSoC has developed a Model Driven Approach, called SysML-Sec, that considers security, safety and performance from the very first methodological stages. The SysML-Sec environment enhances the OMG SysML language with views in which security is explicit: the notion of security requirements, the addition of formal attack trees, the possibility to perform security-aware hardware/software partitioning and the design of security mechanisms and protocols. Evaluated for different systems ranging from small devices to larger systems—industrial systems, automotive systems, Public Safety Networks—, it represents one of the assets of the Connected Cars and Cyber Security (C3S) Chair.

SysML-Sec modeling aspects are totally supported by the free and multi-OS open-source toolkit named TTool, mostly developed by LabSoC's research. TTool is a toolkit dedicated to the edition of UML and SysML diagrams, and to the simulation and formal verification (safety, security, performance) of those diagrams, performing these simulations and mathematical proofs directly from the models. Along with the SysML-Sec environment, it also provides profiles for partitioning embedded systems and for designing embedded software.

Several academic and industrial partners use TTool. For instance, TTool serves as the main tool in a collaboration between Nokia Bell Labs and LabSoC. The collaboration explores how high-level models can be used to efficiently (re) program 5G communication equipment.

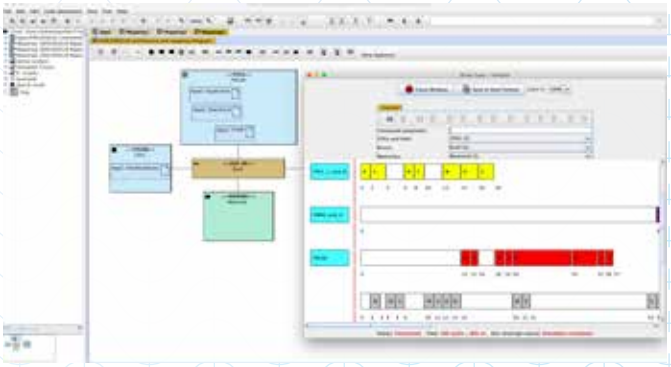
▸ sysml-sec.telecom-paris.fr ▸ ttool.telecom-paris.fr

Performance of an embedded system with security constraints

EN As embedded systems are now frequently connected, security must be taken into consideration during system modeling. However, adding security features as an afterthought can degrade performance. In [1], the trade-off between security and performance is tackled with a new model-based method that can automatically assess the impact of security measures on performance. As security considerations and system modeling are interlinked, designing these systems with a comprehensive model-driven design process, from requirement elicitation to iterative design, can help detect issues or incongruities within the requirements. Article [2] discusses how safety, security, and performance requirements should be assured with a systematic design process, and how these properties can support each other or enter into conflict with one another, as detected during the verification process.

▸ [1] **M. Zoor**, **L. Apvrille**, and **R. Pacalet**. (2020). "Impact of Security Measures on Performance Aspects in SysML Models." In Proceedings of the 8th International Conference on Model-Driven Engineering and Software Development - Volume 1: MODELSWARD, ISBN 978-989-758-400-8, ISSN 2184-4348, p.373-380.

▸ [2] **L. Apvrille**, L. W. Li, "Harmonizing Safety, Security and Performance Requirements in Embedded Systems." Proceedings of the Design Automation and Test in Europe conference (DATE), March 25-29, 2019, Firenze, Italy.



Permanent members
Membres permanents **5**

Publications
Publications **25**

RFM²

Radio Frequency, Microwaves & Millimeter waves
Radio-Fréquences, Micro-ondes et ondes Millimétriques

Group leader
— Responsable d'équipe

Jean-Christophe Cousin

Keywords
Theory and modeling of RF systems, Antenna and RF circuit design, RF instrumentation, Metamaterials and Metasurfaces

Mots-clés
Théorie et modélisation des phénomènes et des systèmes RF, Conception des antennes et des circuits RF, Instrumentation RF, Metamatériaux et Metasurfaces

Web
telecom-paris.fr/rfm2

See also
▸ C2M Chair, p. 35

EN RFM² conducts research to connect humans or machines with wireless systems, whether mobile or embedded, with sensing mechanism to adapt to their environment applications. It addresses long term needs such as wireless communications independent from short term technical inflation and hype, national security and public health. It concentrates expertise on radio front ends with complementary skills that cover circuits and antenna designs, MMIC and antenna characterization, wave propagation and wave human interactions model up to 110 GHz.

Research is organized along three main axes: **energy-efficient RF front-end systems, smart and small antenna design as well as metamaterials and metasurfaces design, radio channel modeling and localization**. This covers the design of components and subsystems for radio links involved in 5G, IoT, satellites, localization, reliable and secured massive communications. The performance of these components and systems is evidenced by the innovative characterization methods in microwaves and millimeter wave domains. RFM² also aims to provide optimal connectivity with respect to cost, energy efficiency, performance and flexibility, in any environment.

Work also focuses on the major challenge of reducing exposure to below the legal limits. One of the RFM² strengths is to formalize both the behavior of components and subsystems and to determine the interaction between waves and humans. In this respect, RFM² is a co-founder of the internationally recognized C2M Chair (Characterization, Modeling and Control of Exposures), a multidisciplinary research framework that is both technological—numerical computation, statistics, antennae, network architecture—sociological and philosophical. This contributes to the characterization, the analysis and the model of exposure to electromagnetic waves induced by telecommunication systems and networks, as well as the study of how the risk linked to this exposure is perceived.

Addressing long term needs such as wireless communications independent from short term technical inflation and hype

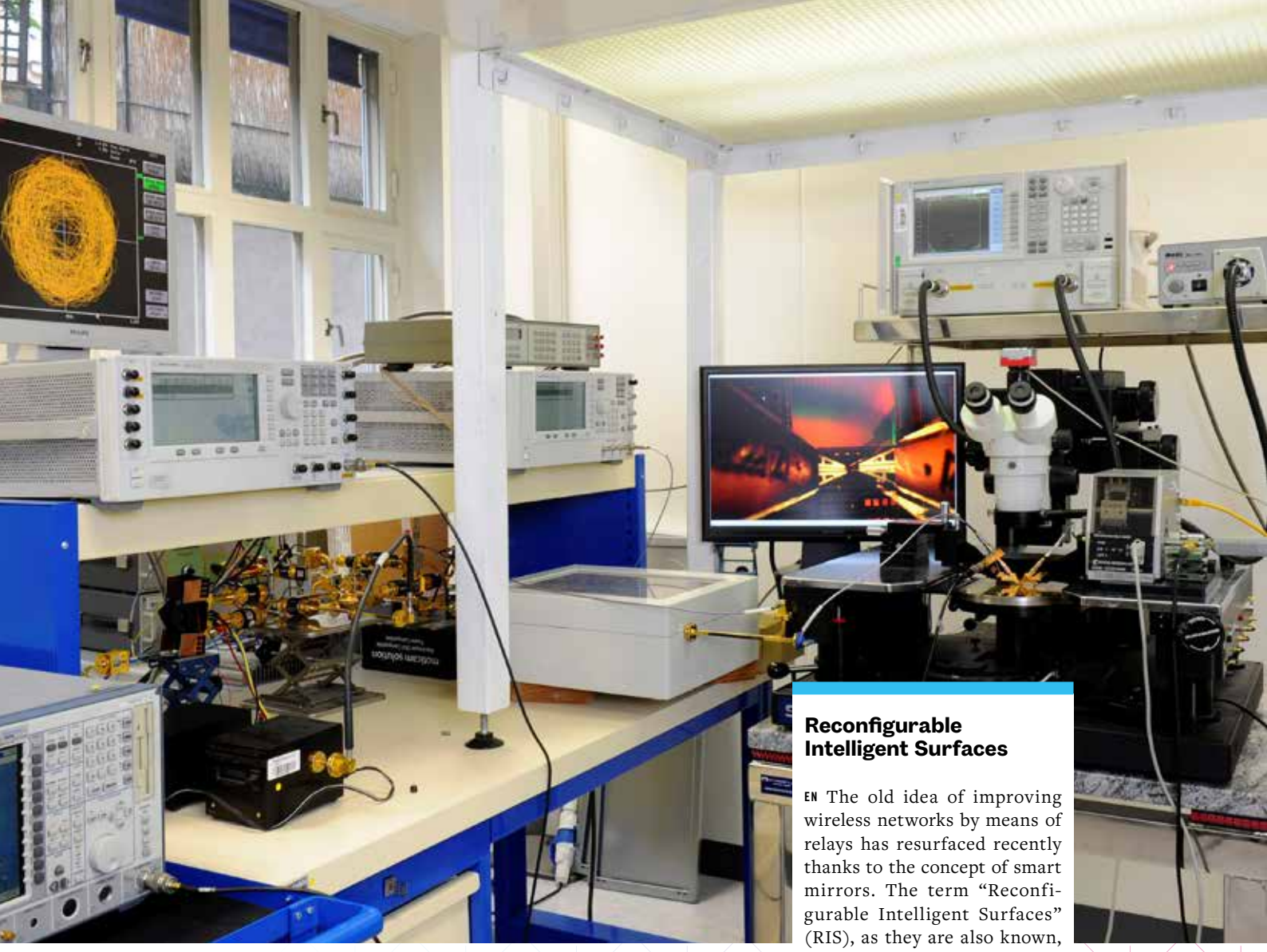
FR RFM² mène des recherches visant à connecter des humains ou des machines à des systèmes sans fil, mobiles ou embarqués, disposant de mécanismes de détection leur permettant de s'adapter à leur environnement. Les travaux sont conduits dans une perspective à long terme, permettant des communications sans fil indépendantes de l'inflation technique et de la frénésie à court terme, ou relevant de la sécurité nationale ou de la santé publique. Son expertise réside sur les frontaux radio, avec des compétences complémentaires couvrant les circuits et la conception d'antennes, la caractérisation des circuits MMIC et des antennes, la propagation des ondes et le modèle d'interaction humaine des ondes jusqu'à 110 GHz.

Les recherches sont organisées selon trois axes principaux : **systèmes frontaux RF à faible consommation d'énergie, conception d'antennes intelligentes et de petite taille ainsi que de métamatériaux et métasurfaces, modélisation de canaux radio et localisation**. Ceci couvre la conception de composants et de sous-systèmes pour les liaisons radio satellites, la 5G, l'Internet des objets, la localisation et les communications massives fiables et sécurisées. Les performances de ces composants et systèmes sont mises en évidence par des méthodes de caractérisation innovantes dans les domaines des micro-ondes et des ondes millimétriques. RFM² vise également à fournir une connectivité optimale en termes de coût, d'efficacité énergétique, de performance et de flexibilité dans tout type d'environnement.

Les travaux se concentrent également sur l'enjeu majeur que représente la réduction de l'exposition aux ondes en deçà des limites légales. Une des compétences de RFM² est de savoir formaliser à la fois le comportement des composants et des sous-systèmes et de déterminer l'interaction entre les ondes et les humains. À cet égard, RFM² est co-fondateur de la Chaire internationalement reconnue C2M (Caractérisation, Modélisation et Contrôle des Expositions) qui fournit un cadre de recherche multidisciplinaire à la fois technologique – calcul numérique, statistiques, antennes, architecture de réseau –, sociologique et philosophique. Les contributions y sont la caractérisation, l'analyse et la modélisation des expositions aux ondes électromagnétiques induites par les systèmes et réseaux de télécommunication, ainsi que l'étude de la perception du risque lié à cette exposition.

▸ chairec2m.wp.imt.fr

Permanent members
Membres permanents **6**



Millimeter waves source-pull/load-pull measurement platform

Source-pull/load-pull measurement platform for the characterization of millimeter-wave devices

EN RFM² operates a characterization platform, initially developed for the 1-18GHz frequency band, extended to the 40-60 GHz band (5G backhaul networks) for millimeter waves. The power amplifier is the most difficult element to design in a transmission chain, requiring trade-offs between power, efficiency, non-linearity and energy consumption. The platform makes precise measurements of these parameters depending on the source-pull / load-pull of the device being tested under real operational conditions, in other words, with complex modulated signals. This type of measurement is crucial, because the behavior of active elements strongly depends on the shape of excitation signals (LF memory effects such as trapping phenomena and thermal effects). RFM² has also developed pre-distortion methods associated with characterization benches. The aim is to compensate upstream the distortions naturally created by these components. The platform is for manufacturers, foundries, circuit designers and designers of non-linear models used in CAD. It applies equally to the design of MMICs, the optimization of technological processes and performance measurement in the field of semi-conductors (GaN, AsGa and other transistors around 40 GHz). It can also check and improve the non-linear electrical models used in PCB CAD libraries.

This plateforme allows to characterize devices in the presence of complex modulated signals with a symbol rate higher than 500 MS/s between 40 and 50 GHz.

Thesis
Thèses soutenues
4

Publications
Publications
22

Reconfigurable Intelligent Surfaces

EN The old idea of improving wireless networks by means of relays has resurfaced recently thanks to the concept of smart mirrors. The term "Reconfigurable Intelligent Surfaces" (RIS), as they are also known, describes the arrangement of a massive amount of inexpensive antenna elements with the objective of capturing and scattering energy in a controllable manner. In the following paper, an impedance controlled RIS is investigated with energy efficiency considerations in mind. A complete signal characterization for a wireless link in the presence of RIS for near-field and far-field region of operation is presented. This work offers a view that unifies the previous seemingly opposite scattering/reflection dual perspectives as a means to identify scenarios and show the strong potential behind the RIS concept. In particular, it clarifies how surface area and distance aspects strongly impact the performance of such devices.

▸ J. C. B. Garcia, **A. Sibille** and M. Kamoun, "Reconfigurable Intelligent Surfaces: Bridging the gap between scattering and reflection", in IEEE Journal on Selected Areas in Communications, doi: 10.1109/JSAC.2020.3007037.

Trustworthy digital technologies

Technologies provide trust when they satisfy both safety and security requirements. They also inspire trust when they are developed responsibly.

EN Trust in the digital era is a research theme that cuts across all levels of hierarchy in digital systems, from hardware to applications, including mathematical tools, software layers, systems, networks and societal issues. Trust has two meanings: the trust that technologies provide when they satisfy both safety and security requirements and the trust that we place in them when they are developed responsibly. Télécom Paris has adopted the approach that consists in developing the tools and methods that ensure a high level of trust and optimal trade-offs given the constraints. Work carried out on transversal projects leads to many partnerships.

The Modeling, Characterization and Control of Electromagnetic Wave Exposure (C2M) Chair, set up at Télécom Paris, is supported by the Agence Nationale des Fréquences (National Frequency Agency). The Chair has been bringing Télécom Paris and IMT Atlantique researchers together since 2015. Its field of expertise is particularly relevant today, with 5G deployment the object of public debate.

Web
chairec2m.wp.imt.fr/

▸ E. Chiaramello, S. Fiocchi, M. Parazzini, P. Ravazzani, **Joe Wiart**. "Stochastic Dosimetry for Radio-Frequency Exposure Assessment in Realistic Scenarios". In Uncertainty Modeling for Engineering Applications. PoliTO Springer Series. Springer, Cham, pp. 89-102, In press

EN Research is also carried with industry players in joint laboratories. The IDentity & Security Alliance with Idemia, on identity protection and data security, should be mentioned here, as should SEIDO (see p. 79) with EDF R&D, on the Internet of Things and the cybersecurity of electrical systems. Blockchain Advanced Research and Technologies (BART) is a joint research initiative on a key technology for trust in the digital era and constitutes a major academic research collective in France (see p. 79).

The work of the Digital Finance Chair, created in 2019, is characteristic of a topic that involves a range of cutting edge and emerging technologies. Its research focus is on innovations, services, products and organizations that are liable to change the practices of financial intermediaries, banks and insurance companies. Research projects address for instance the benefits of predictive analysis, artificial intelligence, cryptocurrency and digital currency.

Web
digit-finance.com

See also
▸ Operational AI Ethics (on p. 62), a multidisciplinary project which is structured around five research themes: Bias and fairness, Explainability, Responsibility, Governance and regulation, AI and public benefit.

EN The **Connected Cars & Cybersecurity (C3S) Chair** was created together with Nokia, Renault, Thales, Valeo and Wavestone. Since 2017, it has been tackling the technical, social, ethical, economic and legal challenges associated with connected and autonomous vehicles. The Chair is led by Houda Labiod (CCN), an expert in the field of cybersecurity for cooperative intelligent transportation systems, and Guillaume Duc (SSH), a specialist in the safety of embedded systems.

Web
chairec3s.wp.imt.fr

EN Valérie Fernandez (ECOGE), a specialist in the economics of digital innovation, and Lara Daetta (INTERACT), a sociologist specialized in the environment and in sustainable development, lead the Responsibility for Digital Identity Chair. Since 2013, the **Values and Policies of Personal Information Chair** has worked on data, identity and trust in the digital era. The chair is led by Claire Levallois-Barth (ECOGE) and brings together a multidisciplinary team covering legal, technical, economic and philosophical aspects. In October 2019, the chair published a second joint survey with Médiamétrie on *"Données personnelles et confiance : évolution des perceptions et usages post-RGPD"* (Personal Data and Trust: Changes in Perception and Usage post-GDPR).

Web
cvpip.wp.imt.fr

SSH

Secure and Safe Hardware

From mathematics to technology

Group leader
— Responsable d'équipe

Jean-Luc Danger

Keywords
Hardware security of embedded systems against physical and cyber attacks, Hardware reliability of embedded systems, Architecture and design methods for embedded systems

Mots-clés
Sécurité matérielle des systèmes embarqués contre les attaques physiques et cyber, Fiabilité matérielle des systèmes embarqués, Architectures et méthodes de conception de systèmes embarqués

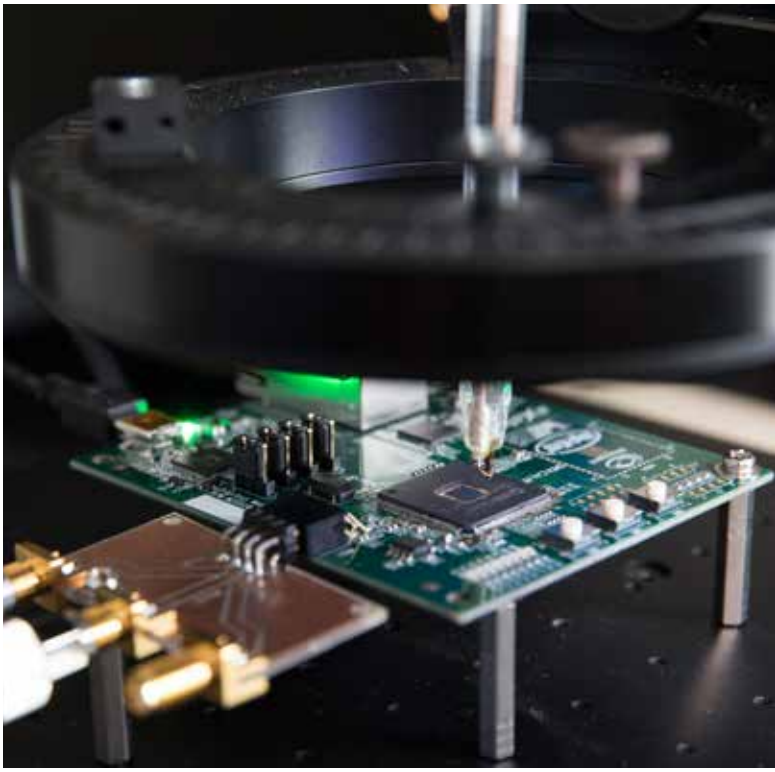
Web
telecom-paris.fr/ssh

See also
▸ C3S Chair, p. 35

EN SSH conducts research on architectures and methods to **design efficient embedded systems and digital electronic circuits** to meet the requirements emerging from the IoT, 5G, autonomous car, smart building, etc. In addition to traditional properties of complexity, energy efficiency, operational speed, low cost and flexibility, SSH concentrates on **Security** and **Safety** constraints—cyber and physical attacks, failures—to propose robust architectures—processors, cryptoprocessors, accelerators, randomness generation—and analysis tools. These properties are becoming vital to tackle the numerous threats linked to the rising number of applications requiring a high level of trust and autonomy in hostile environments.

The study of architecture is particularly helpful when it is associated with solid validation methods. This is why many studies are related to the security/safety analysis which can take many forms: abstract (formal), machine learning, simulation and real circuit such as FPGAs and custom ASICs fabricated using CMOS technologies.

The research of SSH lies at the crossroads of industrial requirements—future technologies but also significant improvement of existing products—and new digital technologies—STT RAM, FD-SOI—with strong international collaborations. SSH scientific output consists in publications and patents, some of which can be directly applied in industry. This is the case with autonomous cars, for instance, through the C3S «Connected Cars & Cybersecurity» Chair.



FR SSH mène des recherches sur les architectures et les méthodes permettant de **concevoir des systèmes embarqués et des circuits électroniques numériques efficaces** pour répondre aux exigences de l'Internet des objets, de la 5G, de la voiture autonome, du bâtiment intelligent, etc. En plus des propriétés traditionnelles de complexité, d'efficacité énergétique, de vitesse opérationnelle, de faible coût et de flexibilité, SSH se concentre sur les contraintes de **sécurité** et de **sûreté** – cyber menaces et attaques physiques, défaillances – pour proposer des architectures robustes – processeurs, cryptoprocesseurs, accélérateurs, génération d'aléas – et des outils d'analyse. Ces propriétés deviennent vitales pour faire face aux nombreuses menaces liées au nombre croissant d'applications nécessitant un haut niveau de confiance et d'autonomie dans des environnements hostiles.

L'étude des architectures prend tout son sens quand elle est associée à des méthodes de validation solides et de sûreté. Les travaux liés à l'analyse de sécurité et sûreté prennent de nombreuses formes : abstraite, avec apprentissage machine, par simulation et sur circuit réel comme les FPGA et les ASIC personnalisés fabriqués en technologies CMOS.

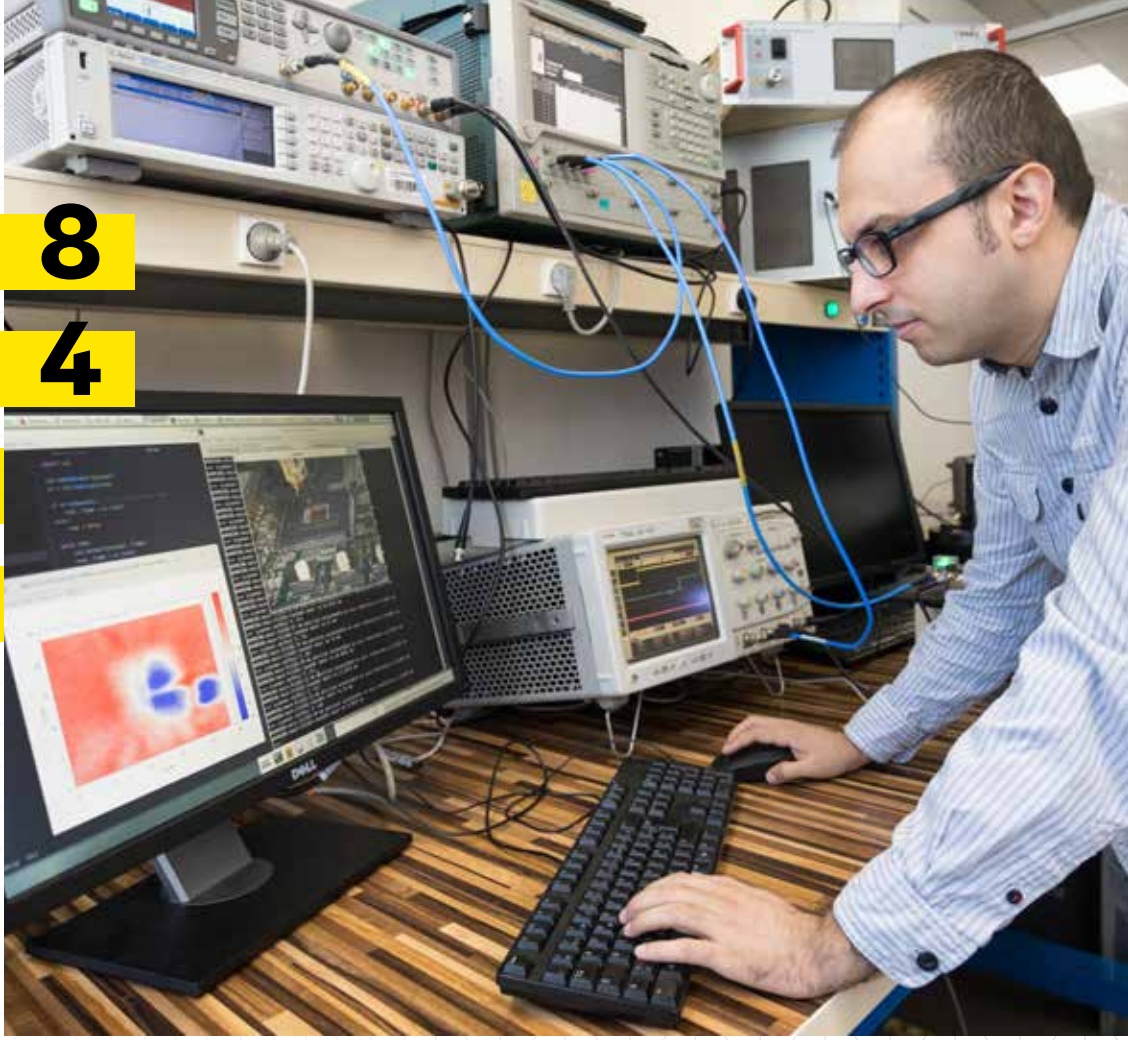
La recherche de SSH se situe au carrefour des exigences industrielles – tant les technologies futures que l'amélioration significative des produits existants – et des nouvelles technologies numériques – STT RAM, FD-SOI – avec de fortes collaborations avec les communautés internationales. La production scientifique comprend des publications et des brevets qui peuvent être directement appliqués par l'industrie comme pour le véhicule autonome par le biais de la chaire C3S (Cyber sécurité du véhicule connecté).

Permanent members
Membres permanents **8**

Thesis
Thèses soutenues **4**

Patents
Brevets **4**

Publications
Publications **28**



Theoretical studies about safety in STT-MRAM

EN In the safety domain, theoretical work is being conducted to take advantage of new technologies and to allow more efficient signal processing.

With CMOS downscaling, spin-based devices represent a promising approach to reduce leakage of power and to increase energy efficiency. Several projects on Magnetic Tunnel Junction (MTJ) based circuits, such as a comprehensive survey of MTJ applications, and investigations about transient disturbances such as the Single Event Transient (SET) over MTJ-based memories—on a 28nm FDSOI NAND-SPIN and on a VCMA-MTJ-based MeRAM in 28nm FDSOI CMOS—have been carried out. Article [1] shows that the NAND-SPIN cell is vulnerable to SET during its write steps, and some hardening strategies in order to improve the write operation robustness are proposed.

Security against physical attacks

EN In the security domain, work on side-channel analysis and fault injection attacks, two typical threats to cryptographic implementations in modern embedded devices, is being conducted. The figure to the left shows how to attack a circuit with an electromagnetic probe located on top of the targeted chip.

Analysis

As IoT devices are increasingly dealing with sensitive data, they depend on the reliability of cryptographic libraries to protect user information. However, when implemented in real systems, cryptographic algorithms are vulnerable to side channel attacks based on their execution behavior, which can be revealed by the measurements of physical quantities such as timing or power consumption. Countermeasures are generally designed at high level description, and when implemented, some residual leakage may persist. Article [2] discusses a methodology to assess the robustness of the MbedTLS library against timing and cache-timing attacks. This comprehensive study of side-channel security identifies the most frequent weaknesses in software cryptographic code and gives hints on how those might be fixed. This work has been conducted in cooperation with Secure-IC, a Télécom Paris spinoff specialized in security expertise, solutions, and hardware & software technologies, for embedded systems and connected objects.

Protection

Masking is a kind of provable countermeasure against side-channel attacks. Inner Product Masking (IPM) is seen as a promising higher-order masking scheme against side-channel analysis, but not yet suitable against fault injection attacks. Article [3] presents a novel masking scheme, IPM-FD built on IPM, which enables fault detection. It has the following properties: the security orders in the word-level probing model, bit-level probing model, and the number of detected faults. It is proven secure both in the word-level and in the bit-level probing models, and allows for end-to-end fault detection against fault injection attacks.

▸ [1] **N. Maciel**, **E. C. Marques**, **L. Naviner**, and J. Yang, "Reliability analysis of NAND-Like spintronic memory,» Microelectronics Reliability, 2019.

▸ [2] **S. Takarabt**, **A. Schaub**, A. Facon, **S. Guilley**, **L. Sauvage**, Y. Souissi, and **Y. Matthieu**. "Cache-Timing Attacks still threaten IoT devices". In: C. Carlet, S. Guilley, A. Nitaj, E. Souidi. (eds) Codes, Cryptology and Information Security. C2SI 2019. Lecture Notes in Computer Science, vol 11445. Springer, Cham.

▸ [3] **W. Cheng**, C. Carlet, **K. Goli**, **J. L. Danger**, **S. Guilley**. "Detecting Faults in Inner Product Masking Scheme". In: K. Heydemann, U. Kühne and L. Li (editors). Proceedings of 8th International Workshop on Security Proofs for Embedded Systems, vol 11, p. 17–32

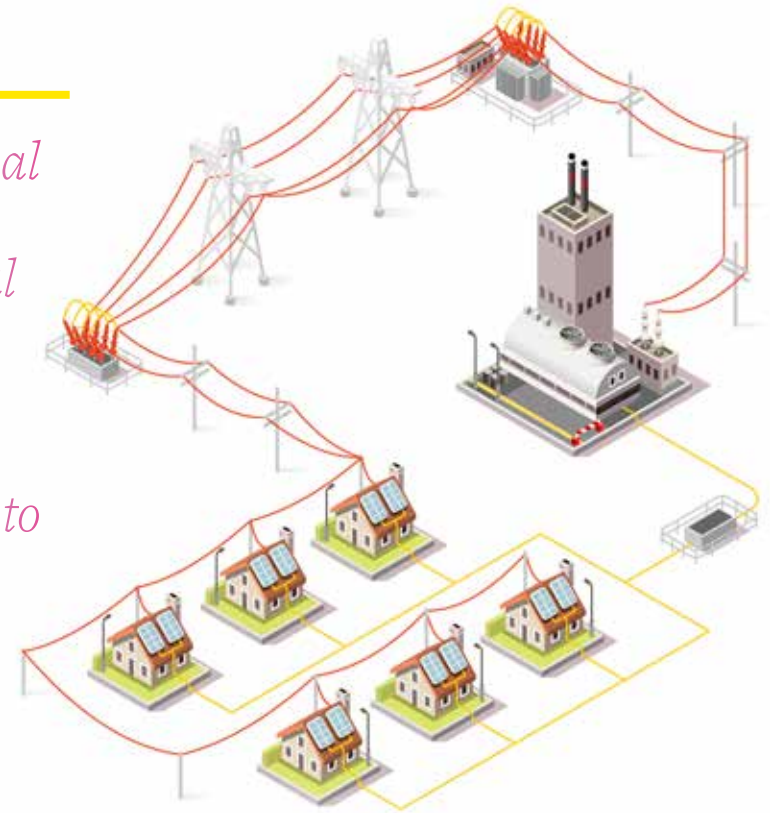
ACES

Autonomous Critical Embedded Systems
Systèmes embarqués critiques autonomes

Group leader
— Responsable d'équipe

Laurent Pautet

Non-functional properties of cyber-physical systems such as criticality, autonomy or security have to be ensured



Keywords
Cyber-Physical Systems, Security and safety, Embedded critical systems, Concurrent and distributed systems, Autonomic systems, Game Theory, Blockchain

Mots-clés
Systèmes Cyber-Physiques, Sécurité et sûreté, Systèmes embarqués critiques, Systèmes concurrents et répartis, Systèmes autonomiques, Théorie des jeux, Blockchain

Web
telecom-paris.fr/aces

See also
▸ Joint laboratories BART, COSYNUS and SEIDO, p. 79
▸ RAMSES tool, p. 83

EN The research topics of ACES address **cyber-physical systems** (**CPS**), for which non-functional properties such as criticality, autonomy or security have to be ensured. These may be systems running in parallel on the same unicore processor, enforcing timing properties as it is the case in real-time embedded systems. They may also consist of distributed systems running on different processors and competitively accessing shared resources in a consistent manner. Similarly, this concurrency can occur in secure systems for which the attacker and the defender are in competition with each other.

To cover the entire continuum of cyber-physical systems, ACES structures its activities around **loosely coupled systems**—distributed services, complex autonomic systems, security in the Internet of things, fault-tolerant and asynchronous distributed computing, model-based testing—and **strongly coupled systems**—real-time systems, deterministic platforms, critical system design process, security and safety, energy consumption of computation. However, this separation remains soft, and the activities overlap and complement each other greatly. For example, critical architectures in the transport domain (mostly categorized as strongly coupled systems) tend to extend to external services—less safe, but more adaptive (mostly categorized as loosely coupled systems).

FR Les thèmes de recherche de ACES portent sur les **systèmes cyber-physiques (CPS)**, pour lesquels des propriétés non fonctionnelles telles que la criticité, l'autonomie ou la sécurité doivent être garanties. Il peut s'agir de systèmes fonctionnant en parallèle sur le même processeur unicore, en appliquant des propriétés de synchronisation comme dans les systèmes embarqués temps réel. Ils peuvent également être des systèmes distribués fonctionnant sur différents processeurs et accédant de manière concurrentielle et cohérente à des ressources partagées. De même, cette concurrence peut se produire dans des systèmes sécurisés pour lesquels l'attaquant et le défenseur agissent en concurrence.

Pour couvrir l'ensemble du continuum des systèmes cyber-physiques, ACES structure ses activités autour de **systèmes faiblement couplés** – services distribués, systèmes autonomes complexes, sécurité dans l'Internet des objets, informatique distribuée tolérante aux pannes et asynchrone, tests reposant sur des modèles – et de **systèmes fortement couplés** – systèmes temps réel, plateformes déterministes, processus de conception de systèmes critiques, sécurité et sûreté, consommation d'énergie de calcul. Toutefois, cette séparation reste souple, et les activités se chevauchent et se complètent largement. Par exemple, les architectures critiques dans le domaine des transports (principalement classées comme systèmes fortement couplés) ont tendance à s'ouvrir aux services externes – moins sûrs, mais plus adaptatifs (principalement classés comme systèmes faiblement couplés).

Safety: Modeling, analysis and synthesis of mixed-criticality systems

EN In safety-critical systems many software components of different criticalities and assurance levels need to interact in a timely manner to keep the system and environment safe. Nowadays, these systems are challenged by technological progress resulting in rapid increases in both software complexity and processing demands. The efficient design of safety-critical systems subject to stringent timing requirements is therefore a challenge and a necessity.

Article [1] considers the mixed-criticality execution model and homogeneous multi-core processors. A task model incorporating mixed-criticality, real-time and precedence constraints in the form of directed acyclic graphs is defined. A meta-heuristic to solve the scheduling problem of this task model is then defined and proved to respect deadlines, even when the system needs to give more processing power to the most critical tasks. The state-of-the-art techniques capable of scheduling a similar task model have only been developed for dual-criticality systems. Conversely, the meta-heuristic we propose has been generalized to support an arbitrary number of criticality levels. We instantiated our meta-heuristic adopting scheduling algorithms such as G-EDF, G-LLF or G-EDZL for each level of criticality. The experiments show excellent results in terms of acceptance ratio and number of preemptions.

In [2], earlier work has been conducted on multi-core architectures, in which time division multiplexing (TDM) is used as a memory arbitration policy ensuring a predictable behavior by bounding access latencies and guaranteed bandwidth to tasks independently from the other tasks. However, TDM has several drawbacks such as inefficiency on access sharing to a DRAM memory—a highly variable latency resource— which causes their underutilization. The article presents dynamic arbitration schemes based on TDM which operate at the granularity of clock cycles by exploiting slack time accumulated from preceding requests.

▸ [1] R. Medina, **E. Borde** and **L. Pautet**, «Generalized Mixed-Criticality Static Scheduling for Periodic Directed Acyclic Graphs on Multi-Core Processors,» in IEEE Transactions on Computers

▸ [2] F. Hebbache, M. Jan, **F. Brandner** and **L. Pautet**, «Shedding the Shackles of Time-Division Multiplexing,» 2018 IEEE Real-Time Systems Symposium (RTSS), Nashville, TN, 2018, pp. 456-468

Security for the power grid

EN In the domain of safety and security in critical systems, attacker behaviors are modeled to assess the threat they represent, either for certification or design improvement purposes. This consists in establishing a model of the attacker's action capabilities and their impact on system assets. Design improvement is related to balancing the budget (skills, time, money and so on) that both the attacker and the system designer are willing to invest to compromise/defend the system.

In the following book chapter, the issue of the security risk management of interdependent communication and electric infrastructures in the smart grid is addressed by proposing an analytical model for hardening security on critical communication equipment used to control the power grid. Using non-cooperative game theory, the behavior of an attacker and of a defender is analyzed. The attacker tries to compromise communication equipment to cause the maximum impact on the power grid. On the other hand, the defender develops optimal defense strategies of the power system by hardening the security on communication equipment, while taking into account the existence of backup control equipment in the communication infrastructure.

This line of work is conducted in the SEIDO laboratory (EDF), the CyberCNI Chair and the C3S Chair.

▸ Z. Ismaïl, **J. Leneutre**, D. Bateman, L. Chen. "Managing Security Risks Interdependencies Between ICT and Electric Infrastructures: A Game Theoretical Analysis". Book chapter in Game Theory for Security and Risk Management Stefan Rass, Stefan Schauer (Editors)

Permanent members / Membres permanents **12**

Thesis / Thèses soutenues **3**

Patents / Brevets **2**

Publications / Publications **37**

CCN

Cybersecurity for Communication and Networking
Sécurité des réseaux

Group leader
— Responsable d'équipe

Patrick Bellot

Keywords
Information system security, Internet of Things, V2X communications security, Trust, Privacy, Cybersecurity, Cooperative Intelligent Transportation Systems (C-ITS), Wireless networks, Autonomic networks, Attack detection, Misbehavior detection

Mots-clés
Sécurité des systèmes informatiques, Internet des Objets, Sécurité des communications V2X, Confiance, Vie privée, Cybersécurité, Systèmes de transport intelligents coopératifs, Réseaux sans fil, Réseaux autonomes, Détection d'attaques, Détection de comportements anormaux

Web
telecom-paris.fr/ccn

See also

▸ Connected Cars and Cyber Security (C3S) Chair, p. 35
▸ Joint Laboratory BART, p. 79

EN In order to address the vast and disparate group of interconnected networks and devices, it is necessary to implement tailored security and confidentiality systems, where underlying mechanisms are closely related to the services involved. Security requirements may vary considerably depending on the services offered.

CCN works on **tailored approaches to security** that are able to meet the broad range of security requirements, and to provide **adaptive security** systems. Such systems address multiple operational and environmental constraints, while taking into account the following properties: flexibility, lightness, autonomy, mobility and interoperability.

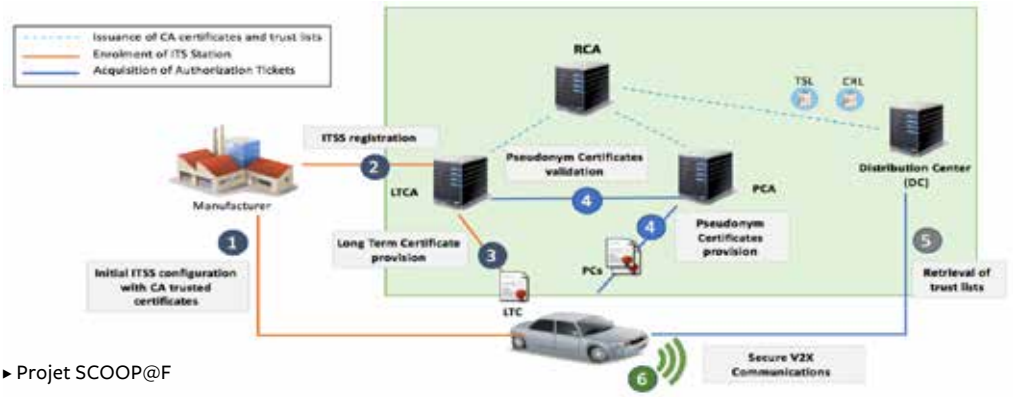
Aiming to defend against a high number of critical attacks, the challenges that CCN address are: adaptive end-to-end security architectures with lightweight and scalable security functions and protocols, scalable trust management with lightweight cryptographic functions/mechanisms and crypto-agility, identity management and lightweight authentication mechanisms, blockchain-based solutions for cybersecurity mainly for access control, integrity and resilience. These application fields can be found in several collaborative research activities split into three topics: security and trust in information and networking systems, attack analysis and misbehavior detection and privacy.

Secure systems take into account flexibility, lightness, autonomy, mobility and interoperability

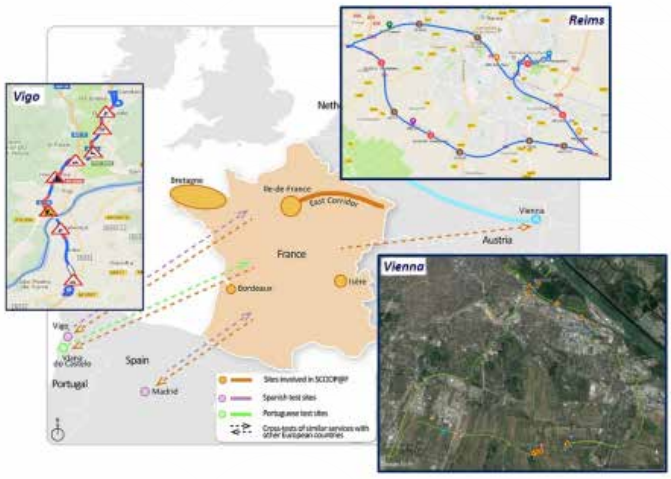
FR Pour faire face au groupe vaste et hétérogène de réseaux et périphériques interconnectés, il est nécessaire de mettre en œuvre des systèmes de sécurité et de confidentialité adaptés, dont les mécanismes sous-jacents sont étroitement liés aux services concernés. Les exigences en matière de sécurité peuvent varier considérablement en fonction des services pris en charge.

Les travaux de recherche de CCN traitent des approches de **sécurité sur mesure**, capables de répondre à la vaste gamme d'exigences de sécurité et fournissant des **systèmes de sécurité adaptatifs**. Ces systèmes répondent à de multiples contraintes opérationnelles et environnementales, tout en tenant compte des propriétés de flexibilité, légèreté, autonomie, mobilité et interopérabilité.

Dans un contexte où il est nécessaire de se défendre contre un nombre élevé d'attaques critiques, les défis que CCN relève sont les suivants : concevoir des architectures de sécurité adaptatives de bout en bout avec des fonctions et des protocoles de sécurité légers et évolutifs, gérer la confiance de manière évolutive avec des fonctions/mécanismes cryptographiques légers et de la crypto-agilité, gérer des identités avec des mécanismes d'authentification légers, élaborer des solutions de cybersécurité fondées sur des chaînes de blocs, notamment pour le contrôle d'accès, l'intégrité et la résilience. Ces domaines d'application se déclinent en plusieurs activités de recherche collaborative réparties en trois thèmes : la sécurité et la confiance dans les systèmes d'information et de réseau, l'analyse des attaques et la détection des mauvais comportements, et la protection de la vie privée.



▸ Projet SCOOP@F



▸ Projet SCOOP@F

Security and trust in C-ITS and IoT networks

EN The deployment of new and expanding networks brings with it new vulnerabilities and new types of malicious attacks. Care should be taken to secure these infrastructures, which are expected to enhance our daily lives and keep us safe.

In the field of wheeled vehicle mobility, academia and industry efforts have recently concentrated on road safety via intelligent transportation systems (ITS). CCN is involved in SCOOP@F, InterCor and C-Roads projects, major European projects which pave the way for the real-life deployment of cooperative intelligent transportation systems (C-ITS). Two key achievements can be mentioned: the deployment of a real ITS PKI in France with a home security system and the specification of the European trust model enabling interoperability at European level (outcome of WG5 of C-ITS Platform). Large-scale tests have validated the trust and security specifications (see InterCor Testfest2, SCOOP@F Tests) [1,2].

In the Internet of Things (IoT) domain, the ad hoc mode is widely used in scenarios such as intelligent transportation system or environment sensing. Despite numerous benefits, some of their characteristics such as the unreliability of wireless links, dynamic topology and energy constraints mean that the development of new protocols ignores security requirements in order to satisfy some quality of service. Article [2] proposes a lightweight and secure routing scheme that combines multipath routing and trust management, that can adapt to different scenarios in the IoT environment. Performance analysis shows that this scheme is highly scalable, more efficient and resilient compared with previous related work and is particularly suitable for insecure large and dense IoT networks.

▸ [1] **J. P. Monteuuis**, J. Petit, **J. Zhang**, **H. Labiod**, S. Mafrica, A. Servel, “Attacker model for Connected and Automated Vehicles”, ACM Computer Science in Cars Symposium (ACM CSCS 2018).

▸ [2] B. Hammi, S. Zeadally, **H. Labiod**, **R. Khatoun**, Y. Begriche and L. Khoukhi. “A Secure Multipath Reactive Protocol for Routing in IoT and HANETs”, Ad Hoc Networks journal, Volume 103,102118, ISSN 1570-8705, 2020.

Privacy preservation and misbehavior detection in C-ITS and IoT systems

EN Quality of Service in the ITS domain cannot be obtained at the cost of vehicle privacy disclosure. For example, prefetching and caching content at road-side units (RSUs) and broadcast-transmission scheduling in order to improve the throughput in vehicular networks may be desirable and could be facilitated by trajectory prediction. However, it is not acceptable to obtain this knowledge via GPS or location tracking. In [3], this privacy issue is tackled by enabling vehicles to disseminate obfuscated location information to the server. The problem becomes a reinforcement learning problem, where the decision variables concern the action to obfuscate disseminated location according to current location and the last disseminated location, with the objective of maximizing a utility function combining the capacity of the network and the level of privacy.

In vehicular networks, radio-frequency jamming attacks are considered a major threat to the availability of control channel (CCH). In particular, vehicles may not be able to receive control messages from roadside units (RSUs) due to persistent interference in the CCH. A cooperative anti-jamming beamforming scheme is proposed in [4], based on the use of the spatial diversity provided by the multiantenna RSU and relay vehicles to improve the transmission reliability of downlink control messages. In addition, the relay selection and the beamformer design problems are jointly considered and modeled as a mixed-integer nonlinear programming problem, addressed by relaxing it into a series of convex subproblems, that are then solved iteratively. The whole method converges rapidly, and significant performance gains can be observed.

▸ [3] **S. Berri**, **J. Zhang**, B. Bensaou, **H. Labiod**. “Privacy-Preserving Data-Prefetching in Vehicular Networks via Reinforcement Learning”, IEEE ICC, Jun 2020, Dublin, Ireland.

▸ [4] P. Gu, C. Hua, W. Xu, **R. Khatoun**, Y. Wu and **A. Serhrouchni**, “Control Channel Anti-Jamming in Vehicular Networks via Cooperative Relay Beamforming”, in IEEE Internet of Things Journal, vol. 7, no. 6, pp. 5064-5077, June 2020

DIG

Data, Intelligence and Graphs
Données, Intelligence et Graphes

From Theory to Software

Group leader
— Responsable d'équipe

Thomas Bonald

Keywords
Data mining, Knowledge bases, Databases, Logic, Graphs, Data streams, Natural language processing, Artificial intelligence, Learning, Cognitive models

Mots-clés
Fouille de données, Bases de connaissances, Bases de données, Logique, Graphes, Flux de données, Traitement du langage naturel, Intelligence artificielle, Apprentissage, Modèles cognitifs

Web
telecom-paris.fr/dig

See also
▸ Open Source Software, pp. 82-83

EN DIG aims at making **data** and **knowledge** easy to extract, process, use and understand. Data here refers to texts, signals (e.g., from IoT devices), graphs (e.g., Web, social networks), log files (e.g., transactions). Knowledge refers to facts and rules.

The research activity of DIG covers both theoretical and practical aspects. On the theoretical side, DIG works on the complexity of query languages for databases and on the analysis of algorithms for large graphs, data streams and time series. DIG also works on cognitive models, like the simplicity theory (see book above), seeking to explain the attractiveness of situations or events to human minds.

On the practical side, DIG develops new algorithms for automatically extracting knowledge from text data, new structures and languages for storing and querying data, new machine learning algorithms and new techniques for answering complex questions (e.g., formulated in natural language), for recommending contents, or for detecting trends or anomalies in social media for instance. The team maintains YAGO, a large general knowledge base, and software such as scikit-multiflow, scikit-network and Inkscape.

EN Professor Fabian Suchanek holds the "NoRDF: Modeling and Extracting Complex Information from Natural Language Text" Chair funded by the French National AI Plan, in collaboration with the French National Research Agency (ANR), the Defence Innovation Agency (AID) and four industrial partners (EDF, BPCE, Schlumberger and Converteo). Its objectives are to enrich knowledge bases with events, causalities, precedences, histories, negations and beliefs.

▸ nordf.telecom-paris.fr

▸ JL Dessalles. Des Intelligences très artificielles, Odile Jacob, 2019

FR DIG cherche à rendre les **données** et les **connaissances** faciles à extraire, à traiter, à exploiter et à comprendre. Les données sont ici des textes, des signaux (par exemple, provenant d'objets connectés), des graphes (le Web, les réseaux sociaux), des transactions, etc. Les connaissances font référence à des faits et à des règles.

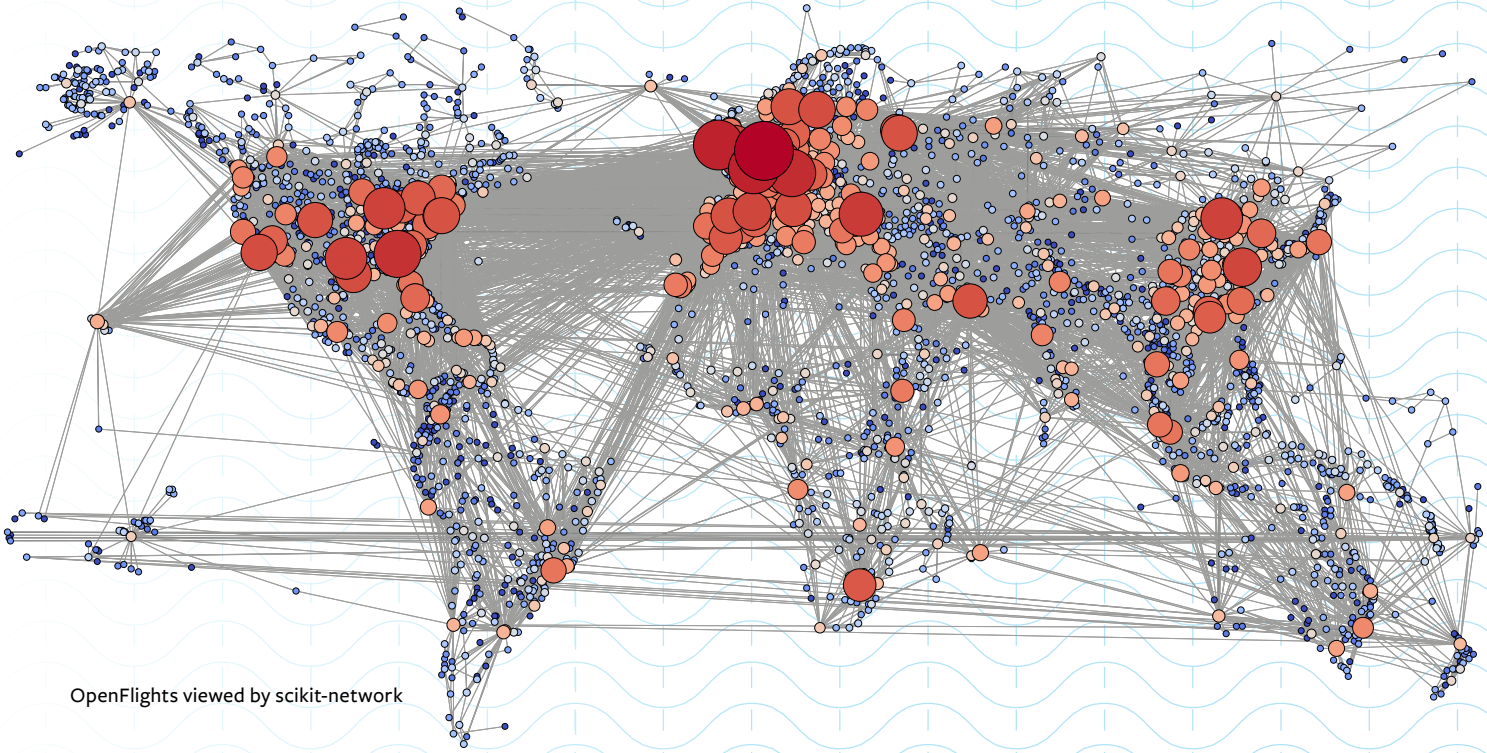
L'activité de recherche de l'équipe couvre à la fois des aspects théoriques et pratiques. Sur le plan théorique, DIG travaille sur la complexité de langages de requêtes pour les bases de données et sur l'analyse d'algorithmes pour le traitement des grands graphes, des flux de données et des séries temporelles. DIG s'intéresse également aux modèles cognitifs, comme la théorie de la simplicité (voir livre ci-dessus), cherchant à expliquer l'attirance de l'esprit humain pour certaines situations ou événements.

Du point de vue pratique, DIG développe de nouveaux algorithmes pour extraire des connaissances de données textuelles, de nouvelles structures et de nouveaux langages pour stocker et extraire des données, de nouveaux algorithmes d'apprentissage automatique et de nouvelles techniques pour répondre à des questions complexes (par exemple, formulées en langage naturel), pour recommander des contenus, ou pour détecter des tendances ou des anomalies dans les médias sociaux par exemple. L'équipe maintient YAGO, une grande base de connaissances générales, et des logiciels comme scikit-multiflow, scikit-network et Inkscape.

Télécom Paris PhD Thesis Award 2020

Céline Comte:
"Resource management in computer clusters: algorithm design and performance analysis"

Permanent members Membres permanents	9	Thesis Thèses soutenues	7	Patent Brevet	1



OpenFlights viewed by scikit-network

Graph mining

EN DIG has strong expertise in graph mining. Article [1] **(best paper award)** presents distributed algorithms to compute approximate solutions for several graph optimization problems (coreness, local density, min-max edge orientation, densest subgraph). The complexity of these algorithms is logarithmic in the number of nodes and, most notably, independent of the graph diameter. Among possible applications, these algorithms could be executed by agents in a social network or a peer-to-peer network, so as to collect relevant statistics on the underlying graph structure. Article [2] studies regularization techniques for spectral graph embedding. It shows that regularization forces the embedding to focus on the structure of the graph, making the representation less sensitive to noise. This work provides theoretical evidence of the importance of regularization observed on real use cases.

The DIG team develops and maintains scikit-network, a Python package inspired by scikit-learn for the analysis of very large graphs. The package provides state-of-the-art algorithms for ranking, clustering, classifying, embedding and visualizing graphs. High performance is achieved through a mix of fast matrix-vector products (using SciPy), compiled code (using Cython) and parallel processing. Source code, documentation and installation instructions are available online.

▸ scikit-network.readthedocs.io

▸ [1] T-H Chan, **M. Sozio**, B. Sun. "Distributed Approximate k-Core Decomposition and Min-Max Edge Orientation: Breaking the Diameter Barrier", 2019 IEEE International Parallel and Distributed Processing Symposium (IPDPS), 2019, Rio de Janeiro, Brazil. 10.1109/IPDPS.2019.00044.

▸ [2] **N. De Lara**, **T. Bonald**, "Spectral Embedding of Regularized Block Models", ICLR 2020.

Machine learning on data streams

EN Today's networks, mobile phones and sensors generate data streams that need to be analyzed in real time. DIG contributes to the state of the art in the analysis of data streams through the design of new algorithms and the development of scikit-multiflow [3], in collaboration with other academic partners, such as École polytechnique (France) and the University of Waikato (New Zealand), as well as with industrial partners, such as Huawei Technologies.

One of the results of the former collaboration is the Streaming Random Patches (SRP) algorithm, an ensemble method specially adapted to stream classification [4]. Tested on several benchmark streaming scenarios, this new algorithm achieves high accuracy with limited resources usage. Part of the research project in collaboration with Huawei focuses on developing streaming and fully dynamic algorithms for anomaly detection in network data. A first result of this collaboration is Random Histogram Forest (RHF) [5], a batch algorithm for unsupervised anomaly detection which consistently achieves higher accuracy than the state of the art. Such an algorithm is currently being adapted into a streaming environment, so as to be able to detect anomalies on network data in real time.

Scikit-multiflow is a package for learning from data streams and multi-output learning in Python. Designed to serve as a platform to encourage the democratization of stream learning research, it provides multiple state-of-the-art learning methods, data generators and evaluators for different stream learning problems, including single-output, multi-output and multi-label. Scikit-multiflow builds upon popular open source frameworks including scikit-learn, MOA and MEKA.

▸ scikit-multiflow.github.io

▸ [3] **J. Montiel**, J. Read, **A. Bifet**, **T. Abdessalem**, "Scikit-multiflow: A multi-output streaming framework". JMLR 2018.

▸ [4] **H. Murilo Gomes**, J. Read, **A. Bifet**. "Streaming Random Patches for Evolving Data Stream Classification". ICDM 2019.

▸ [5] **A. Putina**, **M. Sozio**, **D. Rossi**, J. Navarro. "Random histogram forest for unsupervised anomaly detection". ICDM 2020.

DIVA

Design, Interaction, Visualization & Applications
Design, Interaction, Visualisation & Applications

Group leader
– Responsable d'équipe

Eric Lecolinet

Keywords
Human-computer interaction (HCI), Touch- and gesture-based interfaces, Data visualization, Design, Behavior models, Virtual reality, Augmented reality, Mixed reality

Mots-clés
Interaction humain-machine (IHM), Interfaces tactiles/haptiques et gestuelles, Visualisation des données, Design, Modèles comportementaux, Réalité virtuelle, augmentée et mixte

Web
telecom-paris.fr/diva

See also
▸ Jan Gugenheimer, p. 10

EN DIVA is dedicated to fundamental and applied research on human-computer interaction (HCI), design and data visualization.

DIVA focuses on **novel interaction techniques**, technology mediated environments and on the challenge of constantly representing increasing data volumes, not only on standard computers but also on small, very large, and non-traditional devices. It addresses the complementary aspects of this process by leveraging novel interaction principles and methods, in particular for mixed reality and touch- and gesture-based interfaces, while considering their physical characteristics and studying how they are being used and deployed. It also includes the development of novel interaction and design paradigms, which act as a basis for implementing new interaction techniques for multi-device, multi-surface collaboration and computer science education.

It also studies the so-called **homo numericus**, and aims to establish models of behavior in interactive situations and to exploit these models for the design of interactive objects. This includes predictive and cognitive models for improving performance, novice-to-expert transition, multiscale interface navigation, and reconsidering pointing (Fitts's law) from the angle of information theory. This research theme focuses on understanding the relationship between humans and tools and investigates large-scale, technology-mediated environments such as learning environments where memorization and novice/expert transition are of central importance.

FR DIVA effectue de la recherche fondamentale et appliquée sur l'interaction humain-machine (IHM), la conception et la visualisation de données.

DIVA s'intéresse à des **techniques d'interaction innovantes**, aux environnements à médiation technologique et cherche à relever le défi de représenter de plus en plus de données, tant sur des ordinateurs classiques que sur des petits dispositifs mobiles ou des dispositifs non conventionnels ou de grande taille comme des murs d'écrans. Les aspects complémentaires de ce processus sont abordés en tirant parti de nouveaux principes et méthodes d'interaction, avec un focus sur la réalité mixte et les interfaces tactiles/haptiques et gestuelles, tout en tenant compte de leurs caractéristiques physiques et en étudiant la manière dont ils sont utilisés et déployés. Ces travaux comprennent également le développement de nouveaux paradigmes d'interaction et de conception, qui servent de base à la mise en œuvre de nouvelles techniques d'interaction pour la collaboration multi-surfaces, multi-dispositifs et l'enseignement de l'informatique.

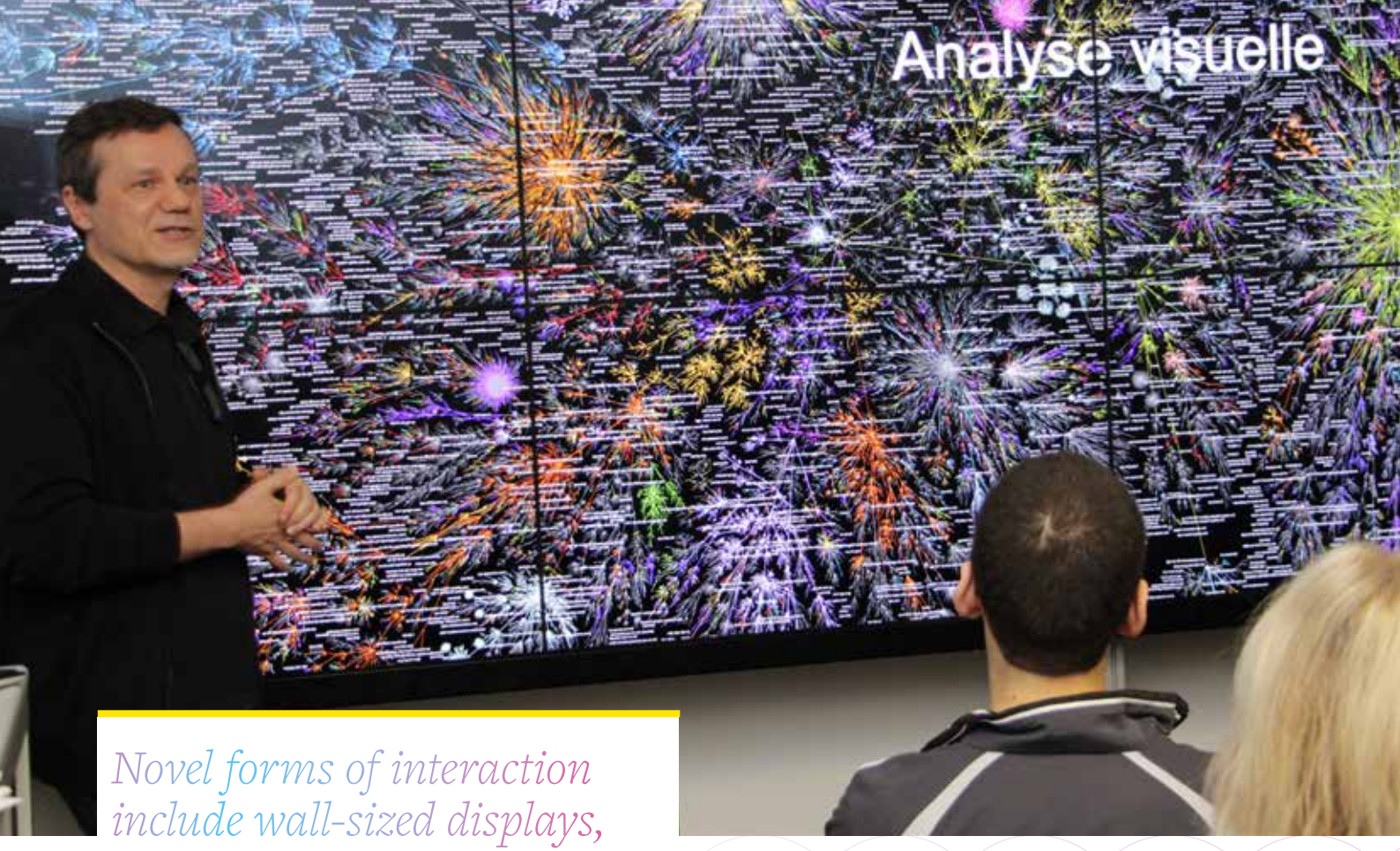
DIVA étudie également l'**homo numericus**, en visant à établir des modèles de comportement dans des situations d'interaction et à exploiter ces modèles pour la conception d'objets interactifs. Cette recherche s'intéresse à des modèles cognitifs et prédictifs visant à améliorer la performance, la transition entre une utilisation novice et experte, l'optimisation de la navigation multi-échelle, ou encore l'étude du pointage (loi de Fitts) qui est reconsidérée sous l'angle de la théorie de l'information. Cet axe de recherche se concentre sur la compréhension de la relation entre l'humain et l'outil, et étudie les environnements à grande échelle, médiés par la technologie, tels que les environnements d'apprentissage où la mémorisation et la transition novice/expert sont d'une importance capitale.

Télécom Paris PhD Thesis Award 2019

Wanyu Liu. "Information theory as a unified tool to understand and design human-computer interaction"

Skin-On interfaces: augmenting interactive devices with artificial skin

Permanent members
Membres permanents **8**



Novel forms of interaction include wall-sized displays, mixed reality, touch- and gesture-based interfaces

Principles of Computer input

EN Working with ComNum p. 24 and the HCC (Human Centered Computing) group in the LRI (Computing Research Laboratory), DIVA contributes to the fundamental study of Fitts's Law, a classic regularity in mathematical psychology, which makes quantitative predictions, relating especially to human-computer interfaces and performance in pointing and target selection. Two PhD theses—including one which has received the Télécom Paris PhD Thesis Award—have recently made a deeper theoretical study of Fitts's law in light of Shannon's information theory. This work, together with its developments, are presented in [1,2]. A study carried out under a different theoretical angle revealed that there are in fact two very distinct forms of this law [3].

▸ [1] **J. Gori**, **O. Rioul**, and **Y. Guiard**. "Speed-accuracy tradeoff of aimed movement: A formal information-theoretic transmission scheme (FITTS)". Proceedings of CHI 2019.

▸ [2] **W. Liu**, **J. Gori**, **O. Rioul**, M. Beaudouin-Lafon and **Y. Guiard**. "How Relevant is Hick's Law for HCI?" Proceedings of CHI 2020.

▸ [3] **Y. Guiard**. "Polar and Cartesian Structure in the Data of Fitts's (1954) Classic Experiments—with a Criterion for Distinguishing a Strong and a Weak Version of Fitts's Law". Journal of motor behavior, 52, 271-293. 2019.

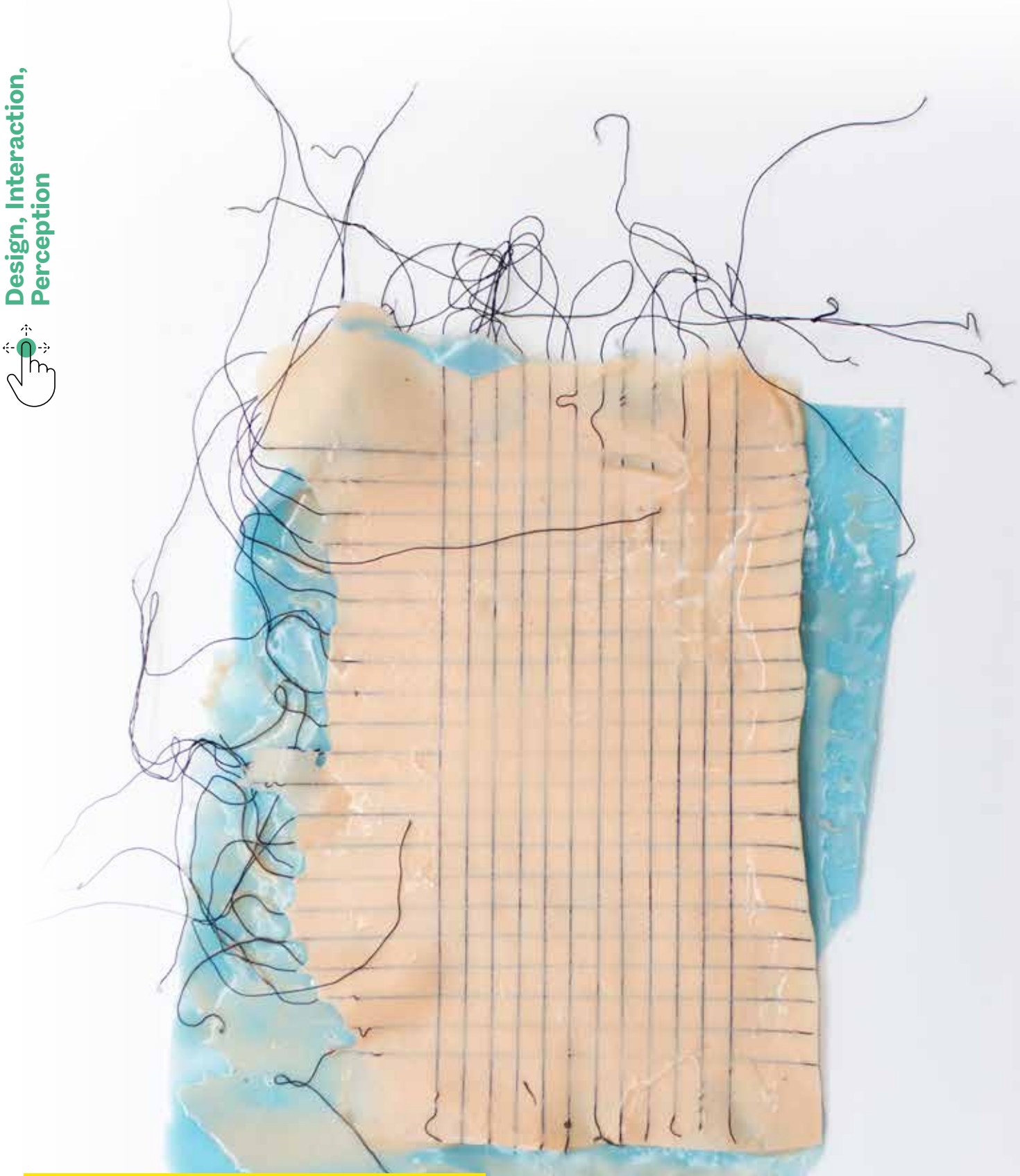
edX Prize for Exceptional Contributions in Online Teaching and Learning

EN The health crisis in 2020 highlighted the importance of online educational tools and provided an opportunity to experiment with new teaching practices, leading to new forms of learning. In that context, the Caleo project aims to design and develop tools that teachers can use to design and implement innovative and collaborative teaching methods more easily. With Codecast, they can record audio-interactive lectures on C and Python languages. Taskgrader is used to validate programming exercises automatically. QuickAlgo offers fun challenges in visual languages, Scratch and Blockly and in Python. The development of Calao relies on advanced technologies—sometimes improved—all of them being available under the free MIT license. It relies on the Debugger Adaptor Protocol, which enables a given tool to communicate in a uniform way with debuggers, and on a load distribution architecture, across multiple servers, so that a far larger number of content creators can work together.

Rémi Sharrock won the prestigious 2019 edX Prize for Exceptional Contributions in Online Teaching and Learning created by MIT and Harvard, for his series of seven MOOCs, "C Programming with Linux".

▸ remisharrock.fr

Thesis Thèses soutenues	6	Patent Brevet	1	Publications Publications	11



How can the sense of touch be incorporated into interactive systems to leverage communicative and emotional channels between humans and machines?

Skin-On Interfaces, a research project by **Marc Teyssier**, Gilles Bailly, **Catherine Pelachaud**, **Eric Lecolinet,** Andrew Conn and Anne Roudaut.

► marcteyssier.com/projects/skin-on

Touch: a little-studied communicative modality

EN DIVA and INTERACT work together on a multi-partner project at the crossroads of human-machine interaction and emotional design: **SocialTouch** aims at understanding, modeling and evaluating social touch in human-machine interactions.

It investigates how the sense of touch can be incorporated into interactive systems to leverage communicative and emotional channels between humans and machines or between humans via machines. Touching is a communicative modality that has been far less studied than other communication channels. However innovative topics such as the role of SocialTouch to encourage engagement or to provide intimate experiences are very promising.

Such a project, in the context of a health crisis, is of first importance. Several use cases are studied, such as how to enhance human interaction with small devices, how to deal with embodied conversational agents and virtual reality environments and how to leverage interpersonal mediated communication.

The objectives are to understand the principles and functions of touch as an emotional way to communicate and to predict its impact on human-machine engagement; to design novel human-machine interaction techniques and devices; to evaluate the effectiveness and acceptability of social touch in the contexts of mediated communication and communication with embodied conversational agents.

SocialTouch is an ANR project with ISIR (Institute for Intelligent Systems and Robotics) and UMR CNRS 7253 Heudiasyc

▸ **Z. Zhang**, **R. Heron**, **E.Lecolinet**, **F. Détienne**, **S. Safin**. VisualTouch: "Enhancing Affective Touch Communication with Multi-modality Stimulation." ICMI 2019 - ACM International Conference on Multimodal Interaction, Oct 2019, Suzhou, China.

▸ **R. Heron**, **F. Détienne**, **S. Safin, M. Baker**, **Z. Zhang**, et al.. "Analysing meaning making of social touch in computer-mediated interaction." IASAT Congress, International Association for the Study of Affective Touch., Sep 2019, Linköping, Sweden.

▸ socialtouch.hds.utc.fr/

EN MobiLimb is a finger-shaped robot, designed to extend the sensory abilities of existing mobile devices, including smartphones. Technology usually serves to extend humans' abilities but this device extends the abilities of inert objects with abilities specific to humans. This research was initially purely exploratory and sat somewhere between IT and human and social sciences. MobiLimb is being considered for three usage scenarios: as a tool that improves Human-Machine interaction; as a partner, to represent emotions or represent virtual objects, in the context of a game for instance; as a device that improves mediated interaction with a human, a robot or an avatar.

▸ **M. Teyssier**, G. Bailly, **C. Pelachaud, E. Lecolinet** "MobiLimb: Augmenting Mobile Devices with a Robotic Limb". UIST 2018 Conference Proceedings: ACM User Interface Software and Technology Symposium, 10/2018.

IQA

Quantum Information and Applications
Information Quantique et Applications

Permanent members Membres permanents	3
Thesis Thèses soutenues	2
Patent Brevet	1
Publications Publications	10

Group leader
— Responsable d'équipe

Isabelle Zaquine

Keywords
Quantum communications, Quantum Cryptography, Quantum computing, Quantum optics, Optical communications, Non-linear optics, Quantum Machine Learning, Quantum Key Distribution (QKD)

Mots-clés
Communications quantiques, Cryptographie quantique, Calcul quantique, Optique quantique, Communications optiques, Optique non linéaire, Apprentissage quantique, Distribution quantique de clé (QKD)

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EN IQA conducts research on quantum information, quantum internet, quantum communication and cryptography. Theoretical work is combined with the development of an experimental platform enabling demonstrations of quantum communication protocols to be made, based on nonlinear and quantum optics.

A research theme brings together theoretical and experimental work on **quantum cryptography**, and in particular continuous variable quantum key distribution (CV-QKD). It also consists in addressing challenges aimed at advancing the integration and impact of quantum cryptography within the cybersecurity ecosystem. This work is being carried out as part of the Quantum Technology Flasghip and of the EuroQCI initiative led by the European Commission.

A more fundamental aspect of the future quantum internet is the experimental investigation of new sources of light for quantum communications that are compatible with fiber-optic telecommunications networks.

Another important activity lies at the intersection of computer science and quantum information, with an emphasis on **optical quantum computing**. In view of this, machine-learning-based techniques are being developed to enable differentiable simulations of quantum optical systems. This constitutes an innovative method to optimize parameterized quantum circuits.

IQA also works on frequency-encoded linear optics **quantum computing**, leveraging telecom-optimized optical components. The objective is to build an experimental multimode quantum processing platform to demonstrate applications in quantum computing and quantum cryptography.

EN IQA is a member of SIRTEQ (regional cluster), an active network of researchers in quantum information in the Paris Region. The group has close links with researchers at the Université Paris-Saclay "Quantum Center" and with the Paris Centre for Quantum Computing (PCQC). IQA also represents the IMT (Institut Mines-Télécom) as a founding member and rapporteur at the ETSI ISG-QKD, which works on the standardization of quantum key distribution (QKD), and is actively involved in the Quantum Technology Flagship, via participation in the CIVQ and OpenQKD projects and the EuroQCI initiative.

FR IQA mène des recherches sur l'information quantique, l'internet quantique, la communication quantique et la cryptographie. Les travaux théoriques sont combinés avec le développement d'une plateforme expérimentale permettant des démonstrations de protocoles de communication quantique fondés sur l'optique non linéaire et quantique.

Un axe de recherche regroupe des travaux théoriques et expérimentaux sur la **cryptographie quantique**, et en particulier la distribution quantique de clé à variable continue (CV-QKD), ainsi que les défis et applications de la cryptographie quantique au sein de l'éco-système cybersécurité. Ces travaux sont menés dans le cadre du Quantum Technology Flagship et de l'initiative pilotée par la Commission Européenne, EuroQCI.

Plus en amont de la réflexion sur le futur internet quantique, des expériences sur de nouvelles sources de lumière pour les communications quantiques compatibles avec les réseaux de télécommunications optiques fibrés sont réalisées.

Une autre activité importante se situe à l'intersection entre l'informatique et l'information quantique, avec un accent sur la **photonique pour le calcul**. Dans cette perspective, des techniques d'apprentissage sont développées en vue d'obtenir des simulations différentiables de systèmes optiques quantiques. Il s'agit d'une méthode innovante pour optimiser des circuits quantiques paramétrés.

IQA s'intéresse également au **calcul quantique** basé sur l'optique linéaire multimode avec encodage sur la fréquence et s'appuyant sur des composants des télécommunications optiques. L'objectif est de construire une plateforme optique multimode de traitement de l'information permettant de démontrer des applications en calcul et en cryptographie quantiques.

Parameterized quantum optical circuits

EN Parameterized quantum optical circuits are a class of quantum circuits in which the carriers of quantum information are photons and the gates are optical transformations. Optimizing these circuits is challenging because of the infinite dimensionality of the photon number vector space that is associated to each optical mode. Truncating the space dimension is unavoidable, and it can lead to incorrect results if the gates populate photon number states beyond the cutoff. To tackle this issue, an algorithm that is orders of magnitude faster than the current state of the art, to recursively compute the exact matrix elements of Gaussian operators and their gradient with respect to a parameterization, is presented. These operators, when augmented with a non-Gaussian transformation such as the Kerr gate, achieve universal quantum computation. The proposed approach offers multiple advantages: first, by computing the matrix elements of Gaussian operators directly, it is not necessary to construct them by combining several other operators; second, one can use any variant of the gradient descent algorithm by plugging the gradients into an automatic differentiation framework such as TensorFlow or PyTorch. The results presented here will accelerate research on quantum optical hardware, quantum machine learning, optical data processing, device discovery and device design.

▸ **F. M. Miatto**, Nicolás Quesada. "Fast optimization of parametrized quantum optical circuits." Quantum Journal, 2020

Gas-filled hollow-core fibers for photo-pair generation

EN Raman-scattering noise in silica has been the key obstacle toward the realization of high quality fiber-based photon-pair sources. In the following paper, an experimental demonstration is conducted on how to get past this limitation by dispersion tailoring a xenon-filled hollow-core photonic crystal fiber. The source operates at room temperature, and is designed to generate Raman-free photon-pairs at useful wavelength ranges, with idler in the telecom range, and signal in the visible range. We achieve a coincidence-to-accidentals ratio as high as 2740 combined with an ultra low heralded second order coherence (0.002), indicating a very high signal to noise ratio and a negligible multi-photon emission probability. Moreover, by gas-pressure tuning, the control of photon frequencies over a range as large as 13 THz, covering S-C and L telecom band for the idler photon, is demonstrated. This work shows that hollow-core photonic crystal fiber is an excellent platform to design high quality photon-pair sources, and could play a driving role in the emerging quantum technology.

▸ **M. Cordier**, P. Delaye, F. Gérôme, F. Benabid, **I. Zaquine**. "Raman-free fibered photon-pair source." Scientific Reports, Nature Publishing Group, 2020, 10, pp. 1650.

Quantum Secure Networks

EN Quantum networks are progressing from lab experiments to large-scale deployments and industrialization. IQA contributes to this process, both in terms of fundamental research, technology development and industry-oriented projects : In the CIVIQ European project, and in collaboration with Yves Jaouën and Cedric Ware (GTO), IQA develops novel ways of designing QKD systems, so that they can be seamlessly incorporated into existing networks. In the OpenQKD project, and within the ETSI-QKD ISG, IQA contributes to the development of standards that will enable the security certification of QKD products. Finally, work carried out in this field aims at considering new hybrid (quantum and computational) security models to propose novel protocol constructions and radically push the performance boundaries and the functionality of quantum cryptography.

▸ **R. Alléaume**, **R. Aymeric**, **C. Ware**, and **Y. Jaouën**, "Technology Trends for Mixed QKD/WDM Transmission up to 80 km," in Optical Fiber Communication Conference (OFC) 2020, OSA Technical Digest (Optical Society of America, 2020), paper M4A.1.

MC2

Mathematics for Information, Communication and Computing
Mathématiques discrètes, Codage et Cryptographie

Group leader
– Responsable d'équipe

Olivier Hudry

Keywords
Combinatorics, Algebraic geometry, Coding and cryptography (mathematical aspects), Algorithmics, Graphs

Mots-clés
Combinatoire, Géométrie algébrique, Codage et cryptographie (aspects mathématiques), Algorithmique, Graphs

Web
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EN MC2 conducts its research activities in **fundamental mathematics**—algebraic geometry, number theory, combinatorial coding theory—, and in areas at the frontier between **discrete mathematics** and computer science—automata, coding theory, cryptography, computational complexity—but still with a predominantly mathematical perspective. Recent work has been carried out on the following topics.

In **algebraic geometry**, projects are chosen first for their intrinsic mathematical interest, and also for their applications in theoretical computer science and information theory, in coding theory, combinatorics, complexity, computability, or cryptography. **Combinatorial coding theory** being one source of methods for coding theory, MC2 explores this theme through Boolean functions and cryptography, minimal codes and their variants, and zero-error information theory and extremal combinatorics.

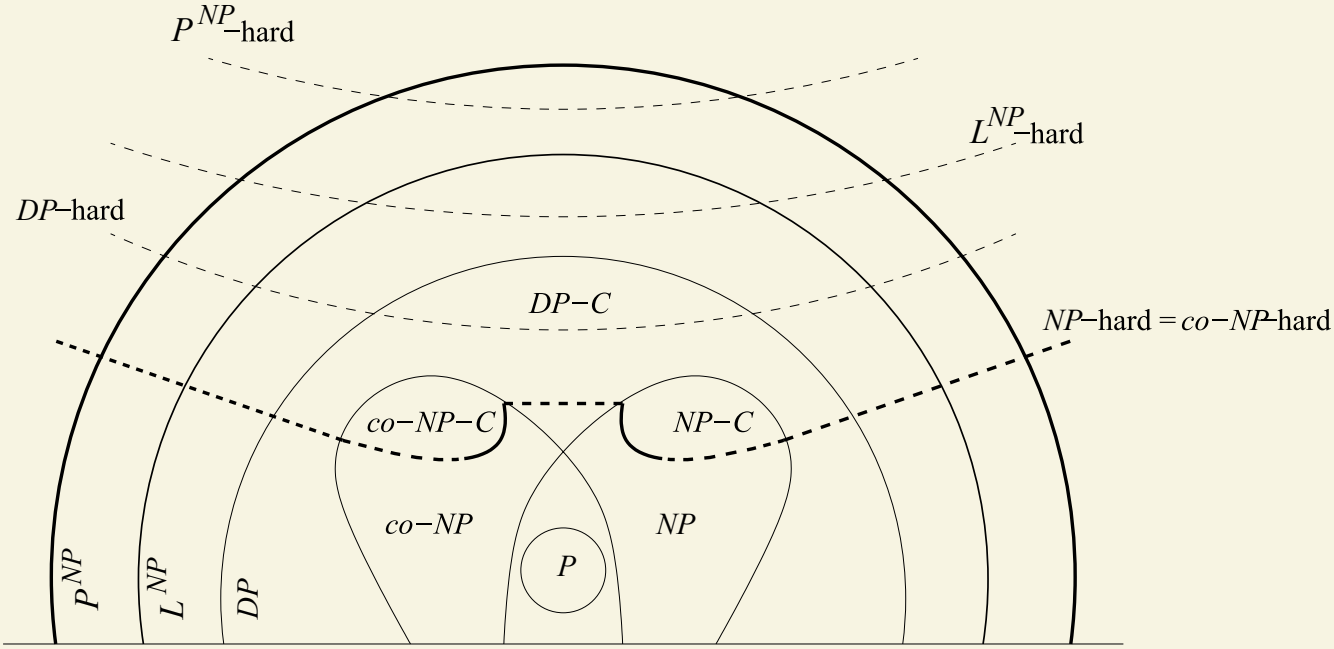
In **graph theory**, MC2 studies several variants of the dominating set problem, and more precisely the notions of locating-dominating codes and identifying codes. The combinatorial properties of these objects are studied, as well as the complexity of some related optimization problems. In a second field where MC2 is a pioneer, problems related to complexity theory are explored, including the study of median orders, or the **uniqueness of optimal solutions** in classical problems and the complexity of decision for existence of a unique solution. Some of these problems do not fall in the usual complexity classes, e.g. $\mathcal{NP}$, but higher in the polynomial or Boolean hierarchy, such as Θ_2, Δ_2, $F\Delta_2$, $\mathcal{DP}$ classes.

Problems related to complexity theory are explored, including the study of median orders, or the uniqueness of optimal solutions

FR MC2 mène ses activités de recherche en **mathématiques fondamentales** – géométrie algébrique, théorie des nombres, théorie du codage combinatoire – et dans des domaines à la frontière entre les **mathématiques discrètes** et l'informatique – automates, théorie du codage, cryptographie, complexité informatique – mais toujours avec une perspective essentiellement mathématique. Des travaux récents ont été réalisés sur les sujets suivants.

En **géométrie algébrique**, les travaux, d'abord motivés par leur propre intérêt mathématique, le sont également par leurs applications en informatique théorique et en théorie de l'information, en théorie du codage, en combinatoire, en complexité, en calculabilité ou en cryptographie. La théorie du codage combinatoire étant une source de méthodes pour la théorie du codage en général, MC2 explore cet axe à travers les fonctions booléennes et la cryptographie, les codes minimaux et leurs variantes, et la théorie de l'information sans erreur et la combinatoire extrémale.

En **théorie des graphes**, MC2 étudie plusieurs variantes du problème de l'ensemble dominant, et plus précisément les notions de codes localisateurs-dominateurs et de codes d'identification. Les propriétés combinatoires de ces objets sont étudiées, ainsi que la complexité de certains problèmes d'optimisation connexes. Dans une deuxième direction où MC2 est pionnier, les problèmes liés à la théorie de la complexité sont explorés, y compris l'étude des ordres médians, ou l'unicité des solutions optimales dans les problèmes classiques et la complexité de la décision pour l'existence d'une solution unique. Certains de ces problèmes ne relèvent pas des classes de complexité habituelles, comme $\mathcal{NP}$, mais plus haut dans la hiérarchie polynomiale ou booléenne, comme les classes Θ_2, Δ_2, $F\Delta_2$, $\mathcal{DP}$.



▸ Some classes of complexity

Algebraic geometry for the safety domain

EN The following article focuses on the differences between the minimal cardinals of a dominating set, a locating-dominating set and an identification set. The purpose of this work can be explained in the context of the operational security of a group of processors. A fault can be detected by replacing some of these processors by "controllers" which warn of an adjacent processor's malfunction and are organized into a dominating set of the complete processor graph. If the controllers make up a locating-dominating set, the fault can be detected without any ambiguity. If controllers are superimposed on certain processors, rather than replacing them, in such a way that the controllers make up an identification set, the fault can be detected without any ambiguity even if it relates to a processor coupled with a controller.

▸ **Olivier Hudry**, **Antoine Lobstein**. "The Compared Costs of Domination, Location-Domination and Identification", Discussiones Mathematicae-Graph Theory 40, 2020, 127-147.

Complexity and Graph theory

EN The vertex cover of a graph G is a subset R of G vertices such that each edge has at least one endpoint in R. The dominating set D in a graph G is a subset of G vertices such that each vertex not in D is adjacent to a member in D. Finding the minimum cardinality vertex cover and finding the minimum cardinality domination set are known to be $\mathcal{NP}$-hard problems. But what about the uniqueness of these covers and dominating sets? These problems are as complex as a variant of the famous logic problem known as "satisfiability", which belongs to the $\mathcal{DP}$ complexity class. The result presented in the following paper broadens the scope of investigation on the complexity of unique solutions to the field of graph theory.

▸ **Olivier Hudry**, **Antoine Lobstein**. "Complexity of Unique (Optimal) Solutions in Graphs: Vertex Cover and Domination", Journal of Combinatorial Mathematics and Combinatorial Computing 110, 2019, 217-240

Permanent members
Membres permanents
8

Publications
Publications
36

RMS

Networks, Mobility and Services
Réseaux, Mobilité et Services

Group leader
— Responsable d'équipe

Marceau Coupechoux

Keywords
Mobile networks, Cellular networks, 5G, 6G, Future Internet, Internet of things, Smart Grids, Data centers, Network storage, Cloud and Edge Computing, Virtualization (SDN/NFV), Network management and control, Metrology, SDR, Performance analysis, Optimization, Mathematical models (stochastic geometry, game theory, algebraic topology), Algorithm design, Artificial Intelligence

Mots-clés
Réseaux mobiles, Réseaux cellulaires, 5G, 6G, Internet du futur, Internet des objets, Réseaux électriques intelligents, Centres de données, Informatique en nuage et en périphérie, Stockage de données, Virtualisation (SDN/NFV), Contrôle et gestion des réseaux, Métrologie, SDR, Analyse de performances, Optimisation, Modélisation mathématique (géométrie stochastique, théorie des jeux, topologie algébrique), Conception d'algorithmes, Intelligence Artificielle

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See also
▸ Platforms FIT & SILECS, p. 55
▸ Joint Laboratory SEIDO, p. 79

EN The research interests of RMS lie in the design and study of future and emerging networking technologies, architectures and services. Research efforts are concentrated around three main themes: **cloudify networking and virtualization, mobile networks and communications, and the Future Internet/Internet of Things**.

The research activities carried out in the RMS group cover a wide range of topics in the general area of networking, ranging from lower layers—access, resource allocation, energy harvesting, radio handover, radio mobility management, data transmission reliability and infrastructure resilience—to higher layers—routing, Information-Centric Networking (ICN), Network Functions Virtualization (NFV), network automation and programmability, edge computing, data centers and cloud architectures, network storage, cloud RAN, IoT networking and service discovery, IP mobility, embedded systems, network telemetry and metrology including quality of user experience.

RMS has a strong expertise in protocol and architecture design. Indeed, RMS is involved in standardization activities (IETF, ETSI) as well as in the design of major research platforms (LISP, FIT, SILECS) for the networking community. Theoretical aspects are tackled using advanced approaches and tools, such as stochastic geometry, simplicial homology, game theory, optimal control and scheduling. RMS is engaged in structural cooperation with international laboratories (Europe, China, India, MENA region). Its expertise is regularly sought by national regulatory bodies and public policy makers. Research activities are also undertaken in the context of national (ANR, FUI) and international research projects (European projects), in close cooperation with major industrial groups in the field.

RMS has joint research laboratories including NewNet@Paris (with CISCO), SEIDO Lab (with EDF), LINCS (with Nokia, Inria, Sorbonne Université and IRT SystemX), and ValaDoE (with Region Pays de la Loire, Nantes Métropole, ENEDIS, and Mines Saint-Étienne).

FR RMS mène ses recherches dans la conception et l'étude de technologies, architectures et services pour les réseaux du futur. Trois axes principaux sont développés : **l'informatique en nuage et la virtualisation, les réseaux et communications mobiles, l'Internet du futur et l'Internet des objets**.

Les activités de recherche menées au sein du groupe RMS couvrent un large éventail de sujets dans le domaine général des Réseaux, allant des couches inférieures – accès, allocation des ressources, moisson énergétique, *handover*, gestion de la mobilité radio, fiabilité de la transmission de données et résilience des infrastructures – aux couches supérieures – routage, réseaux centrés sur l'information (ICN), virtualisation des fonctions réseau (NFV), automatisation et programmabilité du réseau, informatique de périphérie, centres de données et architectures en nuage, réseaux de stockages de données, accès radio en nuage, mise en réseau des objets et découverte de services, mobilité IP, systèmes embarqués, télémétrie et métrologie de réseau, qualité de l'expérience utilisateur.

RMS possède une solide expertise en conception de protocoles et d'architectures. En effet, RMS est impliquée dans des activités de normalisation (IETF, ETSI) ainsi que dans la conception de grandes plateformes de recherche (LISP, FIT, SILECS) pour la communauté des Réseaux. Les aspects théoriques sont abordés à l'aide d'approches et d'outils avancés, tels que la géométrie stochastique, l'homologie simpliciale, la théorie des jeux, le contrôle optimal et l'ordonnancement. RMS mène des coopérations structurelles avec des laboratoires internationaux (Europe, Chine, Inde, Moyen-Orient, Afrique du Nord). Son expertise est régulièrement sollicitée par les régulateurs nationaux et les rédacteurs de politiques publiques. Des activités de recherche sont également menées dans le cadre de projets de recherche nationaux (ANR, FUI) et internationaux (projets européens), en étroite collaboration avec de grands industriels du domaine.

RMS dispose de laboratoires de recherche communs dont NewNet@Paris (avec CISCO), SEIDO Lab (avec EDF), LINCS (avec Nokia, Inria, Sorbonne Université et l'IRT SystemX) et ValaDoE (avec la Région Pays de la Loire, Nantes Métropole, ENEDIS et Mines Saint-Étienne).

Envisioning the world with 5G and beyond

Missions d'expertise
Marceau Coupechoux est membre du Comité d'experts en réseaux mobiles de l'ARCEP. Daniel Kofman est membre du Comité Scientifique de l'ARCEP, du Groupe 5G du Comité Stratégique de Filière Infrastructures Numériques du Conseil National de l'Industrie (CNI) et invité permanent au Comité Scientifique de l'IRT SystemX.

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Thesis 5
Thèses soutenues

Patents 7
Brevets

Publications 36
Publications

5G mobile networks will have to deal simultaneously with three types of traffic: mobile broadband communications, critical communications and the Internet of Things.

EN 5G and beyond need novel approaches taking into account various simultaneous use cases and keeping in mind reliability, data rates and latency. Among research projects that address this cutting edge technology, RMS proposed and evaluated in [1] a hybrid 5G Fiber-Wireless (FiWi) access architecture equipped with Mobile Edge Computing-enabled (MEC) macro base stations. Genetic Algorithms are used to solve the user association problem under differentiated Quality of Service. In [2], a multi-tier wireless network consisting of multi-radio access technology (RAT) small cells is modeled, its performance analyzed and network parameters are optimized to allow network slicing. RMS operates the lisp-lab (Internet of the future), SILECS (Future IoT), and SDR 5G platforms (see next page).

▸[1] P. Foroughi, H. Beyranvand, **M. Gagnaire** and **S. Al Zahr**, "User Association in Hybrid UAV-cellular Networks for Massive Real-time IoT Applications," IEEE INFOCOM 2020 - IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS), Toronto, ON, Canada, 2020, pp. 243-248

▸ [2] G. Ghatak, A. De Domenico and **M. Coupechoux**, "Small Cell Deployment Along Roads: Coverage Analysis and Slice-Aware RAT Selection," in IEEE Transactions on Communications, vol. 67, no. 8, pp. 5875-5891, Aug. 2019

Robust optimization and game theory for smart grids

EN In addition to the ongoing transformation in the power system, attention is being paid to the impact of the high penetration of renewable energy sources on power grids' performance (reliability, quality of supply, voltage and frequency variations, etc.). To cope with these issues, utilities will increasingly take advantage of demand flexibility. Demand response aims to influence, through time-variable pricing or incentives, the ability and willingness of consumers to modify their consumption in line with utilities' needs. However, in a residential area for instance, uncoordinated demand response programs may lead to undesirable outcomes such as rebound peaks at the neighborhood level. Article [3] proposes a robust collaborative demand response solution. The proposed solution enables households to collaborate, achieving overall comfort (e.g., load flattening) while still meeting their own optimization objective (e.g., cost reduction). Robust optimization is used to mitigate the collaboration uncertainty, i.e., whether households collaborate to achieve overall comfort or focus on their optimization objective.

In another electricity supplier related use case, game theory is used to study shared investment models. To achieve a fully decarbonized power grid, a massive deployment of renewable energy resources will be needed, in particular at local level, in which case, because of their intermittent nature, energy storage should also be deployed at the residential level. However, this represents a considerable investment, without any guarantee of profit. In [4], the authors extend the state of the art in cooperative games for modeling the shared investment in storage by adding two crucial extensions: stochasticity of the load and discreteness of the storage device capacity. Simulations use real data and the proposed scheme offers promising results. This paper has been awarded Best Paper runner up at the ACM e-Energy 2020. This work has been carried out at LINCS (a joint research and innovation lab providing a setting for high level international collaboration), as part of a line of research led by RMS that produced 12 international scientific papers as well as open source code.

▸ [3] **S. Al Zahr**, E. Doumith, P. Forestier. (Jan. 2021) "Smart energy: A collaborative demand response solution for smart neighborhood". In: M. A. Khan, F. Algarni, M. T. Quasim, (eds.) Smart cities: A data analytics perspective, Springer 2021.

▸ [4] **D. Kiedanski**, A. Orda, **D. Kofman**. "Discrete and stochastic coalitional storage games". Eleventh ACM International Conference on Future Energy Systems (ACM e-Energy), 2020, Melbourne, Australia.

Learnability & Resource Allocation in Virtualized environments

EN Network applications are now distributed on various and flexible pieces of software that are executed on a commodity server. The server resources (CPUs, NICs, RAM) are provided to clients in accordance with a Service-Level Agreement. This requires a rethink of the way networks are implemented in order to get high speed data packet processing in these virtualized environments, and the way in which performance analyses are performed [5]. Furthermore, as high-speed network applications are often opaque to the operating system, resource allocation procedures are very difficult to implement because of the complexity of quantifying the resource requirements and effectively obtaining measurements in virtualized packet processing functions. In [6], a ML approach is used to learn the performance of the network, by solely looking at the runtime CPU footprint. In [7], a Multi-Cloud configuration to provide Service Chaining, a process where packets are steered through a sequence of services on their way to their destination, is investigated.

This work has been carried out as part of the Cisco NewNet@Paris chair and the German-French academy for the industry of the future.

▸ [5] **L. Linguaglossa**, D. Rossi, S. Pontarelli, D. Barach, D. Marion, P. Pfister, "High-speed data plane and network functions virtualization by vectorizing packet processing", Elsevier Computer Networks, 2019

▸ [6] C. Shelbourne, **L. Linguaglossa**, A. Lipani, T. Zhang, and F. Geyer. 2019. "On the Learnability of Software Router Performance via CPU Measurements". In Proceedings of the 15th International Conference on emerging Networking EXperiments and Technologies (CoNEXT '19).

▸ [7] F. Spinelli, **L. Iannone**, J. Tollet. "Multi-Cloud Chaining with Segment Routing". 2020 IFIP Networking Conference (Networking), 514-518.

Path to the Internet of the Future

EN The Internet of the Future will be able to self-organize and self-optimize, in any scenario. Distinctions between mobile networks and the Internet, between cellular networks and the Internet of Things will become meaningless in a few years' time. How can we deliver the emerging convergence between cellular networks, the Internet of Things and distributed systems and between mobile networks, the Internet and virtualization? How should we analyze and optimize these increasingly complex networks? What mathematical models, what type of algorithm, what kind of metrology should we use? What sort of artificial intelligence will we need to operate and optimize networks, especially with a view to reducing energy consumption? How can we ensure scaling, regulation and competition? These, and many others, are the questions that researchers at Télécom Paris are addressing, to invent the Internet of 2030.

Addressing the convergence between cellular networks, the Internet of Things, distributed systems, mobile networks, virtualization, and the Internet.

Data Storage of the future

EN The Internet of the future also raises the question of data storage in data centers, particularly the issues of optimization and resource allocation. RMS proposes in [1] a distributed storage architecture integrated into the IPv6 network in order to reduce the complexity of storage systems. In [2], RMS studies the implementation of coding solutions optimized for these systems, which can improve recovery time in case of failure. In addition, innovative machine learning solutions for the automatic placement of data, according to their access frequency, are developed. The aim is to automatically assign data to the appropriate storage elements while optimizing re-location costs. These proposals are currently being tested in a Télécom Paris spinoff, in partnership with key manufacturers in the sector.

▸ [1] **G. Ruty, J. L. Rougier**, A. Surcouf, A. Augustin. "An initial evaluation of 6Stor, a dynamically scalable IPv6-centric distributed object storage system". Cluster Computing 22 (4), 1123-1142, 2019

▸ [2] **N. Boukhatem, H. Baccouch**. "Méthodes et dispositifs de codage et de décodage de données", PCT/EP2019/059119, 2019

Experimentation rooms

EN Two experiment rooms have been designed and deployed by RMS (p. 52) in Télécom Paris' premises.

Experimentation room in ISM band (802.15.4, Wifi, LORA)

This room allows members of the academic/industrial community to develop and to deploy images built on open source operating systems in order to conduct experiments on connected objects. It forms part of the FIT Equipex (iot-lab.info) and is currently being upgraded to the national SILECS platform (silecs.net), which is accredited as Very Large Research Infrastructure.

Cellular experimentation room (2G, 3G, 4G, NB-IoT, 5G)

This room, which is part of the national SILECS platform, includes a Faraday cage in which SDR cards are placed. 2G, 4G, NB-IoT and 5G networks, made operational inside the cage, are used to allow specific developments to be tested on one of these systems (with a software defined radio approach). The baseband processing is carried out on dedicated servers placed inside the cage. Core network elements are placed in a datacenter on servers that can be deployed via Openstack or Kubernetes.

See also

▸ Some of these projects benefit from the existence of LINCS (Laboratory of Information, Networking and Communication Sciences), a joint academia-industry research and innovation lab, composed of Inria, Institut Mines-Telecom, Sorbonne Université, Nokia Bell Labs and SystemX - www.lincs.fr

▸ Work carried out under this Very Large Networks and Systems umbrella also studies the future of quantum systems (IQA & GTO collaboration, see Quantum Secure Networks, p. 49).

▸ See also TTool (LabSoC) p. 31, and POM, p. 79.

IMAGES — Image, Modeling, Analysis, GEometry, Synthesis
Image, Modélisation, Analyse, GEométrie, Synthèse

▸ 3D visualization of the white matter fibers of the human brain using the geometric model proposed in the NeuralMetaTracts project (p. 81)

Group leader
— Responsable d'équipe

Florence Tupin

Keywords
Mathematics and artificial intelligence for images, Stochastic image modeling, Machine learning and deep learning, Image and video restoration, Image and video synthesis and editing, Discrete mathematics, Algebraic and structural models, Symbolic AI, Computer graphics, geometrical and topological analysis, Rendering, simulation, Remote sensing imaging, SAR imaging, Medical imaging, Computational photography, Creative industries

Mots-clés
Mathématique et intelligence artificielle pour l'image, Modélisation stochastique des images, Apprentissage, restauration d'images et de vidéos, Synthèse et édition d'images et de vidéos, Mathématiques discrètes, Modèles algébriques et structurels, IA symbolique, Informatique graphique, Analyse géométrique et topologique, rendu, Images et données de télédétection, Imagerie SAR, Imagerie médicale, Photographie computationnelle, Industries créatives

Web
telecom-paris.fr/images

See also
▸ Neural Meta Tracts: visualizing white matter tractograms p. 81

EN IMAGES carries out research in image analysis and understanding, computer vision and 3D computer graphics, covering the entire spectrum of the modeling, analysis, transformation, representation, interpretation and synthesis of images, 3D and digital objects. It focuses on the **modeling of images**, tri-dimensional and numerical objects, with the development of **mathematical models**, ranging from the physical acquisition to the high-level interpretation, and **artificial intelligence models** (logic, knowledge representation, spatial reasoning, machine learning). It also has strong expertise in **computer graphics** for geometric modeling, image synthesis, animation and simulation, virtual reality and 3D interactive systems.

IMAGES's strength is the mastery of the whole chain of **image and data processing**, ranging from acquisition steps to **information extraction** and **higher level understanding**, along with the distinctive characteristic of covering many aspects of AI: recent machine learning methods, including deep learning, as well as symbolic artificial intelligence. It also benefits from the strong interactions between all research topics—for instance, computer graphics, image processing and image analysis.

IMAGES' expertise relies on in-depth knowledge of special application fields—medical imaging, remote sensing imaging, computational photography, interactive games and creative industries—and applications with a societal impact, thanks to strong and long-term collaborations with academic and state or industrial partners.

FR IMAGES conduit des recherches en analyse et interprétation d'images, en vision par ordinateur et en informatique graphique 3D, couvrant tout le spectre de modélisation, d'analyse, de transformation, de représentation, d'interprétation et de synthèse d'images, volumes et objets numériques. Ses travaux portent sur la **modélisation d'images**, d'objets tridimensionnels et numériques, reposant sur le développement de **modèles mathématiques**, allant de l'acquisition physique à l'interprétation de haut niveau, et de **modèles d'intelligence artificielle** (logiques, représentation des connaissances, raisonnement spatial, apprentissage). IMAGES possède également une forte expertise en **informatique graphique** pour la modélisation géométrique, la synthèse d'images, l'animation et la simulation, la réalité virtuelle et les systèmes 3D interactifs.

La force d'IMAGES est la maîtrise de toute la chaîne de **traitement des images et des données**, allant des étapes d'acquisition à l'**extraction d'informations** et à l'**interprétation de haut niveau**, ainsi que sa capacité distinctive à pouvoir couvrir de nombreux aspects de l'IA : des méthodes récentes d'apprentissage, y compris l'apprentissage profond, à l'intelligence artificielle symbolique. Tous les sujets de recherche bénéficient de fortes interactions entre eux. C'est le cas par exemple des liens entre informatique graphique, traitement des images et analyse d'images.

L'expertise d'IMAGES repose sur une connaissance approfondie de domaines d'application privilégiés – imagerie médicale, imagerie de télédétection, photographie numérique, jeux interactifs et industries créatives – et d'applications ayant un impact sociétal, grâce à des collaborations solides et de longue durée avec des partenaires universitaires et des institutions publiques ou industrielles.

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▸ Illustration des objets d'intérêt dans une image d'art pour le modèle Faster RCNN sans recouvrement possible **Nicolas Gonthier**, sous la direction de **Yann Gousseau** et **Saïd Ladjal**

Understanding deep learning methods of image synthesis

EN Autoencoders and Generative Adversarial networks have produced spectacular results in the domain of image synthesis—faces, landscapes—but there is still a severe lack of theoretical understanding of how these networks work. Consequently, practical problems during training or generalization are poorly addressed. This explainability challenge still being in its infancy, it is necessary to analyze the ability of the simplest generative network, the autoencoder, to encode and decode two simple geometric attributes, size and position, for very simple images. In [1], the case of images of centered disks with variable radii, and the encoding and decoding of Dirac delta functions, are analyzed respectively for gaining hints on how size and position are processed by these networks. The investigations allowed us to explain the internal mechanisms of the autoencoder. A regularization approach which is able to overcome a problem related to generalization when data points are missing in the training set is also proposed. This work is extended step by step to more complex shapes and properties such as color and rotation.

▸ [1] Processing Simple Geometric Attributes with Autoencoders, **A. Newson**, A. Almansa, **Y. Gousseau**, **S.Ladjal**, J. Math. Imaging Vis. 62(3): 293-312, 2020

3D surface reconstruction in SAR tomography

EN Synthetic Aperture Radar (SAR) tomography is an original approach to analyze urban areas. By combining multiple images, this technique enables the differentiation of the scatterers inside a vertical cell. SAR tomography reconstruction is generally performed in two steps: (i) reconstruction of the so-called tomogram by vertical focusing, at each radar resolution cell, to extract the complex amplitudes (a 1-D processing); (ii) transformation from radar geometry to ground geometry and extraction of significant scatterers. It is proposed in [2] to perform the tomographic inversion directly in ground geometry in order to enforce spatial regularity in 3-D space. An iterative method based on variable splitting and the augmented Lagrangian technique is proposed to solve an underlying large-scale non-convex optimization problem.

The potential of this approach is illustrated on simulated data and on a TerraSAR-X tomographic dataset. Indeed, high resolution satellites such as TerraSAR-X provide images that can be combined to produce 3-D models. In urban areas, sparsity priors used during the tomographic inversion process, to retrieve the location of scatterers seen within a given radar resolution cell, often miss flat areas such as the ground or rooftops. In order to improve the recovery of these urban surfaces, a surface segmentation algorithm was proposed in [3], based on the computation of the optimal cut in a flow network, illustrated again on real TerraSAR-X tomographic datasets.

This work has been funded by the ALYS project (ASTRID-ANR funding from DGA, Direction Générale de l'Armement) and DigiCosme PhD funding.

▸ alys.wp.imt.fr/publications

▸ [2] Introducing spatial regularization in SAR tomography, **C. Rambour**, L. Denis, **F. Tupin**, H. Oriot, IEEE Trans. on Geoscience and Remote Sensing, 2019

▸ [3] Urban Surface Reconstruction in SAR tomography by Graph-Cuts, **C. Rambour**, L. Denis, **F. Tupin**, H.Oriot, Y. Huang, L. Ferro-Famil, Computer Vision and Image Understanding, 2019

Patents
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6

Publications
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MM

Permanent members Membres permanents	8
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Patents Brevets	18
Publications Publications	20

Group leader
– Responsable d'équipe

Marco Cagnazzo

Keywords
Image and video compression, Transport and orchestration of multimedia content, Immersive media and interactivity, Deep learning for image and video generation, Deep learning with limited supervision

Mots-clés
Compression images et vidéo, Transport et orchestration des contenus multimédia, Médias immersifs et interactivité, Apprentissage profond pour la génération d'images et de vidéos, Apprentissage avec supervision limitée

Web
telecom-paris.fr/mm

See also
▸ GPAC Open Source Software, p. 83

EN MM's research concerns the entire life cycle of multimedia documents and signals—acquisition, coding, transmission, transport, interactivity and recognition. It can be divided into three main areas: compression and transmission of images and videos, interactive service delivery and orchestration, deep learning for image and video compression and processing. The latter is an emerging topic of research and will be incorporated into the first one in the long term.

Traditionally active in **image and video compression**, MM focuses recent projects on emerging **immersive formats** such as multiview and 360 video, high-dynamic-range video and digital holography. Research activities are carried out in the field of robust video transmission, with a consistent set of contributions in the domains of distributed video coding, network coding and, more recently, linear video coding. In addition to these activities, MM continues to work on more traditional but still very relevant problems such as rate-distortion optimization, transcoding, and super-resolution.

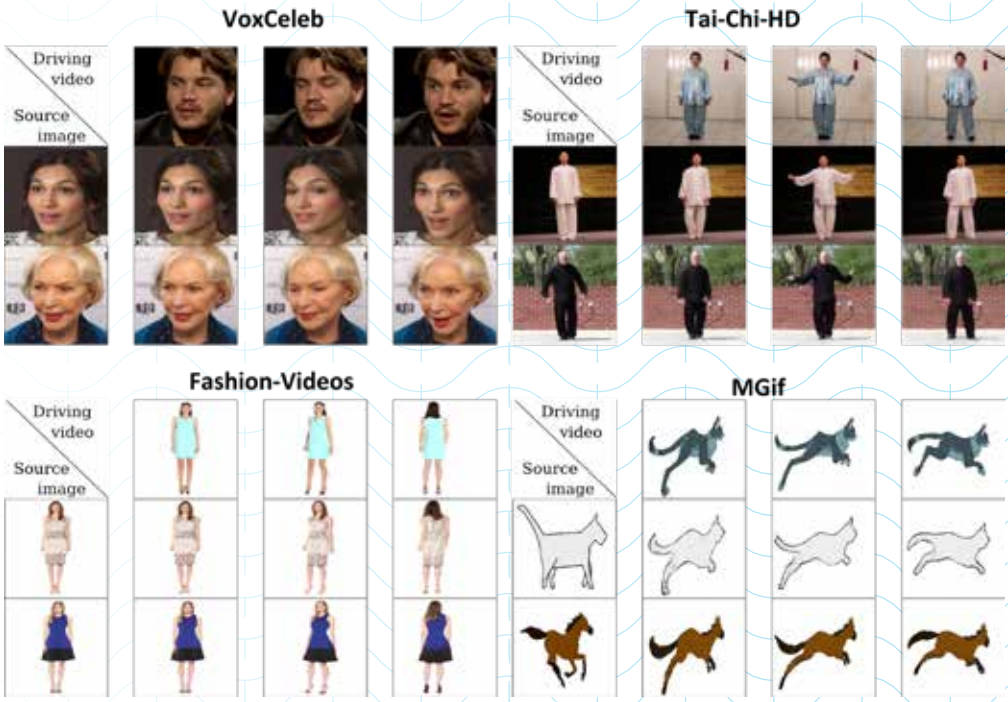
Immersive visual formats require new solutions not only for compression, but also for transmission architectures, which is why MM also works on interactive and adaptive **multimedia streaming**, and on multimedia **orchestration**—using multiple sources and multiple networks to deliver the stream to multiple screens. Furthermore, **deep networks** and large-scale training are being investigated as a promising method for video compression. Generative models could also be used to this end, in addition to their capacity to generate images and videos.

MM focuses recent projects on emerging immersive formats such as multiview and 360 video, high-dynamic-range video and digital holography

FR MM effectue des travaux de recherche sur tout le cycle de vie des documents et signaux multimédia – acquisition, codage, transmission, transport, interactivité et reconnaissance. Trois domaines principaux sont considérés : la compression et la transmission d'images et de vidéos, la fourniture et l'orchestration de services interactifs, l'apprentissage profond pour la compression et le traitement des images et des vidéos. Ce dernier est un sujet de recherche émergent et sera fusionné avec le premier à long terme.

Depuis longtemps active dans la **compression d'images et de vidéos**, MM a récemment développé ses recherches vers les **formats immersifs** émergents tels que la vidéo multi-vues et la vidéo 360°, la vidéo à haute dynamique et l'holographie numérique. Des activités de recherche sont également menées dans le domaine de la transmission robuste, selon un ensemble cohérent de contributions dans les domaines du codage vidéo distribué, du codage en réseau et plus récemment du codage vidéo linéaire. Parallèlement à ces activités, MM continue de travailler sur des problèmes plus traditionnels mais toujours pertinents comme l'optimisation du taux de distorsion, le transcodage et la super-résolution.

Les formats visuels immersifs nécessitant de nouvelles solutions non seulement pour la compression, mais aussi pour les architectures de transmission, MM effectue également des travaux sur le **streaming multimédia** interactif et adaptatif, et sur l'**orchestration multimédia** – en utilisant plusieurs sources et plusieurs réseaux pour diffuser le flux sur plusieurs écrans. En outre, les **réseaux profonds** et les techniques d'apprentissage à grande échelle sont étudiés comme voie prometteuse pour la compression vidéo. Des modèles génératifs sont également étudiés pour être éventuellement utilisés à cette fin, en plus de leur capacité à générer des images et des vidéos.



▸ Example animations produced by the method proposed in [4]. Four different datasets have been used for training: VoxCeleb (top left), Tai-Chi-HD (top right), Fashion-Videos (bottom left) and MGif (bottom right).
For each of the four examples, the motion from the "Driving video" (top row) is used to animate the "Source image" (left column), producing the animated images in the second and third rows.

Distributed media processing and next-generation broadcast

EN Standards such as MPEG-DASH or MMT (MPEG Media Transport), in which MM has been heavily involved, were the first steps towards a re-architecture of MPEG-2 Transport Stream-based broadcast networks. New advances —Linear Video Coding, ATSC ROUTE— show the extent of the issues still to be addressed. The mass delivery of interactive content over upcoming IP protocols such as HTTP/2 and HTTP/3 also needs to be tackled.

Along these lines, work is being conducted to improve Quality of Experience (QoE) via HTTP adaptive streaming with various adaptive bitrate (ABR) algorithms, in a peer-to-peer (P2P) network context. These algorithms can be classified into buffer-based, throughput-based or hybrid buffer-throughput algorithms, with respect to their required input information. In [1], two methodologies are proposed to make these algorithms more efficient in P2P networks regardless of the ABR algorithm used, one favoring overall QoE and one favoring P2P efficiency. Additionally, two new metrics to quantify the P2P efficiency for ABR delivery over P2P are presented.

Article [2] presents a major re-architecture undergone by the GPAC open-source media framework to offer developers and end users a completely configurable media pipeline in a simple way. GPAC can now mix a variety of functionalities, such as network inputs and outputs, multiplexing stacks, compression, uncompressed domain effects and scripting, and realtime processing for live services.

From synthesis and compression to deep learning generation of image and video

EN Traditional compression algorithms operate with a limited understanding of the semantic information that resides in the data. With the rise of machine learning techniques, MM proposes novel approaches for image and video compression where deep learning techniques are used to identify semantic information within the data in order to improve compression. Let us examine a practical example: an airplane cockpit screen.

Recording an airplane cockpit screen is a challenging task since video codecs hardly preserve text details at the low bitrates required by avionic applications. Article [3] presents a scheme for the semantic compression of airplane cockpit video that preserves the readability of text under bitrate and encoder complexity constraints, and its evaluation with multiple video codecs with different prediction schemes. In each frame, text is segmented from the video and encoded as character strings. It is then inpainted, producing a residual video with few high frequency components that are easily encodable with standard codecs. The residual video is transmitted with the encoded text as side-information. At the receiver side, characters are synthesized atop the decoded residual video, leaving the text unaffected by compression artefacts.

In such a use case, the high order semantic information residing in text could be extracted from images and videos by means of deep learning techniques. In that respect, MM now runs a study group named "Machine Learning for Compression" generating interest and collaborations from academic and industrial labs. https://mlcompr.wp.imt.fr/. Stéphane Lathuilière, who has a strong background in deep learning based video processing, joined MM in October 2020. In particular, he worked on motion representation learning for video generation. This research theme addresses both sides: in addition to using neural networks to enhance compression, MM also explores the problem of compressing neural networks.

▸ [1] **H. Yousef**, **J. Le Feuvre**, P. L. Ageneau, and A. Storelli. 2020. "Enabling adaptive bitrate algorithms in hybrid CDN/P2P networks." In Proceedings of the 11th ACM Multimedia Systems Conference (MMSys '20).

▸ [2] **J. Le Feuvre**. 2020. GPAC filters. In Proceedings of the 11th ACM Multimedia Systems Conference (MMSys '20).

▸ [3] **I. Mitrica**, **A. Fiandrotti**, **M. Cagnazzo**, E. Mercier, C. Ruellan. "Cockpit video coding with temporal prediction." European Workshop on Visual Information Processing (EUVIP), Oct 2019, Rome, Italy. **Best Paper Award**

▸ [4] A. Siarohin, **S. Lathuilière**, S. Tulyakov, E. Ricci and N. Sebe. "First Order Motion Model for Image Animation." NeurIPS 2019.

S²A

Signal, Statistics and Learning
Signal Statistique et Apprentissage

Group leader
– Responsable d'équipe

Stephan Clémençon

Keywords
Statistics, Probabilistic Modeling, Machine Learning, Data Science, Audio and Social Signal Processing

Mots-clés
Statistique, Modélisation Probabiliste, Apprentissage Machine, Science des Données, Traitement des signaux audio et sociaux

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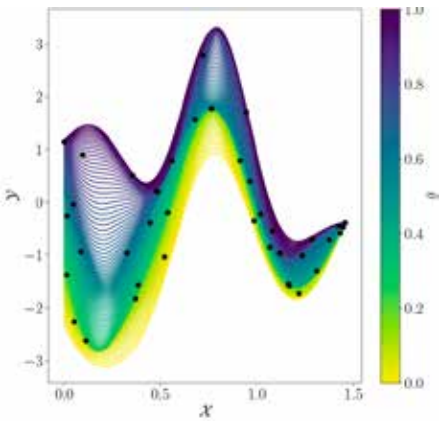
See also

- Pavlo Mozharovskyi p. 11
- Florence d'Alché-Buc p. 14
- DSAIDIS Chair, p. 7

Finding a sparse, adaptive representation of information

EN S²A structures its research around four interconnected topics: **Probabilistic modeling, simulation and mathematical statistics, Machine Learning and optimization, Audio data analysis and signal processing, Social computing**. Work is conducted on a wide variety of data—high-dimensional, structured, heterogeneous / multiscale, massive, incomplete / censored data, data streams, audio signals, text, weak signals and extreme and rare events—and use cases—including anomaly detection, brain data analysis and emotion recognition via handwriting or EEGs, audio data analysis, signal processing, recommender systems and graph inference, chatbots, opinion-mining and human-agent interaction, ranging from social signal perception to generation. This data, which comes from the Internet of Things or from distributed file systems, is often massive, needing massively parallelized / distributed computation, large scale learning and real time processing.

In addition to these constraints and parameters, a key to efficient data processing explored by S²A, and a major problem in mathematics, is to find a sparse, adaptive representation of information and to devise algorithms to calculate it quickly. From an operational point of view, embedding predictive models should not compromise the autonomy of the systems they rely on, and should take the constraints of (nearly) real time operations into account. This raises questions on compression information and the rules for processing it. Moving up to the socio-technical aspects, S²A's work also considers the level of delegation to be granted to smart systems, as well as questions of reliability, interpretable decisions, privacy preservation and ethics. These high level considerations are taken into account by S²A to develop statistical learning techniques that hold up even if part of the data has been contaminated, due to biases in measurements or the deliberate intention to impair the operation of an automated system.



FR S²A structure ses recherches autour de quatre thèmes étroitement liés : **la modélisation probabiliste, la simulation et les statistiques mathématiques ; l'apprentissage automatique et l'optimisation ; l'analyse des données audio et le traitement du signal ; l'informatique sociale**. Les travaux sont menés sur une grande variété de données – données à haute dimension, structurées, hétérogènes / multi-échelles, massives, incomplètes / censurées, flux de données, signaux audio, textes, signaux faibles et événements extrêmes et rares – et de cas d'utilisation – de la détection d'anomalies, l'analyse de données cérébrales, la reconnaissance d'émotions à travers l'écriture ou des encéphalogrammes, l'analyse de données audio et le traitement du signal, à la recommandation de systèmes et l'inférence de graphes, les chatbots, l'exploration des opinions et l'interaction humain-agent allant de la perception de signaux sociaux à leur génération. Ces données, provenant de l'Internet des objets ou de systèmes de fichiers distribués, sont souvent massives, nécessitant un calcul massivement parallélisé / distribué, un apprentissage à grande échelle et un traitement en temps réel.

Parallèlement à ces contraintes et paramètres, une des clés de l'efficacité du traitement des données explorées par S2A, qui est un problème majeur en mathématiques, est de trouver une représentation adaptative et clairsemée de l'information, et d'élaborer des algorithmes permettant de la calculer rapidement. D'un point de vue opérationnel, l'intégration de modèles prédictifs ne doit pas non plus compromettre l'autonomie des systèmes sur lesquels ils reposent et doit tenir compte des contraintes d'opérations (presque) en temps réel. Cela soulève des questions sur la compression des informations et leurs règles de traitement. Puis, remontant vers les aspects socio-techniques, les travaux de S²A examinent également le niveau de délégation à accorder aux systèmes intelligents, et les questions de fiabilité, de décisions interprétables, de préservation de la vie privée et d'éthique. Ces considérations de haut niveau sont reprises par S²A pour développer des techniques d'apprentissage statistique qui restent valables même si une partie des données a été contaminée, suite à des biais dans les mesures ou l'intention délibérée de nuire au fonctionnement d'un système automatisé.

▸ Régression quantile multiple

Outlier detection and robustness guarantees

EN Diagnosis and decision in critical environments and industrial contexts need advanced machine learning tools with a large spectrum of guarantees such as correctness, traceability and interpretability of decision, robustness, ability to abstain in order to let human experts take over at the right moment, and even additional high-level properties such as privacy and fairness. Guarantees for robustness is the objective for one of the four themes of the Data Science & Artificial Intelligence for Digitalized Industry & Service Chair created in 2019, namely: "Machine Learning for trusted and robust decision". It covers outlier awareness, extreme value theory, robust regression and robust clustering, quantile regression and theoretical guarantees on learning methods.

Research in this area is still in its infancy, making its way in the machine learning paradigm through the development of methods tied to these guarantees. The study of extreme values and subsequent outlier detection is such a research topic, in which models are created to describe observations in the extreme locations of the data space, as in the following paper. Anomalies in the behavior of a complex system often correspond to the simultaneous occurrence of extreme values for certain subgroups of observed variables. Under the heavy-tail assumption, statistical methods relying on multivariate extreme value theory have been developed in the past few years to identify such subgroups. In the paper, this approach is studied much further and a novel mixt model enables extreme observations to be clustered and an informative 2-d representation of anomalies to be obtained using standard graph-mining tools, the relevance and usefulness of which is illustrated on simulated datasets and real observations in the aeronautics application domain.

▸ M. Chiapino, **S. Clémençon**, V. Feuillard and **A. Sabourin**. "A multivariate extreme value theory approach to anomaly clustering and visualization". Computational Statistics 35, 607–628 (2020)

▸ www.telecom-paris.fr/dsaidis

From audio signals to social signals

EN A significant part of S²A's research is dedicated to audio data analysis and signal processing, around data analysis methods primarily targeting audio data. Two types of tasks are addressed: source separation and human activity-related scene and content analysis. Applications cover machine listening, music information retrieval (MIR), heterogeneous, multi-view or multimodal—multimedia content—data analysis, brain—M/EEG—data signal analysis, audio signal transformation and musical acoustics.

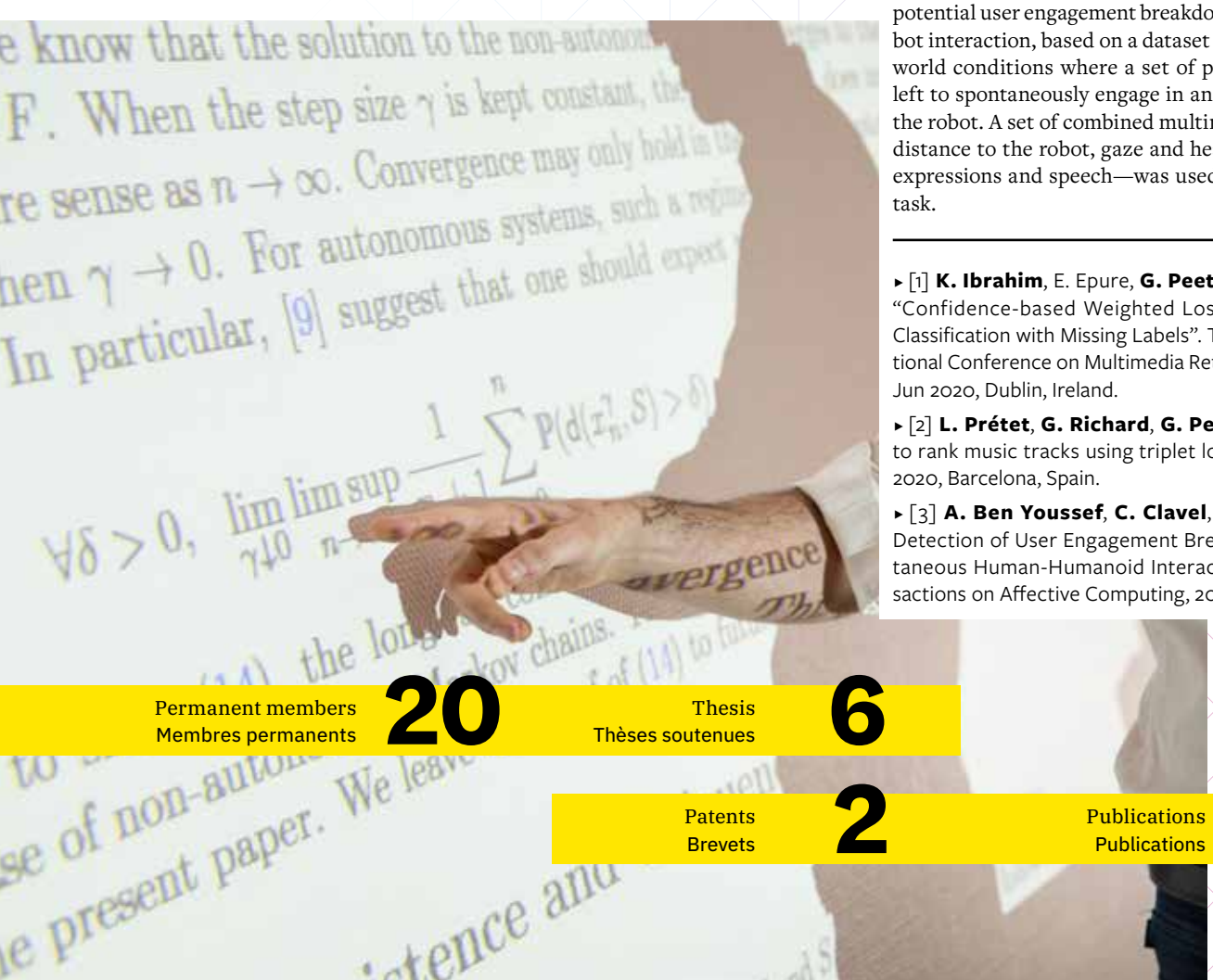
The following papers are relevant to the MIR topic. In article [1], a common challenge that is prevalent in domains such as image annotation and auto-tagging, the problem of multi-label classification with missing labels (MLML), is tackled. A weighted loss function to account for the confidence in each label/sample pair that can easily be incorporated to fine-tune a pre-trained model on an incomplete dataset is proposed. Performances of this model improve as the ratio of missing labels increases. In article [2], a method for direct recommendation based on the audio content without explicitly tagging the music tracks is proposed.

Methods developed in various fields of signal processing (e.g speech signal processing for the recognition of emotions) are also used in social computing—research around computational models for the analysis of social interactions for both web analysis and social robotics. They are used in conjunction with methods from psychology, sociology, and linguistics, in a multidisciplinary approach. Article [3] presents a supervized classification system for forecasting a potential user engagement breakdown in human-robot interaction, based on a dataset collected in real-world conditions where a set of participants were left to spontaneously engage in an interaction with the robot. A set of combined multimodal features—distance to the robot, gaze and head motion, facial expressions and speech—was used to perform this task.

▸ [1] **K. Ibrahim**, E. Epure, **G. Peeters**, **G. Richard**. "Confidence-based Weighted Loss for Multi-label Classification with Missing Labels". The 2020 International Conference on Multimedia Retrieval (ICMR '20), Jun 2020, Dublin, Ireland.

▸ [2] **L. Prétet**, **G. Richard**, **G. Peeters**. "Learning to rank music tracks using triplet loss". ICASSP, May 2020, Barcelona, Spain.

▸ [3] **A. Ben Youssef**, **C. Clavel**, **S. Essid**. "Early Detection of User Engagement Breakdown in Spontaneous Human-Humanoid Interaction", IEEE Transactions on Affective Computing, 2019



Permanent members / Membres permanents **20**

Thesis / Thèses soutenues **6**

Patents / Brevets **2**

Publications / Publications **70**

Comparison of algorithms for TV+L1-regularized regression at various regularization parameters, from [1]

Coordinate Descent Primal-Dual algorithm and solver

EN Coordinate descent is an optimization algorithm where a subset of the coordinates of the primal and dual iterates is updated at each iteration, the other coordinates being maintained at their past value. In [1], a method enabling optimization problems to be solved with a combination of differentiable functions, constraints, as well as non-separable and non-differentiable regularizers, is presented. This is done by combining features of two seemingly incompatible versions of coordinate descent: one based on Fejér monotonicity, which allows non-separable non-smooth functions, and one based on the decrease of the function value, which enables a large step size. The sequences generated by this algorithm almost certainly converge to a saddle point, for a wider range of parameter values than previous methods. Its performances are illustrated on a total-variation regularized least squares regression problem and on large scale support vector machine problems. In article [2], a coordinate descent solver fitted to the above algorithm is presented. Equipped with a modeling language in Python for piloting the solver at run time, it can be used to solve a large variety of problems including Lasso, sparse multinomial logistic regression, and linear and quadratic programmes.

▸ [1] **O. Fercoq**, **P. Bianchi**. "A Coordinate Descent Primal-Dual Algorithm with Large Step Size and Possibly Non Separable Functions". SIAM Journal on Optimization, Society for Industrial and Applied Mathematics, 2019, 29 (1), pp. 100-134

▸ [2] **O. Fercoq**. "A generic coordinate descent solver for non-smooth convex optimisation". Optimization Methods and Software, 2019. 1-21. 10.1080/10556788.2019.1658758.

Operational AI Ethics Project

EN Digital trust lies at the heart of all major technological strategies. The current massive use of data and artificial intelligence systems raises many issues on trust which need to take priority. This is what the European Commission advised in its White Paper, "Artificial intelligence: a European approach based on excellence and trust". Trust can be established with the development of algorithms that are both transparent and explainable. In 2019, Télécom Paris launched Operational AI Ethics, a multi-disciplinary research project—applied mathematics, statistics, computing, economics, law and sociology—which aims to create operational artificial intelligence tools that incorporate, right from the design stage, ethical principles for the development of AI that serves the common good. The project is organized in five lines of research—Bias and equity, Explainability, Responsibility, Governance and regulation, AI and the common good—and brings together some of the work carried out by research chairs: NoRDF project, Data Science and Artificial Intelligence for Digitalized Industry and Services, Explainable AI for Anti-Money Laundering and Digital Finance. In April 2020, this multidisciplinary team published a report summarizing the state of the art in the field and proposed four contextual factors to contribute to the improvement of algorithm explainability.

▸ [3] **V. Beaudouin**, **I. Bloch**, **D. Bounie**, **S. Clémençon**, **F. d'Alché-Buc**, **J. Eagan**, **W. Maxwell**, **P. Mozharovskyi**, **J. Parekh**. "Flexible and Context-Specific AI Explainability: A Multidisciplinary Approach". 2020

▸ telecom-paris.fr/explainable-artificial-intelligence

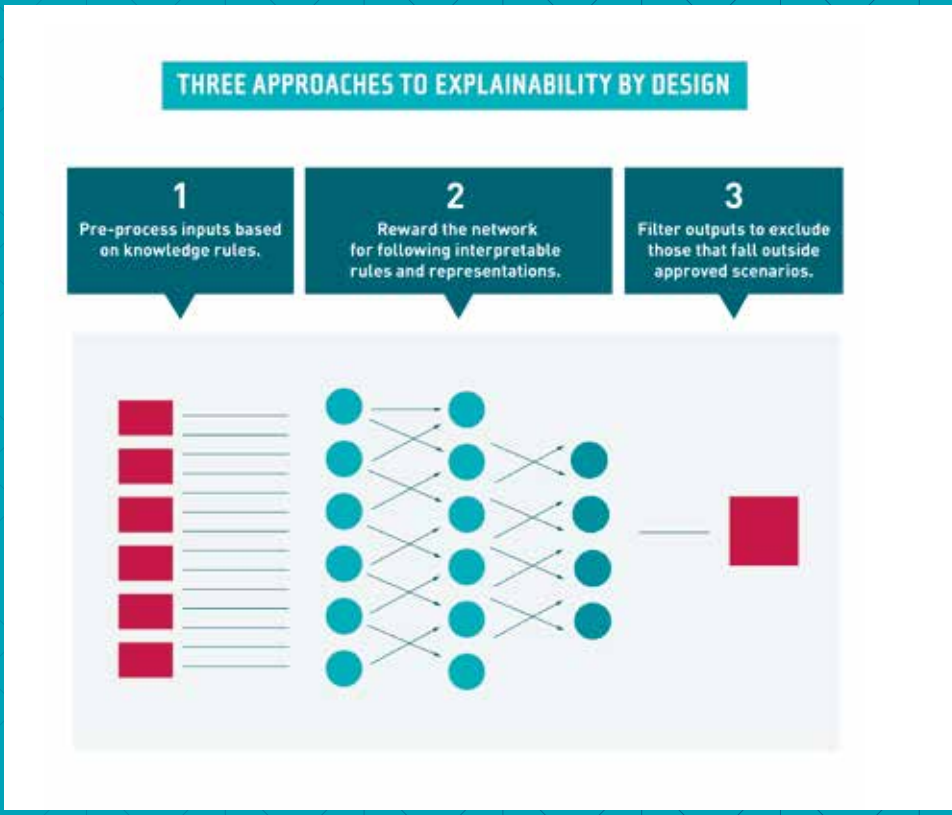
Scaling up in a multidimensional domain

EN While the last few years have seen unprecedented achievements in artificial and convolutional neural networks in computer vision tasks (detection, classification, motion estimation, synthesis and enhancement of visual data), with deep networks and large-scale training being among the key factors of success, the entire field of **Machine Learning and Artificial Intelligence** (ML/AI) has now broadly spread to nearly all human activities: transportation, energy, medicine, security, banking, insurance, commerce, etc. The two main challenges of the ML/AI domain are scaling up, managing the complexity and explainability of algorithms on the one hand and taking advantage of the multidisciplinary dimension on the other hand, by combining methods, technologies and uses. In other words, research is conducted to both study the management and analysis of data in all its forms—massive volumes, complex, heterogeneous, uncertain—and to develop practical applications in many areas as varied as health and medical imaging, the Internet of Things and cybersecurity, new media services and creative industry, and socio-emotional interaction.

This focus area draws on research teams' expertise in statistics, mathematics and computer science as well as law, economics and social sciences, all combined, with a permanent call for more interdisciplinarity. This broad spectrum of research interests, from advancing the mathematical foundations of ML/AI to bringing up high-level sociotechnical considerations, can be illustrated by the two research pojects presenteed opposite.

The main challenges of this domain are scaling up, managing the complexity and explainability of algorithms, and taking advantage of the multidisciplinary dimension

Excerpt from [3]



i3

interdisciplinary
institute on
innovation

“i3 is able to position itself at the cutting edge of international research on a topic that is essential to societies and economies, by tackling the issue of innovation in a broad sense (not just technological innovation, but also organizational, societal and regulatory innovation) and by doing so across disciplines. The work conducted in the lab aims to achieve theoretical understanding of the phenomenon and to help solve practical and managerial problems.”

Hervé Dumez
Professor at Ecole Polytechnique,
Director of the i3 Mixed Research Unit
Directeur de l’UMR i3

EN i3 has more than 200 members, including over 70 professor-researchers and more than 100 PhD students. The high-level research produced by the institute combines academic excellence with relevant findings for research users.
The LTCI and i3 labs frequently work together on topics that call on their respective disciplines. Projects include research on social touch (p. 47) and on the explainability of artificial intelligence to combat money laundering and the funding of terrorism, which forms the object of a research chair (XAI4AML), as part of the Operational AI Ethics project (p. 62).
In 2017, the High Council for Evaluation of Research and Higher Education (HCERES) assessed i3 and awarded it the highest grade for the quality of its research.

You will find in the following pages the presentation of the three Télécom Paris teams participating in i3, alongside researchers from Mines ParisTech and Ecole Polytechnique.

FR i3 rassemble plus de 200 personnes dont plus de 70 enseignants chercheurs permanents et plus d’une centaine de doctorants. L’institut développe une recherche de haut niveau conciliant excellence académique et pertinence pour l’ensemble des acteurs de la recherche.
Les deux laboratoires LTCI et i3 collaborent régulièrement sur des sujets convoquant leurs disciplines respectives. Citons ainsi les travaux sur le toucher social (p. 47) et ceux sur l’explicabilité de l’intelligence artificielle pour le blanchiment et le financement du terrorisme qui font l’objet d’une chaire de recherche (XAI4AML) dans le cadre de l’initiative Operational AI Ethics (p. 62).
En 2017, le Haut Conseil de l’Évaluation de la Recherche et de l’Enseignement Supérieur (HCERES) a évalué le laboratoire et lui a attribué la note maximale pour la qualité de ses recherches.

Vous trouverez dans les pages suivantes la présentation des trois équipes de Télécom Paris qui participent à i3, aux côtés de chercheurs de Mines ParisTech et de l’Ecole polytechnique.

Web
i3.cnrs.fr

EN **The Interdisciplinary Institute on Innovation** (i3) was created in 2012 by Mines ParisTech and Télécom Paris. Ecole Polytechnique joined it in 2014. On January 1, 2015, i3 became a CNRS Mixed Research Unit (UMR 9217), which comprises five research teams who work on innovation and social sciences. The Télécom Paris Economics and Social Sciences Department (ECOGE, INTERACT, SID) constitutes one of those five teams, together with the Ecole Polytechnique Management Research Center (CRG) and the CERNA, CGS and CSI teams at Mines ParisTech.

Innovation is a multidimensional phenomenon and central to the way societies operate. A proper understanding of its multiple dimensions requires exchanges among a range of disciplines, including economics, management, sociology, design and the psychology of ergonomics. The institute's researchers deal with fundamental issues that bring together very active international research communities, and are also highly relevant to companies and decision makers.

Research projects are organized into four cross-disciplinary themes, covering the entire field of innovation. Each theme offers an effective forum for exchanges among disciplines and among the institute's various teams. **Transformation in innovative companies; Design theories and models; Innovation regulation; Innovation practices, take-up and democratization.** With its research and training activities, i3 helps meet today's major challenges: the digital world, healthcare, innovation, energy and sustainable development.

Research is usually carried out in partnerships involving companies, not-for-profits or government agencies. The institute also heads the work of several research and training chairs. It engages in discussions with companies, not-for-profit organizations and public authorities using innovative exchange platforms.

FR L'**institut interdisciplinaire de l'innovation** (i3) a été créé en 2012 à l'initiative des Mines ParisTech et de Télécom Paris. En 2014, l'École polytechnique s'y est associée. Le 1er janvier 2015, i3 est devenu une unité mixte de recherche CNRS (UMR 9217) composée de cinq équipes de recherche autour de l'innovation et des sciences sociales. Le département Sciences Économiques et Sociales de Télécom Paris (ECOGE, INTERACT, SID) représente une de ces cinq équipes (avec le Centre de Recherche en Gestion (CRG) de l'École Polytechnique, ainsi que le CERNA, le CGS et le CSI des Mines ParisTech).

L'innovation est un phénomène multidimensionnel et central dans la dynamique de nos sociétés. Pour être compris dans ses différentes dimensions, il exige le dialogue entre différentes disciplines, dont l'économie, la gestion, la sociologie, le design et la psychologie ergonomique. Les recherches de l'institut traitent de questions fondamentales qui fédèrent des communautés de recherche très actives au niveau international, tout en étant pertinentes pour les entreprises et les décideurs.

Cette recherche est organisée en quatre thématiques transverses qui couvrent l'ensemble du champ de l'innovation. Chacune de ces thématiques permet de créer un réel espace de discussion entre des disciplines et entre les différentes équipes de l'institut : **Transformations de l'entreprise innovante ; Théories et modèles de la conception ; Régulations de l'innovation ; Usages, participation, démocratisation de l'innovation**. Par ses activités de recherche et de formation, i3 participe à relever les grands défis de l'heure : le numérique, la santé, l'innovation, l'énergie et le développement durable.

Les recherches sont souvent effectuées dans le cadre de contrats avec des entreprises, des associations ou des administrations publiques. L'institut porte également des chaires d'enseignement et recherche. Il est engagé dans le dialogue avec les entreprises, le monde associatif et les pouvoirs publics via des plates-formes innovantes de dialogue.

ECOGE

Economics and Management
Économie Gestion

Group leaders
– Responsables d'équipe

Marc Bourreau
David Massé

Keywords
Digital Platforms, Data, Innovation, Telecommunications, Infrastructure, Strategy, Digital Transformation, Public Policy, Regulation, Competition Policy, Intellectual Property, Privacy, Industrial Organization, Econometrics, Qualitative Methods

Mots-clés
Plateformes numériques, Données, Innovation, Télécommunications, Infrastructures, Stratégie d'entreprise, Transformation numérique, Politique publique, Régulation, Politique de la concurrence, Propriété intellectuelle, Vie privée, Économie industrielle, Économétrie, Méthodes qualitatives

Web
telecom-paris.fr/ecoge

See also
▸ Laurie Ciaramella, p. 11

EN ECOGE is a multidisciplinary group that focuses on economics, law and management and whose research projects explore our understanding of digital transformations and their impact on the economy, companies and public policy. Research activities are based on a wide range of quantitative and qualitative methodologies and, in keeping with the group's mission, research is both theoretical and empirical, and intended for academics as well as for public bodies. For instance, ECOGE has designed a theoretical data taxation model, which has contributed to France Stratégie's work on that topic. Research projects provide fresh insight on topics that include digital platforms, blockchain, artificial intelligence, algorithms, data, the sharing economy, digital entrepreneurship, frugal innovation and data privacy.

Some of the research is conducted in partnership with companies or public institutions, as part of the activities carried out by six research chairs. In this way, theories can be developed, discussed and redefined, with the assurance that the knowledge produced is relevant and of a high scientific standard.

Research projects provide fresh insight on digital platforms, blockchain, AI, algorithms, the sharing economy, digital entrepreneurship, frugal innovation, data privacy…

FR Multidisciplinaire – économie, droit et gestion –, ECOGE mène des recherches autour de la compréhension des transformations numériques et de leurs impacts pour l'économie, l'entreprise et les politiques publiques. Reflétant cette ambition, les travaux, qui s'appuient sur une grande variété de méthodologies (quantitatives et qualitatives), sont tour à tour théoriques et empiriques, académiques et à destination des autorités publiques – ECOGE a ainsi conçu un modèle théorique sur la taxation des données en soutien aux travaux de France Stratégie sur le sujet. Ils permettent de nourrir des points de vue complémentaires sur des sujets comme les plateformes numériques, la blockchain, l'intelligence artificielle, les algorithmes, les données, l'économie collaborative, l'entrepreneuriat numérique, l'innovation frugale, ou encore la protection des informations personnelles.

Une partie des travaux de recherche sont conduits en partenariat avec des entreprises ou organisations publiques, à travers notamment six chaires de recherche. Cette démarche permet l'élaboration, la discussion et la redéfinition des théories existantes, tout en garantissant la pertinence et la qualité scientifique des connaissances produites.

▸ "Données personnelles et confiance : évolution des perceptions et usages post-RGPD" 18es Rencontres de la Chaire Valeurs et Politiques des Informations Personnelles
www.informations-personnelles.org

Platforms, algorithms, AI and data

EN Platforms disrupt value chains and markets and the key role they play is a cause for concern in terms of competition and consumer protection. Platform regulation options can be studied, thanks to theoretical models based on game theory, such as neutrality rules, which can show their impact on service provider participation [1]. Other empirical research [2], in the field of hotel reservation platforms reveals that, when a user makes a request, the platform makes strategic manipulations to hotel rankings in order to dissuade hotels from offering more attractive prices on competing platforms or on their own website. The user data collected can be used to create personalized pricing, making data intermediaries key players in data movement and accessibility [3].

▸ [1] **M. Bourreau**, R. Lestage. "Net neutrality and asymmetric platform competition." Journal of Regulatory Economics (2019) 55:140–171

▸ [2] M. Hunol, R. Kesler, **U. Laitenberger**, 2020. «Rankings of Online Travel Agents, Channel Pricing, and Consumer Protection,» Marketing Science, INFORMS, vol. 39(1), p. 92-116, January.

▸ [3] **D. Bounie** and **A. Dubus**, and **P. Waelbroeck**, "Market for Information and Selling Mechanisms" (2020), forthcoming in the RAND Journal of Economics.

Digital transformations for workers and companies

EN In the past few years, every single industry, company and worker has been affected by the digital revolution. Several ECOGE projects have explored this phenomenon, which has produced radical change in many companies' organization and processes and more broadly, in work practices. For instance, research shows that IT companies pay developers who work on free software projects, which has led to new hybrid forms of work. [4]. Other studies have also focused on the development of new collaborative locations known as "third places", showing how these places transform new work practices, or make them visible, as evidenced by urban policies as regards innovation. [5] Lastly, the development of corporate digital tools can lead to significant tensions among projects and departments within a company. Article [6] explores how "knowledge brokers" alleviate these tensions.

▸ [4] M. O'Neil, **L. Muselli**, M. Raissi and S. Zacchiroli, (2020). "'Open source has won and lost the war': Legitimising commercial–communal hybridisation in a FOSS project." New Media & Society, 1461444820907022.

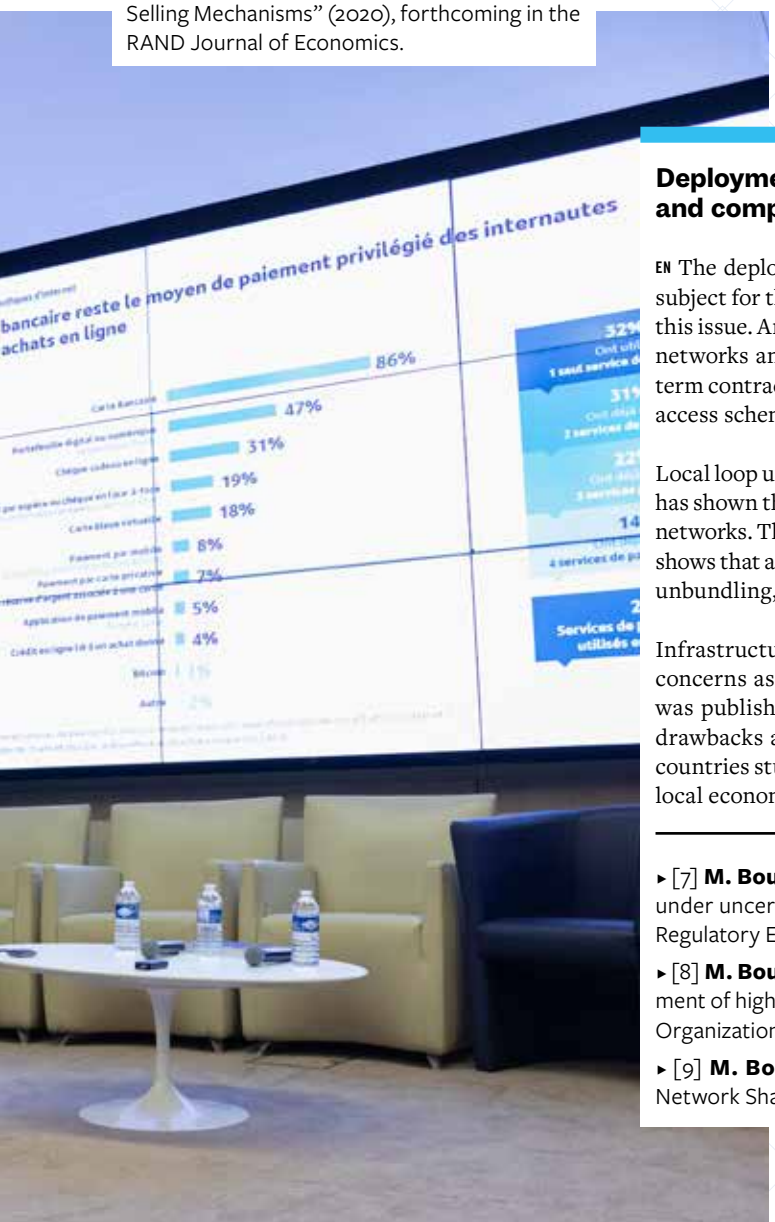
▸ [5] C. Renaud, **V. Fernandez**, G. Puel and Z. Feng, (2019). "Urban Modes of Assemblage: The Changing Spaces of Innovation in Shanghai." Management international/International Management/Gestiòn Internacional, 23(3).

▸ [6] P. Chiambaretto, **D. Massé**, N. Mirc, (2019), "'All for One and One for All?' - Knowledge broker roles in managing tensions of internal coopetition: The Ubisoft case", Research Policy, vol. 48, n°3, p. 584-600.

Permanent members / Membres permanents **14**

Thesis / Thèses soutenues **4**

Publications / Publications **38**



Deployment of broadband network infrastructures: regulation and competition

EN The deployment of broadband network infrastructures provides an interesting subject for the study of the various regulatory approaches. Several projects address this issue. Article [7] reviews various schemes of regulated access to next generation networks and in particular, the way in which risk premia, access options or long-term contracts provide more incentives to invest than the more traditional network access schemes.

Local loop unbundling has created competition in the broadband market and a study has shown that it now affects operators' strategies as regards the deployment of fiber networks. This study [8], combining theoretical modeling and empirical estimations, shows that a higher level of local competition in the broadband market, which follows unbundling, leads to slower deployment of optical fiber networks.

Infrastructure sharing is one way of accelerating network deployment but it raises concerns as to its possible adverse effects on competition. A report on this topic was published by CERRE (Centre on Regulation in Europe) [9], listing benefits, drawbacks and lessons learnt. Other research projects carried out in developing countries study the impact of telecommunication infrastructure deployment on the local economy and on inequality reduction.

▸ [7] **M. Bourreau**, C. Cambini, S. Hoernig, I. Vogelsang. "Fiber investment and access under uncertainty: long-term contracts, risk premia, and access options." Journal of Regulatory Economics (2020) 57:105–117

▸ [8] **M. Bourreau**, **L.Grzybowski**, M. Hasbi. "Unbundling the incumbent and deployment of high-speed internet: Evidence from France." International Journal of Industrial Organization 67 (2019) 102526

▸ [9] **M. Bourreau**, S. Hoernig, **W. Maxwell**. "Implementing Co-Investment and Network Sharing." Report for the Centre on Regulation in Europe, May 2020

INTERACT — Interaction, activities, technologies
Interactions activités technologies

Group leaders
— Responsables d'équipe

Françoise Détienne (CNRS)
Christian Licoppe

Keywords
Interaction, Activity, Mobility, Collaboration, Community, Interaction Design, Creative Design, User Experience, Technology-mediated Interaction, Social Robotics

Mots-clés
Interaction, Activité, Mobilités, Collaboration, Communauté, Design d'interaction, Conception créative, Expérience utilisateur, Interaction médiée par la technologie, Robotique sociale

EN The research carried out by INTERACT is firmly embedded in innovation issues: supporting innovation with creativity and participatory approaches and the study of appropriation and uses. INTERACT relies on a combination of methods—interaction analysis, analysis from the subject's point of view, participatory methods—to make use situations visible. The group organizes its work, structured around ANR and H2020 programs, into four themes.

The **Interaction and activity** theme focuses on understanding the organization patterns of human interactions, especially in environments with a high digital technology component. Research projects study the organization of communication exchanges in "fragmented ecologies", the interactions in institutional and professional environments, where forms of speech may be constrained, and the interactions between humans and virtual agents and robots.

The **Collaboration and Communities** theme aims to understand and equip design and collaboration activities, understood as activities that are productive, targeting the co-development of a physical or digital artifact, constructive, targeting the co-development of knowledge in an interaction and socio-relational, targeting the regulation of emotions and the development of a collective approach.

The **Mobility** theme analyzes the in situ practices of technology-driven mobility: behavior linked to the new forms of mobility in urban settings, taking into account attention, risks and constraints, shared mobility, their use and appropriation, new mobile services and mobility in a transnational context, such as migrants and diasporas.

Lastly, the **Design and Creativity** theme focuses, with a non-deterministic view of creativity, on analyzing and understanding the socio-cognitive, emotional and technical processes involved in design, as well as experimenting with new situations, methods and devices for creativity.

FR Les recherches menées par INTERACT s'ancrent fortement dans des problématiques d'innovation : l'accompagnement de l'innovation par la créativité et par des approches participatives, et l'étude de l'appropriation et des usages. S'appuyant sur un ensemble de méthodes – analyse des interactions, analyse du point de vue du sujet, méthodes participatives – combinées pour rendre visibles les situations d'usage, INTERACT articule ses recherches, structurées autour de programmes ANR ou H2020, selon 4 axes.

L'axe **Interaction et activité** porte sur la compréhension des modes d'organisation de l'interaction humaine, en particulier dans des environnements riches en technologies numériques. Les recherches s'intéressent à l'organisation des échanges communicationnels dans des « écologies fragmentées », aux interactions dans des environnements institutionnels et professionnels où les formes de prise de parole et de participation peuvent être contraintes, et enfin aux interactions entre humains et agents virtuels ou robots.

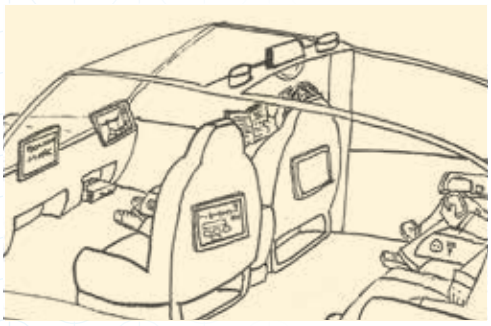
L'axe **Collaboration et Communautés** vise à comprendre et à outiller les activités de conception et de collaboration, appréhendées comme des activités à la fois productives, visant la co-élaboration d'un artefact, matériel ou immatériel, constructives, visant la co-élaboration de connaissances dans le dialogue, et socio-relationnelles, visant la régulation des émotions et la construction du collectif.

L'axe **Mobilités** s'intéresse à l'analyse des pratiques in situ de mobilités outillées par des technologies : comportements liés aux nouvelles formes de mobilités dans les espaces urbains, prenant en compte l'attention, les risques et les contraintes, les mobilités partagées, leurs usages et leur appropriation, les nouveaux services mobiles, et les mobilités dans un contexte transnational, comme les migrants et les diasporas.

Enfin, l'axe **Design et Créativité**, dans une perspective non-déterministe de la créativité, porte sur l'analyse et la compréhension des processus socio-cognitifs, affectifs et techniques mis en œuvre dans la conception, ainsi que sur l'expérimentation de situations, méthodes et dispositifs nouveaux pour la créativité.

See also
▸ Social Touch, p. 47
▸ JokaJobs, p. 81

Web
telecom-paris.fr/interact



▸ Futur robot-taxi partagé sans chauffeur (étude pour la Plateforme automobile, **B. Cahour**, M. Hoarau)

▸ Autonomous weather station, presenting the energy mix on demand. Work produced during **Samuel Lacroix**'s CIFRE thesis, supervised at EDF by Guillaume Foissac and in the INTERACT team by **Francoise Détienne** and **Samuel Huron**. Image: Design Lab I²R EDF 4 patents pending.

Permanent members Membres permanents	7
Publications Publications	38
Patents Brevets	4

Entanglement of creativity and design

EN Studying the relationship between creativity and design entails analyzing and understanding the socio-cognitive, emotional and technical processes involved, as well as experimenting with situations, methods and devices. Research probes the facilitating processes, mediation tools and representational, physical, digital and hybrid materials in design activities in various fields: visualizing and understanding located data, identifying design opportunities for innovation, usage- and user-led design, appropriation of places and sites, usage forecasting through design. In a collaboration with the *Royal College of Art* and *Tokyo Institute of Technology*, [1] aims to understand how argumentative interactions, involving role-play, with subsequent group reflection, lead to collaborative creative design. The joint dynamics of collaboration and design is studied in [2], based on a multidimensional model for assessing the quality of collaboration, in the context of an architectural design studio. A new methodology paradigm, "design by immersion", is presented in [3], together with six case studies. This method embeds transdisciplinary experiences at the center of a visualization process linked to a domain, enabling the exploration of new domain-inspired visualization design spaces, richer domain understanding through personal experiences, and strong transdisciplinary relationships.

▸ [1] **M. Baker**, **F. Détienne**, C. Mougenot, T. Corvin, M. Pennington. "Argumentation, Eureka and emotion: An analysis of group projects in creative design training." Learning, Culture and Social Interaction, Elsevier, 2020, 26, pp. 100436.

▸ [2] **S. Safin**, **F. Détienne**, J. M. Burkhardt, A. M. Hébert, P. Leclercq. "The interplay between quality of collaboration, design project evolution and outcome in an architectural design studio." CoDesign, Taylor & Francis, 2019, pp. 1-18.

▸ [3] K. Wm Hall, A. J. Bradley, U. Hinrichs, **S. Huron**, J. Wood, C. Collins, S. Carpendale "Design by immersion: A transdisciplinary approach to problem-driven visualizations", in IEEE Transactions on Visualization and Computer Graphics, vol. 26, no. 1, pp. 109-118, Jan. 2020

Taking leave of a robot

EN The conversation analysis of closing exchanges between humans and robots, based on a corpus of filmed interactions reveals two separate dimensions: interactional tact—the extent to which robots are treated more or less like a partner—and the more or less collaborative aspect of disengagement. This multimodal study of disengagement phases in social robotics, which was undertaken in collaboration with S²A and Softbank Robotics, reveals practices whose analysis provides a better understanding of how interaction and design should be connected.

Humans are particularly sensitive to situations where robots appear to display an understanding of their prior actions. Disengagement phases come in different forms, from a sudden and sharp closing statement, known as mechanical (such as "end of conversation") to pre-closing sequences, characteristic of ordinary human interactions. In the latter situation, there should be a distinction between cases where human participants hurry to close the exchange or give the robot a chance to reply.

▸ **N. Rollet**, **C. Clave**l. "Talk to you later." Interaction Studies, J. Benjamins Publishing Co, 2020, 21 (2), pp. 268-292.

▸ **C. Licoppe**, **N. Rollet**, (2020), "« Je dois y aller ». Analyses de séquences de clôtures entre humains et robot", Réseaux, vol. 220-221, no. 2, pp. 151-193.

▸ M. Sahin, **M. Relieu**, and A. Francillon. 2017. "Using chatbots against voice spam: analyzing Lenny's effectiveness." In Proceedings of the Thirteenth USENIX Conference on Usable Privacy and Security (SOUPS '17). USENIX Association, USA, 319–337.

SID

Sociology, Information & Communication Sciences, Design
Sociologie, Information & Communication, Design

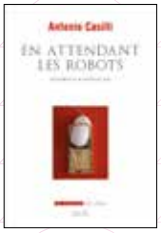
Group leaders
— Responsables d'équipe

Valérie Beaudouin
Christophe Prieur

Keywords
Science and technology studies, Participation, Democratization, Amateurs, Citizens, Digital labour, Design, Art-science

Mots-clés
Sociologie des techniques, usages, Participation, Démocratisation, Amateurs, Citoyens, Digital labour, Design, art-science

Web
telecom-paris.fr/sid



▸ **Antonio Casilli**, En attendant les robots. Enquête sur le travail du clic. Éditions du Seuil, 2019.

▸ **Annie Gentès**, The In-Discipline of Design: Bridging the Gap Between Humanities and Engineering, Gewerbestrasse, Springer, Coll. "Design research fondations", 2017.

▸ **Olivier Fournout** et Sylvie Bouchet, Le champ des possibles. Dialoguer autrement pour agir, Paris, SIKIT, 2019.

EN Very rarely does an established innovation resemble the innovation its inventors had in mind initially. Observing the differences between the two—by way of field surveys on how users appropriated it and on the design process in labs—enables innovations to be adapted and to lessen any societal controversies which may have emerged. This is the context in which SID conducts its research, which is structured around several ANR (French National Research Agency) programs and addresses two key themes:

The Internet and Society focuses on the transformation of social practices in the context of the Internet. In particular, this theme explores digital cultures and their innovative tools for creation and mediation, how the public arena is changing, individual usage and the new forms of collective contribution and organization (communities of friends, citizens, experts and activists). It also pays particular attention to power issues and forms of exploitation which may arise (governance of digital technology, microwork, surveillance, breach of privacy and so on).

Art and Science (design and creation), explores how art practices can lead to new representations of society and science. Art becomes a tool for learning, understanding and experiencing current societal shifts and social debates. SID members are well aware that art contributes to the advancement of knowledge. Most of them are art practitioners themselves or involved in personal creative projects. Exploring creative processes, analyzing forms of creativity and developing teaching and research tools that draw on art and design all provide a better appreciation of the role that creativity plays in our understanding of the world and in our ability to develop thinking skills and a sense of responsibility.

SID participates in the CNRS Research Center "Internet, AI and Society" cis.cnrs.fr/gdr2091

SID is a founder of the Exalt Design Lab, a joint research laboratory, and a member of its scientific committee. The lab aims to promote design in companies and value creation through experience. exalt.design/en

Forms of usage cannot be predicted a priori

FR Il est très rare qu'une innovation diffusée ressemble à l'innovation telle qu'elle avait été imaginée par ses inventeurs. L'observation de ces décalages – par des enquêtes de terrain sur les formes d'appropriation par les utilisateurs et sur les processus de conception dans les laboratoires – permet d'adapter l'innovation et de dégonfler les controverses sociétales qui apparaissent. C'est dans ce cadre que SID mène ses recherches, structurées autour de plusieurs programmes ANR et articulées autour de deux grands axes :

Internet et Société porte sur la transformation des pratiques sociales dans le contexte d'internet. Cet axe s'intéresse notamment aux cultures du numérique, à leurs dispositifs innovants de création et de médiation, aux mutations de l'espace public, aux usages individuels ainsi qu'aux nouvelles formes de participation et d'organisation collectives (communautés amicales, citoyennes, épistémiques ou militantes). Il accorde également une attention particulière aux enjeux de pouvoir et aux formes d'exploitation qui peuvent s'y déployer (gouvernance du numérique, « travail du clic », surveillance, atteintes à la vie privée, etc.).

Art et Science (conception et création) explore comment les pratiques artistiques peuvent constituer de nouvelles formes de discours sur la société et sur la science. L'art devient une ressource pour apprendre, percevoir et ressentir les transformations sociétales et les débats de société en cours. Il participe de l'élaboration des savoirs, ce que savent bien les membres de SID qui pour la plupart ont une pratique artistique ou des activités de créativité personnelles. Explorer le processus créatif, analyser les formes créatives, mettre en place des dispositifs pédagogiques et de recherche mobilisant l'art et le design permettent de mieux comprendre le rôle que joue la création dans notre connaissance du monde, et de développer ses capacités réflexives et son sens des responsabilités.

SID participe au GDR du CNRS « Internet, IA et société » cis.cnrs.fr/gdr2091

SID est fondatrice et membre du comité scientifique du Laboratoire de recherche commun Exalt Design Lab, dédié à la valorisation du design en entreprise et à la création de valeur par l'expérience. exalt.design

Citizens and the Internet: engagement and resistance

EN Two current ANR projects describe two different types of relationship between the Internet and society: in the first, citizen engagement is encouraged, in the other, citizens need to devise by-passing strategies.

MACIV [1], led by Caroline Rizza, focuses on the way in which information streams can be reorganized, in a crisis management situation, between citizens/volunteers who are on-site or online and first responders and crisis managers, to involve the former more and to reinforce the resilience of the communities affected. A mediation platform is being developed, which incorporates heterogeneous data from social media and then translates it into meaningful information for managers.

Resistic [2] analyzes the way in which Russian Internet players resist and adapt the new national rules that were enforced in the early 2010s.

▸ [1] **R. Batard**, A. Montarnal, F. Benaben, **C. Rizza**, **C. Prieur**, et al.. "Integrating citizen initiatives in a technological platform for collaborative crisis management." ISCRAM 2019 – 16th International conference on Information Systems for Crisis Response and Management, May 2019, València, Spain.

▸ [2] **B. Loveluck**. (2019), "The many shades of digital vigilantism. A typology of online self-justice", Global Crime.

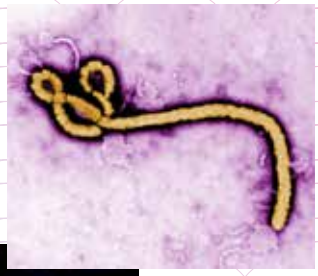
Art & design revitalize debates

EN Several fictionalization experiments were conducted with students (theater play, short film, sound scape, performance poetry, etc.) in order to assess the role collective creativity plays in teaching about controversies. These activities were carried out as part of the European (ANR IDEFI) FORCCAST project on controversies. In 2019, the topic: "Transhumanism or bioconservatism? Can we or should we go beyond the limits of the human body?" led to different artistic representations including a play created by actors and an illustrated fictionalized account, described in [3]. In addition, an experiment involving the parties to the controversy—on the issue of pesticides and climate change—showed how collective creativity provided a better understanding of the issues surrounding the controversy and more importantly, how it re-ignited communication when debate in the public arena is blocked. (The experiment is described in a book, Le Champ des possibles).

The French National Library is undertaking another type of action-research [4]. The Library is seeking to improve the way in which new visitors are welcomed and then guided as they explore the resources available for the first time. Researchers, with the help of designers, are devising new survey and feedback tools to help the thinking on how public areas should be reorganized.

▸ [3] **O. Fournout**. "From Candide to Candide, the controversy of transhumanism." 2019.

▸ [4] **V. Beaudouin, I. Garron, A. Gentès, S. Safin**. "Une semaine d'observation à la Bibliothèque Nationale de France" [Rapport de recherche] Institut Polytechnique de Paris-BNF. 2019.



Permanent members 9
Membres permanents

Thesis 3
Thèses soutenues

Patents 4
Brevets

Publications 33
Publications

Test plateform of semiconductor lasers
Banc de test de lasers à semiconducteur

02 Innovation & transfer

— Innovation & transfert

Editorial

Édito

According to the 999 Law on Innovation and Research, inovation describes socio-economic impact, the implementation of research results and the development of startups and spinoffs.

EN The 1999 French Law on Innovation and Research provided new terminology and a new vision. Research describes the scientific impact and success of laboratories, identified as being essential to the nation. Innovation describes socio-economic impact, the implementation of research results, technology transfer and the development of startups and spinoffs.

1999 was also the year when Télécom Paris launched its incubator and combined it with a teaching unit, "Business creation". Although this type of organization is now widespread, it was rare twenty years ago. Back then, entrepreneurship was not really a priority for engineering schools. Yet over that period, Télécom Paris, which operates under the auspices of the Ministry for the Economy, actively promoted a spirit of innovation among its researchers and graduates, with our incubator producing more than 450 businesses.

The success stories of the past twenty years owe much to a very nurturing environment, rooted in the digital sciences, thanks to ready access to Télécom Paris researchers and students and also to the relations established with our alumni, startups and graduates, and with major companies close to our school as well as with the Mines-Télécom Foundation and its members, who support our work.

2019 was a record year, which placed us among the best academic institutions in Europe.

Our researchers invented 27 patents—a record number—many technology transfer agreements were signed and the alumni's startups in our incubator raised €89m.*

Lastly, with the momentum provided by the Institut Polytechnique de Paris, our incubator has continued to work closely with Ecole Polytechnique's facilities and has been renamed the Télécom Paris Novation Center. We are delighted to now represent the Paris home for entrepreneurship at Institut Polytechnique de Paris.

* only for those that left the incubator less than five years ago

Over the past 20 years Télécom Paris actively promoted a spirit of innovation, with its incubator producing more than 450 businesses.

Nicolas Glady Dean and President, Directeur

FR La Loi sur l'Innovation et la Recherche de 1999 a consacré en France un vocabulaire et une vision. La Recherche vise l'impact scientifique des laboratoires, leur notoriété, affirmés comme essentiels à la Nation. L'Innovation désigne l'impact socio-économique, la mise en œuvre des résultats, le transfert des technologies, le développement des *startups* et des *spinoffs*.

Cette même année, Télécom Paris lance son incubateur et y associe une unité d'enseignement « Création d'entreprise ». Ce qui est banal aujourd'hui était rare il y a vingt ans, où les écoles d'ingénieur se souciaient encore peu d'entrepreneuriat. Sur cette période, Télécom Paris, qui dépend du ministère de l'Économie, a vigoureusement développé l'esprit d'Innovation de ses chercheurs et diplômés : plus de 450 entreprises sont ainsi sorties de notre incubateur.

Les succès enregistrés au cours de ces deux décennies doivent beaucoup au terreau naturel plus que favorable, très fortement ancré dans le numérique, dû tout à la fois à la proximité avec les chercheurs et élèves de Télécom Paris, mais également aux liens avec nos alumni, startups et diplômés, et avec les grands comptes proches de l'école, la Fondation Mines-Télécom et ses membres qui soutiennent nos actions.

2019 est une année de records qui nous a amenés au niveau des meilleures institutions académiques en Europe.

Nos chercheurs ont inventé 27 brevets, chiffre qui n'avait jamais été atteint, de nombreux transferts de technologies ont été signés, les startups alumni de l'incubateur ont levé 89 M€.*

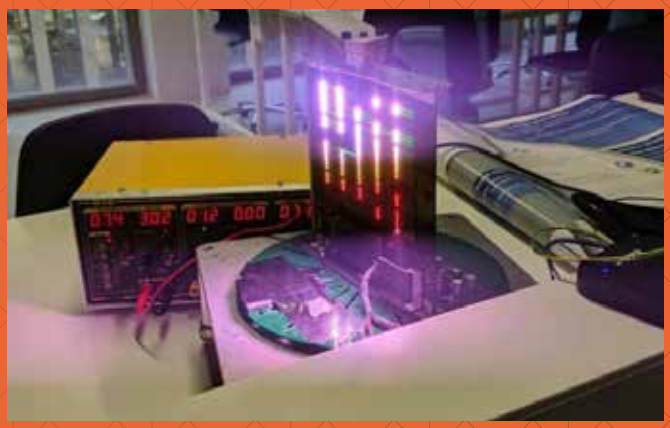
Dans une dynamique de convergence avec les écoles de l'Institut Polytechnique de Paris, notre incubateur a poursuivi son rapprochement avec celui de l'École polytechnique et a été rebaptisé Télécom Paris Novation Center. Nous nous réjouissons d'être désormais le site parisien de l'entrepreneuriat de l'Institut Polytechnique de Paris.

* comptabilisés dans le seul horizon de 5 ans maximum après leur sortie

Deep Tech Factory

Creuset à Deep Tech

PRIM / ROSE Project 2020 by Nathan Claudel



EN Télécom Paris is actively engaged in supporting innovation via a number of teaching and research projects in partnership with industry. This provides students and research teams with practical usage cases and enjoys world-class multidisciplinary expertise. Cooperation varies widely in form and involves many faculty members in different scenarios, including partnership-based doctorates, bilateral contracts, ANR- and H2020-type projects, joint labs, teaching and research chairs, technology transfer and the support of startups and spinoffs. In 2019, Télécom Paris derived income from the commercialization of a dozen patents and software programs.

Among the current teaching and research chairs at Télécom Paris, which were created in partnership with companies and in some cases with the support of the Mines Télécom Foundation—including those whose activities ceased in 2019—two of them have a direct link with the field of digital innovation. The "Innovation and Regulation in Digital Services" chair contributed to exploring and developing a landmark theoretical framework in this field. The "Engineering and Frugal Innovation" chair has developed and disseminated the expertise and experience from industry which are crucial to sustainable development.

In 2019, there were 63 ongoing PhDs in partnership with companies (including Facebook, Google, Orange, Thales), in the form of Industrial Agreements for Training through Research (CIFRE) for a third of them.

Since 2013, Télécom Paris has also been offering a one-semester training program on innovation: Research and Innovation Master Projects (PRIM). These provide an opportunity to develop a real innovation project or the creation of a business, liaising with a Télécom Paris lab and/or a corporate partner.

Patents are the natural products of research. As such, they attract particular attention from the Ministry for the Economy, as they aim to serve national and European markets and represent an increasing demand from industry partners who would like to protect their work before it is disseminated. 17 of the 27 patents invented by our researchers in 2019 were invented as part of a collaborative project with industry and are therefore likely candidates for effective application.

Patents invented in 2019
Brevets inventés en 2019
27

FR Télécom Paris poursuit activement une politique de soutien à l'innovation à travers plusieurs initiatives d'enseignement et de recherche en partenariat avec l'industrie. Cette dernière fournit aux élèves et aux équipes de recherche des cas d'usages concrets et bénéficie d'une expertise pluri-disciplinaire d'excellence. Ces collaborations prennent des formes très diverses et impliquent de nombreux enseignants-chercheurs, que ce soit à travers des thèses en partenariat, des contrats bilatéraux, des projets coopératifs type ANR ou H2020, des laboratoires communs, des chaires d'enseignement et de recherche, du transfert technologique ou l'accompagnement de startups et de spinoffs. À cet égard, en 2019, Télécom Paris a perçu des revenus d'une douzaine de contrats de valorisation de brevets et logiciels.

Parmi les treize chaires d'enseignement-recherche ou de recherche en activité à Télécom Paris ou qui se sont achevées en 2019, chaires créées en partenariat avec des entreprises et pour certaines avec le soutien de la Fondation Mines-Télécom, deux sont ainsi directement liées au domaine de l'innovation numérique. La chaire « Innovation et Régulation des services numériques » a contribué à l'élaboration et l'animation d'une réflexion théorique de référence sur son domaine. La chaire « Ingénierie et innovation frugales » a développé et diffusé ces savoirs et expériences industrielles essentiels pour une innovation soutenable.

63 thèses en partenariat avec des entreprises (Facebook, Google, Orange, Thales…) étaient en cours en 2019, sous forme en particulier de convention CIFRE, soit un tiers des thèses sur cette période.

Télécom Paris propose également depuis 2013 un dispositif pédagogique de formation à l'innovation sur un semestre : les Projets de Recherche et d'Innovation Master (PRIM). Ils sont l'occasion d'élaborer un projet d'innovation réel ou un projet de création d'entreprise, en interaction avec un laboratoire de l'école et/ou une entreprise partenaire.

Prolongement naturel de la recherche, les brevets retiennent particulièrement l'attention du ministère de l'Économie qui vise à servir le tissu économique national et européen et sont une préoccupation croissante des partenaires industriels qui souhaitent que les travaux soient protégés avant publication. Sur les 27 brevets de nos chercheurs en 2019, 17 ont été inventés dans le cadre d'une coopération industrielle et sont ainsi susceptibles d'application effective.

20 years of innovation

for Télécom Paris Novation Center

EN Seen as one of the leading incubators for digital sciences innovation in France, the incubator based at the heart of Télécom Paris turned twenty in the spring of 2019. It has led to the creation of almost 450 companies. With a satellite at Sophia Antipolis since 2006, it became known as ParisTech Entrepreneurs in 2009, serving students, researchers and alumni from ParisTech schools. It is also open to entrepreneurs in Paris from different backgrounds. In 2016, SME Builder—a startup accelerator—was set up to complement the other facilities. Its aims is to create strong SMEs in the digital industry.

The Paris site hosts 22 startups at any given time for a period of 18 months, and a further 8 startups in the 24-month SME Builder program and 5 spinoff projects. In Sophia Antipolis, more than 10 startups are hosted over the same time periods. Companies with disruptive projects based on digital technologies and usage are selected for their potential synergy with Télécom Paris' research labs and their potential for business, growth and international development. They benefit from a mentoring program and partnerships with many players in business and science.

In May 2018, 38 of the incubator's startups were selected by the VivaTech Challenges, where they featured prominently alongside major companies.

On December 9, 2019, the incubator changed its name to **Télécom Paris Novation Center**.

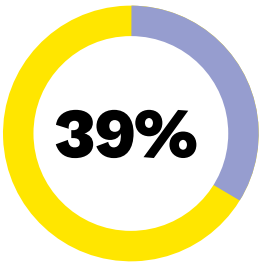
FR Considéré comme l'un des incubateurs de référence pour l'innovation dans le numérique en France, l'incubateur situé au coeur de Télécom Paris a fêté ses 20 ans au printemps 2019 et compte près de 450 entreprises créées. Disposant depuis 2006 d'une antenne à Sophia Antipolis, il devient en 2009 ParisTech Entrepreneurs, au service des étudiants, chercheurs et alumni des écoles de ParisTech et ouvert à des entrepreneurs d'autres horizons sur la place de Paris. L'accélérateur de startups SME Builder est créé en complément du dispositif en 2016 pour viser la création de PME solides dans le domaine numérique.

Les locaux parisiens accueillent en permanence 22 startups incubées sur des périodes de 18 mois, plus 8 autres au sein du programme de 24 mois SME Builder, et 5 projets de spinoffs. Sur Sophia Antipolis, ce sont plus de 10 startups qui sont accompagnées sur les mêmes périodes. Les entreprises, porteuses de projets disruptifs sur des technologies et des usages du numérique, sont sélectionnées pour leurs synergies possibles avec les laboratoires de recherche de Télécom Paris et pour leur potentiel économique, de croissance et de développement international. Elles bénéficient d'un programme de mentorat et de partenariats avec de nombreux acteurs économiques et scientifiques.

En mai 2019, 38 startups de l'incubateur, sélectionnées par les Challenges VivaTech, étaient présentes et bien visibles sur les stands des grandes entreprises.

Le 9 décembre 2019, l'incubateur change de nom et devient **Télécom Paris Novation Center**.

1999-2019 data / chiffres

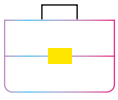


... of startups have at least one founder with a PhD from a university or *grande école*
... des startups ont à minima un docteur universitaire ou d'une grande école parmi leurs fondateurs

442 Startups created
Startups créées

+200 Patents filed
Brevets déposés

123600.000€
...raised in 2019 by startups in or having left the incubator
...de fonds levés en 2019 pour les startups issues de l'incubateur et en cours



+ 3000
Jobs created
Emplois créés

Web
telecomparis-entrepreneurs.fr

Nicolas Glady, Directeur de Télécom Paris et Éric Labaye, président de l'École polytechnique et de l'Institut Polytechnique de Paris, lors du 20e anniversaire du Télécom Paris Novation Center

Startups and Spinoffs hitting the headlines

Web
telecom-paris.fr/en/innovation-and-entrepreneurship/spin-offs

Scalinx, supplier of Signal Conversion ASIC & ASSP

EN One of C2S' main areas of expertise (p. 22) is the design of high performance reconfigurable ADCs, and particularly CMOS 65 nm technology. Work has been carried out over the years to design a general purpose continuous-time (CT) delta sigma ($\Delta\Sigma$) ADC, as part of the European ENIAC ARTEMOS and CATRENE CORTIF projects, in collaboration with NXP France. Thanks to its reconfigurable 10/20/40 MHz bandwidth, its high resolution (>11 bits of Dynamic Range (DR)), its high linearity (>12 bits of measured Total harmonic distortion), its low energy consumption (<100 mW of measured energy consumption) and its inherent filtering, this ADC could target a diversity of applications such as the Zigbee moderator, DVB-T receivers and bio-medical imaging. Based on the very promising results of this research Hussein Fakhoury (then member of C2S) founded **Scalinx** in 2015 as a Télécom Paris **spinoff**. Scalinx, which is specialized in the design of signal conversion ASIC and ASSP, has attracted the attention of stakeholders and offers innovative solutions in strategic fields and markets such as test and measurement, defense & aerospace and communications.

▸ scalinx.com

Energysquare, the Power by Contact® technology

EN **Energysquare** is a **startup** cofounded by Timothée Le Quesne and Daniel Lollo, both Télécom Paris graduates (2015). They created a wireless system for charging tablets and mobile phones simultaneously on a single surface—a sticker and a metal plate. Thanks to advanced microelectronics and algorithms, all devices are charged at maximum speed, with no electromagnetic waves and no energy loss. Unlike the broadly used induction charging solutions, the choice made by Energysquare of a conduction charging technology totally at the opposite end of the market offers many benefits to electronics manufacturers and users: there is no interference, no risk of components overheating and no health risks. In January 2020, the young startup signed a technological partnership with Chinese industrial giant Lenovo, to explore integration into their new laptop models.

Energysquare won the 2019 CES Best of Innovation Award. In June 2020, Energysquare announced a €3M fundraising round with Partech, thus enabling its development to accelerate in Asia and in the United States.

▸ energysquare.co

▸ Energysquare wireless charging technology

Joint laboratories

EN “Alternative” joint laboratories, typically set up for a five-year period, are groupings that bring together the research potential of Télécom Paris, together with that of one or several companies, higher education institutions and research centers on a given topic.

SEIDO, Internet of Things and Cybersecurity for electrical systems

EN SEIDO, which was created in 2012 by EDF R&D and Télécom Paris, and then extended to new partners (Télécom SudParis, CNRS LAAS), has set itself the objective of preparing electrical systems for the development of smart grids and the interoperability of objects (vehicles, household appliances, etc.), within the constraints of a stable network, in line with environmental and legislative requirements and with guaranteed security (access control, confidentiality, etc.) Applications such as energy optimization and efficiency in smart homes, smart buildings and smart communities are being explored. ACES (p. 39, “Security for the power grid”), RMS (p. 52), DIG (p. 42) and SSH (p. 36) contribute to this work on behalf of Télécom Paris.

Every year, the lab organizes a workshop, during which the teams’ research is presented, together with work relating to similar or related fields, making for productive interactions. To date, SEIDO has filed five patents, including one European patent, enabled four PhD theses to be defended (seven are ongoing) and published more than 20 articles, as well as four book chapters.

▸ seido-lab.com

Other joint laboratories

EN Télécom Paris’ strategic research lines extend to other joint laboratories: Valeo.IA (Artificial Intelligence for Autonomous Vehicles), ISA (Security and Identity), AllegoRI (3D Sciences and Technologies), Exalt Design Lab (Design in Companies), BibliLab (Digital Heritage of Libraries), ICT4V (ICT for Verticals, a lab based in Montevideo, Uruguay) and Lincs (Internet of the Future).

ΣΚΦ, the first joint lab at Institut Polytechnique de Paris, was created by ACES at Télécom Paris, COSYNUS (Ecole polytechnique) and U2IS (ENSTA Paris). Its research focuses on cyber-physical systems.

Blockchain Advanced Research and Technologies (BART)

EN BART, which was launched in 2018 for a six-year period with Inria, IRT SystemX and Télécom SudParis, is the largest academic research group in France dedicated to blockchain. ACES and CCN contribute to BART’s activities on behalf of Télécom Paris. Projects are structured around six lines of research: theoretical models, scaling up and monitoring tools, security, architectures, data privacy and business models/regulation. The work carried out aims to overcome all the scientific and technological barriers to blockchain, in line with the needs of society and industry surrounding this trust-based technology in a digital era.

▸ bart-blockchain.fr

Model-Oriented Programming (POM)

EN The aim of this joint laboratory, which was launched in June 2018 with Nokia Bell Labs France, is to offer methods and tools which will simplify the programming of digital infrastructures (including telecommunication networks and cloud technology) that use different types of processors (such as CPUs and FPGAs). The widely varying and highly complex electronic hardware architectures that support current and future telecommunication standards (beyond 5G), benefit from the layer of abstraction that model-oriented programming provides. The work carried out by POM means that re-writing code and optimizing architectures is disconnected from low-level code implementation in processors. This research has generated several publications in conferences and international journals, as well as a chapter of a book published by Springer, Model-Driven Engineering and Software Development.

This joint laboratory operates as part of the Carnot Télécom & Société Numérique (p. 84).

Research and innovation ecosystems

- ▶ École Doctorale de Mathématiques Hadamard
- ▶ LMH : Labex Mathématique Hadamard
- ▶ Labex DigiCosme
- ▶ Quantum, Centre de Sciences et Technologies Quantiques

Institut Polytechnique de Paris

- ▶ **Télécom Paris**
- ▶ **École Doctorale Institut Polytechnique de Paris**
- ▶ **Centres Interdisciplinaires** (E4C, CIEDS, HI PARIS)

Université Paris-Saclay

- ▶ **Maison des Sciences de l'homme Paris-Saclay**

HEC

- ▶ FMJH : Fondation Mathématique Jacques Hadamard
- ▶ Fondation Mines-Télécom
- ▶ Institut DataIA
- ▶ SATT Paris-Saclay
- ▶ IRT SystemX
- ▶ NanoInnov

Plateau Orsay - Palaiseau - Saclay

JokaJobs, making a game of job searching

EN The JokaJobs mobile application is a geolocation-based serious game to help young people access the labor market. Its aim is to make job searching rewarding and accessible, in a fun format with an attractive design. The guiding principle is based on work by Dana Diminescu, a sociologist at INTERACT (p. 68), who has shown that achieving job security is correlated with an individual's mobility in a city and with multiple "weak links" being created, via a network of young people, recruiters and voluntary workers. JokaJobs has been supported by the **Paris-Saclay SATT** (Technology Transfer Accelerator) since early 2019. Having signed an incubation and funding agreement, it represents the first Human and Social Sciences project to be included in the SATT's portfolio of more than 70 projects. The game, now available, was subjected to full-scale testing in 2020 in two French towns, Lens and Liévin, with support from Bouygues Bâtiment, local job seekers' organizations and Pôle Emploi (French Public Employment Service).

▸ jokajobs.com

Neural Meta Tracts: modeling, visualizing and analyzing white matter tractograms

EN The **DigiCosme** Labex is an Excellence Laboratory Center on digital science with funding from the Ministry of Higher Education and Research, and supported by Paris-Saclay, whose scientific lead was Florence d'Alché-Buc (S²A) from 2017 to 2019. Three main themes are developed: Software reliability and security, Communication network, and Data Intelligence. Within the latter, Pietro Gori (IMAGES, p. 56), working with hospitals, coordinates a research program, Neural Meta Tracts, on parsimonious multi-resolution representations for modeling, visualizing and analyzing brain tractograms statistically, in a fast, robust and reliable way. The proposed representations carry all the attributes of the original fibers, namely geometry, connectivity and functional signals.

▸ **A. Delmonte**, **C. Mercier**, J. Pallud, **I. Bloch** and **P. Gori**, "White Matter Multi-Resolution Segmentation Using Fuzzy Set Theory", 2019 IEEE 16th International Symposium on Biomedical Imaging (ISBI 2019), Venice, Italy, 2019, pp. 459-462

▸ **C. Mercier**, **S. Rousseau**, **P. Gori**, **I. Bloch** and **T. Boubekeur**, "QFib: Fast and Efficient Brain Tractogram Compression". Neuroinform 18, 627–640 (2020)

▸ digicosme.lri.fr/tiki-index.php?page=Emergence+MetaTracts

Paris & region

Domaines d'intérêt Majeur

- ▶ DIM RFSI
- ▶ DIM MathInnov
- ▶ DIM SIRTEC

Systematic

Cap Digital

National

CEA

Inria

CNRS

IMT

Institut Carnot Télécom et Société numérique

Open Source Software

Logiciels libres

EN Digital science could not function without software to design, test, model, assess and apply its research activities. Télécom Paris has a specific policy of advocating free open source software, which forms an integral part of its innovation strategy. Télécom Paris COSI (Center for Open Software Innovation) groups all the projects staff have initiated or contributed to. Some thirty software packages have been made available to everyone. They cover four major fields: multimedia, data science and artificial intelligence, programming and smart networks and objects. Opposite, we present a selection of projects that have recently seen major updates.

FR Les sciences du numérique ne sauraient se passer de logiciels pour concevoir, tester, modéliser, évaluer ou mettre en application les travaux de recherche. Télécom Paris mène en particulier une politique volontariste pour les logiciels libres qui sont une partie intégrante de sa stratégie d'innovation. L'ensemble des projets auxquels contribuent des personnels de l'école ou bien qu'ils ont initiés est réuni au sein du Centre pour l'innovation des logiciels libres (COSI) de Télécom Paris. Une trentaine de logiciels sont ainsi disponibles pour tous, couvrant quatre grands domaines : multimédia, science des données et intelligence artificielle, programmation, réseaux et objets communicants. Nous présentons ci-contre une sélection de projets qui ont connu récemment des mises à jour majeures.

Web
telecom-paris.fr/cosi

GPAC

EN This multimedia platform is intended for a broad audience: students, web content creators and developers who want to experiment with new standards for interactive technologies and how they are shared, including reading on mobile devices and setting up streaming servers. GPAC is being developed under the supervision of Jean Le Feuvre (MM).

FR Cette plateforme multimédia s'adresse à un large public : étudiants, créateurs de contenu et développeurs qui souhaitent expérimenter de nouvelles normes pour les technologies interactives et leur diffusion : lecture sur les appareils mobiles, mise en place de serveurs pour les applications de diffusion multimédia en continu… GPAC est développé sous la supervision de Jean Le Feuvre (MM).

Inkscape

EN Inkscape is a vector graphics editor that is free, open source and offers a large range of functionalities. It is widely used for artistic and technical illustrations, such as cartoons, clipart, logos, typography, diagramming and flowcharting. Marc Jeanmougin (DIG), an Inkscape contributor, is also responsible for version 1.0

FR Inkscape est un éditeur de graphiques vectoriels libre et open source qui offre un riche ensemble de fonctionnalités et est largement utilisé pour les illustrations artistiques et techniques telles que dessins animés, clipart, logos, typographie, diagrammes et organigrammes. Marc Jeanmougin (DIG), contributeur du logiciel, est également responsable de sa version 1.0.

YAGO

EN YAGO, one of the first public knowledge databases, has been based on Wikidata and Schema.org. since version 4. Fabian Suchanek, is the man behind the software, which he developed together with researchers from the Max Planck Institute for Informatics. In 2018, the designers of YAGO had won the Test of Time Award at The Web conference.

FR Une des premières grandes bases de connaissance publiques, YAGO est depuis sa version 4 basée sur Wikidata et Schema.org. Elle a été initiée par Fabian Suchanek (DIG) et développée en collaboration avec des chercheurs du Max Planck Institute for Informatics. En 2018, les concepteurs de YAGO se sont vu décerner le Test of Time Award à The Web Conference.

Scikit-network

EN A Python library for the analysis of large graphs such as social media, web graphs and relational data. Thomas Bonald (DIG), the creator and principal contributor to scikit-network, says that "the school's open source strategy applies equally to initial and continuous training."

FR Librairie Python pour l'analyse de graphes de grande taille comme les réseaux sociaux, les graphes du Web et les données relationnelles. Thomas Bonald (DIG), créateur et principal contributeur de scikit-network, précise que « la stratégie open source de l'école est déclinée dans les enseignements aussi bien pour la formation initiale que pour la formation continue. »

Scikit-multiflow

EN This machine learning platform, dedicated to multiple output and multi-label data, and to data streams, is the object of an international partnership with the University of Waikato in New-Zealand. Data flows may come from connected objects and receptors. Albert Bifet (DIG) explains that "scikit-multiflow complements scikit-learn by broadening the range of machine learning tools available on Python". The project was supported in its early stages by the DigiCosme Labex, as part of the Internet of Things Analytics (IOTA) project.

FR La plateforme d'apprentissage statistique, dédiée aux données à sorties multiples ou multi-étiquettes et aux flux de données, fait l'objet d'une collaboration internationale avec l'Université de Waikato en Nouvelle-Zélande. Les flux de données peuvent provenir des objets et capteurs connectés. Albert Bifet (DIG) explique que « scikit-multiflow complète ainsi scikit-learn en élargissant la gamme des outils d'apprentissage automatique disponible sur Python ». Ce projet a bénéficié à son début d'un financement du Labex DigiCosme, dans le cadre du projet Internet of Things Analytics (IOTA).

RAMSES

EN "RAMSES is a platform that helps design critical real-time embedded systems, with a significant time component: if a computing operator takes longer than expected, a critical system failure could occur" says Etienne Borde (ACES). Carnot TSN (p. 84) has recognized the application potential of RAMSES in industries such as transportation and robotics and has made it a part of its technology platform.

FR « RAMSES est une plateforme d'aide à la conception des systèmes temps réel embarqués critiques dont la dimension temporelle est particulièrement importante : si une opération informatique prend plus de temps que prévu pour être réalisée, il peut y avoir une défaillance critique du système» explique Etienne Borde (ACES). Le Carnot Télécom & Société numérique (p. 84) a reconnu le potentiel d'application de RAMSES dans les secteurs industriels comme les transports ou la robotique et l'a intégré à son offre de plateformes technologiques.

Carnot Télécom & Société numérique

INSTITUT CARNOT
Télécom & Société numérique

EN The Carnot label was created in 2006 to promote research projects undertaken by both public research players and those from the socio-economic world. Télécom Paris is a member of Carnot Télécom & Société Numérique (TSN), the first Carnot dedicated to information and communication science and technology, which is part of a network of 29 Carnot Institutes. The Carnot TSN comprises 30 research laboratories, including the LTCI at Télécom Paris, totaling more than 1,700 researchers and PhD students. It provides cutting-edge research and integrated solutions to issues related to ICT (information and communication technology).

FR Le label Carnot a été créé en 2006 pour favoriser la conduite de travaux de recherche entre des acteurs de la recherche publique et ceux du monde socio-économique. Télécom Paris est une des composantes du Carnot Télécom & Société numérique (TSN), le premier Carnot consacré aux sciences et technologies de l'information et de la communication au sein d'un réseau de 29 instituts Carnot. Le Carnot TSN regroupe plus de 30 laboratoires de recherche, dont le LTCI de Télécom Paris, totalisant plus de 1700 chercheurs et doctorants, afin de proposer une recherche de pointe et des solutions intégrées aux problématiques liées aux technologies de l'information et de la communication.

▸ carnot-tsn.fr

Recherche partenariale

Partnership-based research

Special thanks to our partner companies and organizations who supported and collaborated on our research projects

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▶ telecom-paris.fr