UMR IRISA

Activity Report 2019

Team ADOPNET

Advanced Technologies for Operated Networks

D2 – Networks, Telecommunications and Services

CentraleSupélec cnrs rennes IMT Atlantique Bretagne-Pays de la Loire École Mines-Télécom Inria INSA RENNES Université Bretagne Sud ubs: UNIVERSITÉ DE RENNES 1

1 Team composition

Faculty Members

Xavier Lagrange, Professor (HDR), IMT Atlantique (leader of the team)
Alberto Blanc, Associate Professor, IMT Atlantique
Bernard Cousin, Professor (HDR), UR1
Cédric Gueguen, Associate Professor, UR1
Romaric Ludinard, Associate Professor, IMT Atlantique
Loutfi Nuaymi, Professor (HDR), IMT Atlantique
Gwendal Simon, Professor (HDR), IMT Atlantique
Bruno Stévant, Research Engineer, IMT Atlantique
Géraldine Texier, Associate Professor (HDR), IMT Atlantique

Annie Gravey retired in 2019. Isabel Amigo and Sandrine Vaton joined Lab-STICC (CNRS UMR 6285) in 2019 and thus left Adopnet.

Post-Doctoral Fellows

Hristina Hristova, IMT Atlantique

PhD students

Tania Alhajj, IMT Atlantique, since October 2019
Anas El Ankouri, Orange Labs, CIFRE, since October 2017
Mariem Ben Yahia, Orange Labs CIFRE, till May 2019
Ayman Chouayakh, Orange Labs, CIFRE, since March 2017
Romuald Corbel, Orange Labs CIFRE, till December 2019
Ali El Amine, IMT Atlantique, till November 2019
Ahmad Fadel, Univ. Rennes 1, since January 2017
Malo Manini, IRT B-COM, since September 2017
Maha Mdini, Astellia CIFRE, till September 2019
Cédric Morin, IRT B-Com CIFRE, since December 2016
Flavien Ronteix–Jacquet, Orange Labs CIFRE, since October 2019
Cesar Vargas, Orange Labs CIFRE, since January 2017
Juan-Carlos Vargas, Enensys CIFRE, since December 2019

Administrative assistant

Gaelle Tworkowski (part-time), Inria
Sandrine Frouin (part-time), IMT Atlantique

2 Overall objectives

2.1 Overview

To access the Internet, end-users can use various types of network access technologies (e.g., optical, cellular, and WiFi). This variety of technologies is one of today's approaches to cope with two sustained trends:

- The growing heterogeneity of terminals that are connected to the Internet, driven, in part, by the increasing adoption of Machine to Machine (M2M) communication. For example a home media center with a fiber connection differs from a connected drone on multiple aspects, including mobility, energy constraints, and availability.

- The growing heterogeneity of applications that rely on the Internet to communicate. For example, a Ultra High Definition (UHD) video service requires a bandwidth greater than 20 megabits per second (Mbps) while uploading measurements from a sensor can require only a few bytes per minute.

Very different transmission technologies are required on the access to cope with this heterogeneity. Even though the IP protocol has been widely adopted, leading to a widespread *connectivity*, by itself it is not enough to offer *seamless communications*. For instance, somebody using a smart phone connected to a WiFi network will have to restart most of his communications (e.g., downloading a file, a VoIP call) when switching to a 4G interface.

Operators, motivated by reducing capital expenditures, are interested in using the same physical infrastructure to consolidate different access and aggregation networks, a process often referred to as *network convergence*. One of the key problems that has not yet been addressed by the research community is to unify the control planes of the different networks. Such a solution can offer several advantages, including energy efficiency, reliability, availability, privacy, security, and ease of configuration. It is however still an open challenge.

To deal with heterogeneous applications and terminals, network operators also have to design new content delivery systems. Although the research community has worked on increasing the transmission rate for years, the demand of content providers has changed. In particular, the next generation content delivery systems are expected to be more adaptive (to deal with heterogeneous terminals), and more reactive (to support interactive services). The new architectures and protocols will rely in particular on the availability of computing and storage resources at the edge of the network, and on the widespread adoption of software-based solutions, especially service virtualization. The research is still in its infancy in the area, despite a growing attention in recent years, especially with the intensive work on 5G.

The higher degree of heterogeneity leads to an increased variability of the behavior of the network, over time and over space. The availability of services, some of them being central for the resilience of the network, is also under threat because of the increasing complexity and intensity of attacks against infrastructures. Thus, network monitoring is a key function for operators in order to enable the network to detect anomalies, to

take counter-measures to mitigate them and to adapt to the behavior of end users and applications.

The ADOPNET team will contribute to the specification of architectures, protocols, control mechanisms, and monitoring mechanisms for the next generation access and aggregation networks. Our goal is to build networks that are flexible, adaptive, energy-efficient, secure, and able to deliver content on a large scale to various types of terminals. The ADOPNET project will in particular address the convergence of access networks, the combination of radio and optical technologies, and adaptive software-based content delivery networks.

The focus of the ADOPNET project is on the access and aggregation networks. The core networks will be only marginally addressed and the field of ad-hoc networks and home networks is clearly excluded from the project. We distinguish three main research axis: (*i*) content delivery, (*ii*) network control, and (*iii*) network monitoring.

2.2 Scientific foundations

Since the objective of a network is to interconnect various types of devices and to share different types of resource (information, storage capacity, computing power), studying network is by nature a multi-disciplinary activity. Furthermore, it requires an holistic approach because the global optimization of network must take into account several criteria (including transmission bit rate, latency, energy) and various types of constraints (*e.g.*, robustness and simplicity of the protocols, and scalability). In many cases, simulations and implementations on test beds are required to analyze the global performance. However, when the analysis is focused on a particular mechanism, several scientific tools can be used like stochastic analysis or discrete optimization.

2.2.1 Mathematical methods and models

Keywords: decision theory, estimation theory, classification, data stream mining, queuing systems analysis, Markov chains, large deviation theory, game theory, linear programming.

Traffic is an object of studies in itself and as such it can be analyzed in order to discover interesting properties such as long range dependence, non stationarities, non-gaussianity, or heavy tailed distributions. It is necessary to produce accurate traffic models in order to predict, for example, the utilization of ressources or the quality of service. Very often traffic models are of stochastic nature. They can be very simple such as a Poisson process or more sophisticated such as Markov modulated models or, for example, fractional Brownian motions. These models are often parametric and their parameters must be estimated by the analysis of traffic captures.

The theory of queuing systems is used in order to predict the performance offered to the applications. It can be used to analyse the cost of mobility management in mobile networks as signalling related to mobility management represents a more and more important part of the total traffic. It is also useful for the analysis of the performance of complex link layer protocols in radio networks.

2.2.2 Discrete Optimization

Keywords: optimization, integer linear programs, approximate algorithms, exact algorithms, heuristics.

Operations research is a scientific area that has developed a special relation with network. The network resource (memory, processing, data rate, radio spectrum) is inherently limited. However, network operators should provide a quality of service (QoS) as good as possible. It is thus common that network scientists formulate optimization problems with an objective function to minimize (or maximize) subject to various constraints.

For example, network design relies on minimizing the cost of the resources requested to support a given traffic matrix. The traffic matrix is based on "busy hour" traffic flow predictions by the operator. Supporting the traffic on the network can often be expressed as a set of linear equations, involving traffic flows and sets of resources. Linear programming is then used to minimize the cost of resources. For small networks, an exact solution can be identified, thanks to mathematical solvers whereas large network design often relies on various heuristics.

2.2.3 Hardware and software traffic processing

Keywords: traffic analysis, commodity hardwaren, Linux, DPDK, Lua, hardware acceleration, FPGA, SDN.

A major challenge for network operators is to be able to process traffic at very high bit rates. They have to face an exponential increase in the traffic because of the deployment of optic fiber based technologies in the access and because of the rise of video traffic demand. On the other hand one has to implement more and more sophisticated treatments in order to optimize bandwidth usage, to offer a good quality of service and to guarantee the security of the network. In order to deal with high bit rate traffic several approaches must be used. One can leverage on the capabilities offered by parallelization on multi-core architectures or even on GPU. Optimized commodity hardware based traffic capture and analysis can scale up to dozens of Gb/sec without packet loss. Another solution is to use hardware acceleration on FPGA boards in order to speed up some treatments. Software defined networking (SDN) with OpenFlow is an innovating technology to permit a centralized control of network ressources and to implement with a software approach various traffic management protocols.

2.2.4 Protocol Design for Optical Networks

Keywords: Medium Access Control, Label Based Switching, Reservation, Scheduling, GMPLS, SDN, POADM, TWIN.

Introducing optical technologies into network architecture implies designing new protocols for both transfer and control planes. This is mostly true for *transparent* or *translucent* optical technologies, that do not rely at all (or rely only partially) on Optical

to Electronic (OE) conversions.

Optical circuits build upon the sets of wavelengths made available by WDM are commonly used in the backbone's transport layer. However, a wavelength granularity may be too coarse in many situations where some small flows have to be supported as e.g. in metro/aggregation networks. In that case, a finer (sub-wavelength) granularity is requested, that can be delivered by Optical Packet Switching (OPS) or Optical Burst Switching (OBS). Both OPS and OBS offer an optical packet-based transfer but differ by the method used to carry control information; in OPS, a header is appended to each data packet on the wavelength uses to carry client data whereas in OBS, a separate wavelength is used to carry control-related information.

Optical transfer plane significantly differs from existing electronic transfer planes. One major difference is the lack of easily implemented buffering facilities in the optical domain, which precludes implementing buffering as the major contention control mechanism. Therefore, contention has to be avoided in other manners, e.g. by designing complex scheduling mechanisms, as in the upstream direction of Passive Optical Networks. Static or dynamic reservation schemes can also be implemented in the control plane in order to avoid contention in the transfer plane. Another difference between electronic and optical networks is that the transfer rate of a given optical channel can be dynamically controlled; this feature is very useful e.g. to activate backup resources in case of failures.

2.3 Application domains

2.3.1 Content Delivery

Participants: Bernard Cousin, Gwendal Simon, Bruno Stévant, Mariem Ben Yahia, Hristina Hristova.

The traffic related to multimedia content, and in particular video, has increased significantly over the past few years. This growth is expected to continue with the advent of new video formats (e.g., HEVC, multi-view, and Ultra High Definition) and the integration of multimedia into our daily lives (e.g., video in education). More generally, the world is switching from TV with a handful of broadcasters to OTT (Over-The-Top) video services with thousands of broadcasters. And even bigger challenge is presented by the new features of multimedia services, such as interactivity, personalization, and adaptability.

Today's multimedia services offer some interactive features, where the end-users can control the video consumption to some extent. Multimedia services have more stringent requirements related to interactivity. For example, cloud gaming requires an overall response time below 120 ms for an acceptable Quality of Experience (QoE). This trend is expected to be even stronger in the next years due to the popularity of haptic controllers. The latency of today's cloud architecture is not low enough to guarantee QoE for users of such interactive services. To address the needs in content delivery with ultra-low response time, the most appealing architecture is a Content Delivery Network (CDN) with servers that are very close to the end-users, in other words at the edges of the network. It is thus natural that network operators develop their ability to leverage

devices close to the end-users.

In the meantime, the personalization of multimedia services is also a major, sustainable trend. With the wide adoption of HTTP Adaptive Streaming technologies, the servers propose several representations of a given video, and it is up to the end-users to choose the representation that best matches their characteristics. The CDNs have to take into account the characteristics of every end-user to prepare the content, distribute it to the edge servers, and deliver it to the end-users.

The objective of ADOPNET is twofold:

- to contribute to the development of new technologies to enhance multimedia delivery. For example Adaptive Streaming for Multimedia Broadcast Multicast Services (eMBMS) and video-friendly Multi-Path End-to-End Protocols (MPTCP).
- to work on architectures for content delivery. For example content placement, network dimensioning and server management in the fog.

2.3.2 Network Control

Participants: Alberto Blanc, Bernard Cousin, Cédric Gueguen, Xavier Lagrange, Romaric Ludinard, Loutfi Nuaymi, Gwendal Simon, Géraldine Texier, Tania Alhajj, Ayman Chouayakh, Ali El Amine, Ahmad Fadel, Cédric Morin, Flavien Ronteix–Jacquet, Cesar Vargas, Juan-Carlos Vargas.

Today, customers can access services via fixed line networks or via radio access networks (RAN). Controlling these access networks consists in both performing control of each access network, and allowing concurrent access to several such networks. Up to now, fixed and mobile access networks have been optimized and have evolved independently, with partly contradicting trends (e.g., centralization of fixed networks, decentralization of mobile networks). Currently, there is a complete functional and physical separation of fixed line access/aggregation networks and mobile networks.

Fixed Mobile Convergence (FMC) at network level focuses on the design of procedures enabling the users to dynamically select one access network (or possibly several) for a given service, and enabling network operators to effectively share deployed resources (links and equipment) between fixed and mobile accesses. The advent of Digital-Radio-over-the-Fiber technologies (and the companion Cloud-RAN concept) and the generalization of heterogeneous cellular networks increases both the dynamicity and the heterogeneity of the traffic flows that the access/aggregation networks should accommodate. It raises new issues for optical networks, which can be addressed by developing virtualization techniques in order to have easily manageable networks and optical switching in order to combine energy efficiency and high quality of service. From a pure radio point of view, it also extends the possibility of developing multi-radio-access-technology (RAT) selection algorithms and opportunistic energy efficient radio resource management procedures.

- *Virtualization of optical networks.* Transmissions on optical fibers have unique features: large bandwidth, low loss, low cost, light weight, immunity to electromagnetic interference and corrosion resistance. However, the management of

optical network is a very challenging task. Network virtualization can provide a very efficient management and thus, a very efficient use of available network resources. By using network virtualization solutions, network resources can be managed as logical services, rather than physical resources. Due to the high degree of manageability provided by network virtualization, network operators can improve network efficiency and maintain high standards of flexibility, scalability, security, and availability. As a result, it reduces capital and operational costs for network operators.

- *Advanced optical networks.* Several forecasts have emphasized that distribution/aggregation networks, also called Metro Area Networks (MAN), are particularly impacted by traffic evolution. Future MANs should fulfill several requirements: quick adaptation to varying traffic demands, efficient support of both fine granularity and large volumes of traffic demands, possible isolation of different clients' flows, together with an excellent QoS, energy efficiency and low Operational Expenditures (OPEX). Optical packet/burst switching (OPS/OBS) combines sub-wavelength granularity, optical transparency and is thus energy efficient. The challenge is to achieve a high multiplexing gain together with a QoS similar to the one provided by electronic switching and to develop efficient MAC (Medium Access Control mechanisms) with contention avoidance. In the context of Fixed-Mobile Convergence, fiber-based access technologies can be used for fronthauling and backhauling traffic generated by mobile users. Our objective is to propose a dynamical and adaptive control of interfaces and routes to allow an efficient use of available resources in access and aggregation networks.

- *Multiple Access Technology Selection.* Different RATs, including 3GPP families and IEEE ones, are now widely deployed. A key feature will be an increased integration of both the fixed access and the different RATs. Our objective is to consider two aspects: i) the optimization of the architecture to allow a better integration of the different access technologies in a convergence perspective, ii) the optimization of the selection algorithms.

- *Radio Resource Management.* Radio Resource Management (RRM) algorithms or heuristics are a key element for providing high system throughput and high mobile user satisfaction. We focus on two aspects of RRM: power allocation and scheduling. We work on RRM issues in cellular networks where part of the energy comes from renewable sources such as wind and solar. We also consider RRM proposals for cellular M2M with different QoS requirements and according to different criteria, starting with energy efficiency. We propose opportunistic scheduling techniques, which take advantage of multi-path fading and multi-user diversity to provide high throughput. Our specific approach is to take into account the variability of the traffic and the queuing aspects. We propose scheduling algorithms for hybrid networks where a terminal can relay the traffic of some others and propose to combine it with opportunistic routing.

- *Traffic Engineering and Quality of Service.* Traffic engineering techniques allow to control networks for better resource utilization, resiliency, robustness and quality of service. However, the ossification of the Internet, among others, puts limits to end-to-end QoS. New paradigms such as SDN allows to rethink control of networks

in the WAN-scale and at the inter-domain level, through the introduction of a centralized brain which allows for more complex solutions, which are at the same time more easily implemented thanks to standardization and abstractions.

2.3.3 Network Monitoring

Participants: Alberto Blanc, Gwendal Simon, Maha Mdini.

Network monitoring refers to the observation of network and traffic by means of probes of different types and by the analysis of measurements. The goal is to gain information about the traffic or the state of the network and its devices.

The dramatic increase of traffic due to the popularity of video contents and increased data rates in access networks puts high pressure on the design of probes: they should be fast enough to capture traffic without sampling and easily configurable. Advanced data analysis methods should be used in order to process measurements, build traffic models or rise alarms in case of anomalies. It is also necessary to orchestrate the measurements at different probes, to semantically analyse the different sources of information and to communicate from the measurement layer to other layers to trigger counter-measures.

Network monitoring finds applications in various areas. A first application is the characterization of network usage (e.g. bandwidth consumption and variability). A second application is to characterize the network infrastructure in order to assist the network operator in the task of operating and maintaining the network. A third application of network monitoring addresses security issues, for example the early detection of attacks distributed through botnets. A fourth application concerns monitoring users' quality of experience, for example the quality of web navigation.

3 Scientific achievements

3.1 New technologies to enhance multimedia delivery

Participants: Mariem Ben Yahia, Bernard Cousin, Hristina Hristova, Loutfi Nuaymi, Gwendal Simon.

Virtual Reality and Omnidirectional Videos.

Delivering rich, high quality 3D scenes over the internet is challenged by the size of the 3D objects in terms of geometry and textures. In [23], we propose a new method for the delivery of textures, which are encoded and delivered as a video sequence, rather than independently. Implemented on the existing video delivery infrastructure, our method provides a fine-grained control on the quality of the resulting video sequence.

Augmented Reality (AR) superimposes digital content on top of the real world, to enhance it and provide a new generation of media experiences. To provide a realistic AR experience, objects in the scene should be delivered with both high photorealism

and low latency. Current AR experiences are mostly delivered with a download-and-play strategy, where the whole scene is considered a monolithic entity for delivery. This approach results in high start-up latencies and therefore a poor user experience. A similar problem in the video domain has already been tackled with the HTTP Adaptive Streaming (HAS) principle, where the video is split into segments, and a rate adaptation heuristic dynamically adapts the video quality based on the available network resources. In [21], we apply the adaptive streaming principle from the video to the AR domain, and propose a streaming framework for AR applications. In our proposed framework, the AR objects are available at different Levels-Of-Detail (LODs) and can be streamed independently from each other. An LOD adaptation heuristic is in charge of dynamically deciding what object should be fetched from the server and at what LOD level. Our heuristic prioritizes content that is more likely to be viewed by the user and selects the best LOD to maximize the object's perceived visual quality. Moreover, the adaptation takes into account the available bandwidth resources to ensure a timely delivery of the AR objects. Experiments carried out over the Internet using an AR streaming prototype developed on an iOS device allow us to show the gains brought by the proposed framework. Particularly, our approach can decrease start-up latency up to 90% with respect to a download-and-play baseline, and decrease the amount of data needed to deliver the AR experience up to 79%, without sacrificing on the visual quality of the AR objects.

The authors of [XWZ+18] proposed the *MiniView* Layout to efficiently encode omnidirectional views in 360-degree video streams. We worked with these authors and provide in [26] source code, scripts and datasets required to reproduce the experimental figures in the evaluation of [XWZ+18]. The artifact reports the comparison results among the standard cube layout (CUBE), the equi-angular layout (EAC), and the MiniView layout (MVL) in terms of compressed video size, visual quality of views and decoding and rendering time.

Improving Live Rate-Adaptive Video Streaming.

The delivery of live video on the Internet is still a major research problem given the increasing popularity of the services (for example Netflix) and the growth of the video quality. We have made some contributions to improve the performance of the now widely adopted rate-adaptive streaming such as DASH (Dynamic Adaptive Streaming over HTTP).

In [6] we propose video delivery schemes insuring around one-second delivery latency with Dynamic Adaptive Streaming over HTTP (DASH), which is a standard version of HTTP Live Streaming (HLS), so as to benefit from the video representation switching between successive video segments. We also propose HTTP/2-based algorithms to apply video frame discarding policies inside a video segment when a selected DASH representation does not match with the available network resources. The current solutions with small buffer suffer from rebuffering events. Rebuffering does not only impact

[XWZ+18] M. Xiao, S. Wang, C. Zhou, L. Liu, Z. Li, Y. Liu, S. Chen, "MiniView Layout for Bandwidth-Efficient 360-Degree Video", *in: 2018 ACM Multimedia Conference on Multimedia Conference*, ACM, p. 914–922, 2018.

the Quality of Experience (QoE) but it also increases the delivery delay between the displayed and the original video streams. We completely eliminate rebuffering events by developing optimal and practical video frame discarding algorithms insuring an acceptable video quality with at least a Peak Signal to Noise Ratio (PSNR) of 35 dB compared to 25 dB of the basic First In First Out (FIFO) algorithm. We also quantify and qualify the resulting temporal distortion of the video segments per algorithm. A We show that both, the optimal Integer Linear Program (ILP) and practical algorithms, decrease the frequency and duration of the jitters. For example, practical algorithms reduce the number of crashed displayed videos (presenting one jitter longer than 1350 ms) with 22% compared to the basic FIFO algorithm. We also show that requesting video frames separately with HTTP/2 slightly increases the overhead from 4.34% to 5.76%.

Mariem Ben Yahia successfully defended her PhD in may 2019. This PhD thesis [1] studied the benefits of using the HTTP/2 reset stream and priority features in the context of low latency streaming services. Today, HTTP Adaptive Streaming (HAS) is widely used by Over The Top (OTT) platforms. The video content is encoded at different quality levels, called representations. The client is equipped with a rate adaptation algorithm that dynamically decides the best representation to request based on a prediction of the bandwidth. However, inaccurate predictions can happen and may lead to a decrease of the Quality of Experience (QoE). We propose throughout this study HTTP/2-based delivery strategies in order to deal with the prediction errors and insure a continuous playout for different services.

3.2 Function and Service Placement in Networks

Participants: Alberto Blanc, Gwendal Simon, Bruno Stévant,.

Placement of Micro-Services on Edge Infrastructure.

In order to avoir using third-party infrastructures, some users might be interested in using their own devices to host their services. These voluntary-provided devices can be considered together as an edge infrastructure where services can be deployed the same way as in a datacenter. Micro-services oriented applications are interesting in this context as they can be placed independently on the different devices of the infrastructure, offering different solutions for the deployment. But each deployment will result in variable performance of the application as the micro-services will be hosted on devices with different CPU or network capabilities.

Finding the optimal placement for the micro-services over such edge infrastructure giving the optimal performance is a NP-hard problem. To solve it we defined a model of the application performance depending of the placement and proposed a heuristic based on Particle-Swarm Optimization. The solutions found by this heuristic have been tested and validated on a platform emulating an edge infrastructure interconnecting micro-services with variable QoS.

This work is done as part of Bruno Stévant thesis under supervision of Jean-Louis

Pazat, from MYRIADS team, advised by Alberto Blanc.

3.3 Advanced management of optical networks

Participants: Bernard Cousin.

Transmissions on optical fibers have unique features: large bandwidth, low loss, low cost, light weight, immunity to electromagnetic interference and corrosion resistance. However, the management of optical network is a very challenging task [Muk00]. First, due to the physical constraints in all-optical WDM networks (e.g., same wavelength throughout a path), the management of such networks may require specific algorithms and specific adaptations of the protocols. Second, the management of any heterogeneous and large network requires powerful methods for its coherent and complete management. For instance, one may want to establish a light path over several networks operated by different network operators, each network having various optical devices managed by its own policy. Third, advanced capabilities which can be provided by optical networks require appropriate management tools. For instance, advanced optical packet switching, on-demand optical resource management, automatic protection of optical connections, multipoint optical connections, etc. are some of these advanced capabilities. Thus we propose an advanced management of optical networks.

Reconfiguration of multicast connexions in Optical Networks.

Reconfiguration of unicast or multicast connections in an optical network is a critical task. Indeed, if it is not carried out correctly, it can lead to optical flow interruptions that can cause damage to the optical network. It is therefore common to perform the reconfiguration in several steps to avoid flow interruption. In this study, we focused on multicast connection reconfiguration because multicast connections become more attractive and an efficient technique to transmit the optical flows of multicast applications. A multicast connection in an optical network can be represented by a point-to-multipoint all-optical path called light-tree. In this work [28], we explain how to select a pair of sub-trees (current sub-tree, new sub-tree) to be reconfigured at a given step of the reconfiguration process.

3.4 QoS management in fixed and mobile networks

Participants: Cédric Morin, Géraldine Texier.

Toward an Internet with Quality of Service guarantees.

The global traffic carried on the Internet is experiencing unprecedented growth due to profound changes in usage (Internet of Things (IoT), video traffic, etc.). At present,

[Muk00] B. Mukherjee, "WDM optical communication networks: progress and challenges", *IEEE Journal on Selected Areas in Communications 18*, 10, 2000, p. 1810 – 1824.

the Internet operates in a mode called Best Effort (without any guarantee of service or performance) based on the overprovisioning of the operator networks that will not be sufficient to maintain an acceptable Internet service. The alternative is to better manage traffic through quality of service (QoS) and traffic engineering mechanisms.

Géraldine Texier's HDR manuscript [5] summarizes her research work, both architectural and protocol-based, with the use of traffic engineering techniques and the formalization of routing problems by linear programs to enhance resource management and to cope with the imminent profound changes in the Internet. The focus is put on transit flows among operators and in different contexts (multimedia applications and live broadcasting , sensor networks or smart cities).

At the same time, the emergence of Software Defined Networking (SDN) and Network Function Virtualization (NFV) architectures to automate network management while making it dynamic introduces new mechanisms to push the use of traffic engineering to the point where it is possible to propose a dynamic adaptation of virtualized network infrastructures. These promising evolutions offer the opportunity to share a physical infrastructure between several virtualized networks while adapting their structure to the specific needs of customers.

Virtualized Network Function management.

Network Function Virtualization (NFV) turns traditional physical middelboxes into software virtual network functions (VNFs) running over generic servers. Among other benefits, VNFs break the vendor dependence, allow frequent updates, reduce installation and management costs and introduce flexibility in terms of scaling and placement.

In parallel, the emergence of 5G is leading to the creation of new network services, with increased traffic and latency constraints. Due to their proximity with end users, edge resources are crucial to reach ultra low latency requirements, but their scarcity imposes a wise management. So, despite VNF promise of flexibility and scalability, we must focus on edge resources in addition to those of the cloud.

With the NFV-MANO standard (MANagement and Orchestration), ETSI introduces a new architecture to manage the NFV deployment and the network services instantiation. In order to provide a network service, the Network Function Virtualization Orchestrator receives a request to create a Virtual Network Function Chain under specific constraints. This is what we call the Virtual Network Function Chain Placement Problem (VNFCPP). The orchestrator decides where to place and how to connect the VNFs, based on the topology information provided by the Virtualized Infrastructure Managers. Then, the virtualized infrastructure manager reserves resources in the virtual infrastructure according to the placement decision. The architecture is called mono-tenant when the orchestrator and the virtualized infrastructure manager are operated by the same provider, and multi-tenant when the orchestrator solicits virtualized infrastructure managers belonging to other providers to implant VNF on their infrastructure. The VNFCPP supposes the full cooperation of all entities. That can be achieved in a mono-tenant architecture but is not possible in a multi-tenant architecture since virtualized infrastructure managers may be reluctant to disclose confidential information such as their topology.

In [20], we propose an algorithm that solves the Virtual Network Function Chain Placement Problem allowing a fine management of these rare resources in order to respond to the greatest number of requests possible. The optimization strategy is to maximize the acceptation of new virtual network function chains by reserving in priority resources on links and nodes where they are abundant, saving low capacity elements for requests with stronger requirements. We formalize this strategy as an ILP problem, and propose an extensive analysis of its performance depending on requests and topology characteristics in a mono-tenant environment. Then, we propose a heuristic based on network abstraction to handle both computational complexity and multi-tenant context challenges. We leverage this approach to address the complexity of the problem in large mono- or multi-tenant networks.

Urban wireless sensor network infrastructures and crowdsensing.

The widespread deployment of connected Things in our cities allows for the enhanced management of the urban space. However, due to environmental constraints, the connected Things are often battery-powered, which affects the lifetime of the IoT Networks. We believe that the urban IoT networks must leverage the power of the crowd, leading to combine the fixed urban IoT networks with the crowdsensing capabilities of the citizens' smartphones. That is, we integrate the offloading of a portion of the traffic generated by the fixed network to mobile crowdsensing devices that also contribute with relevant urban observations (e.g., for noise pollution monitoring). [24] highlights the key technical features of the resulting solution, whose evaluation shows that we are able to extend the lifetime of the battery-operated IoT network by a up to 7 factor.

Fairness and transport protocols.

Changes are continually being made to meet user needs and new services. Congestion is one of the most critical issues as it impacts the performance of Internet networks. Hence, there is a need for congestion control algorithms to prevent or eliminate it. Today, no algorithm perfectly meets the expected requirements, and a lot of research work is underway. New algorithms may affect the fairness of the network since the behaviour of the transport protocol may change radically depending on the congestion control algorithm used at the end points. In recent years, transport protocols have undergone major changes. A recent significant example is Quick UDP Internet Connections (QUIC), a protocol introduced by Google, which aims to replace two widely used transport and security protocols, namely Transmission Control Protocol (TCP) and Transport Layer Security (TLS). QUIC is implemented in user applications (rather than in the operating system kernel). It is designed to be resistant to ossification and therefore more versatile. This then makes content providers, such as Google, hegemonic over the throughput of its users.

Due to the progressive development of congestion control algorithms and the evolving nature of transportation protocols, new challenges in providing fairness arise. The thesis of Romuald Corbel [2] thus focused on the development of a test platform to

measure network fairness based on the flow rate of different flows. Furthermore, in order to characterize fairness as perceived by a user, we focused on the determination of an unbiased procedure for assessing fairness during a whole session of a flow with two methods named Session Fairness Assessment (SFA) and Weighted Session Fairness Assessment (WSFA). Based on these elements, we specifically analyzed the fairness of protocols when TCP and QUIC flows coexist on a fixed and mobile network. In our fairness assessments, we identified the impact of QUIC implementation aspects such as: emulating multiple TCP connections, limiting the size of congestion windows and using the hybrid start option (hystart). The results show that these mechanisms have a strong influence on fairness in both fixed and mobile networks. Indeed, a wrong setting of the default parameters of these mechanisms or the activation of the hystart option can affect the performance of the transport protocols and consequently fairness. Regarding the evaluation of congestion control algorithms, the results show that the fairness between two different algorithms depends on the network configuration. This conclusion shows that a measurement procedure, such as the one presented in tbe thesis, is relevant to perform the evaluation of the equity between two different algorithms.

3.5 Radio Resource Management

Participants: Bernard Cousin, Cédric Guéguen, Xavier Lagrange, Loutfi Nuaymi, Ali El Amine, Cesar Vargas.

Radio Resource Management (RRM) algorithms or heuristics are a key element for providing high system throughput, low energy consumption and high mobile user satisfaction. The past decades have witnessed intense research efforts on RRM. Though the energy constraint has received a lot of attentions for a couple of years, developing energy-efficient RRM is still a research issue. In our team, we focus on several aspects of radio resource management: interference coordination, scheduling, energy-efficient power control, radio carrier aggregation or user selection strategies.

Radio Access Network Selection.

Mobile terminals can now use a wide variety of technologies, always including 3G, 4G and WiFi access points. In [12], we propose a method to optimize the Radio Access Technologies (RATs) selection and resource allocation in multitechnology wireless networks during a time period. We consider a realistic topology of Base Stations (BS) with overlaps of the cellular coverage and dynamic users traffic (arrival and departure). The optimization takes into account the requested services, different user contracts and user satisfaction functions. Furthermore, in the proposed approach, we add constraints to avoid session drops and handovers for static users. For each instance, we formulate the problem as a linear optimization problem and we optimize it successively. The aim of the optimization is to jointly maximize the overall user satisfaction and the number of users connected.

Radio Resource Management in 5G networks.

Lack of coordination between network layers limits the performance of current proposed solutions for the new challenges presented by5G wireless networks. To overcome such limitations, cross-layer physical and medium access (PHY-MAC) design for multi-input-multi-output orthogonal frequency division multiple access system in heterogeneous networks (HetNETs) is proposed. In [17], we formulate an optimization problem for hybrid beamforming, in a multi-user HetNET scenario aiming to maximize the total system throughput. Furthermore, analog beamforming is selected from a codebook containing a limited number of candidates for steering vectors. The proposed problem is non-convex and hard to solve. Thus it is relaxed by transforming it into a subtraction form of two convex functions. Afterward we apply a group of well-known metaheuristic algorithms to calculate the normalized hybrid beamforming vectors. The optimal solution is obtained using an exhaustive search (ES) algorithm that provides an ideal solution, but with high complexity. In addition, zero-forcing-based approach (ZFA), matched filter (MF), and QR-based approach (QR) are applied to get quick sub-optimal solutions. Hence, we analyze the performance of our systems using the throughput metric. The simulation results show that QR algorithm outperforms ZFA and MF in low and middle signal-to-noise ratio (SNR) regime, while ZFA outperforms QR and MF at higher SNRs. Moreover, QR is close to the optimal solution ES.

Opportunistic scheduling.

One key phenomenon of wireless transmissions is multi-path propagation. It generates fast fading or in other words quick variations of the channel state (few milliseconds timescale), which are thus specific to each terminal in a cellular network. Contrary to conventional access methods like Round Robin (RR), opportunistic scheduling techniques originally proposed by [KH95,WC99] take advantage of multi-path fading and multi-user diversity to provide high throughput: they wait for the most favorable transmission conditions for a given terminal to serve it. An implicit assumption is that the terminal has always data packets to transmit or to receive at any time. In our work, we take into account the variability of the traffic and the queuing aspects. We have proposed new efficient heuristics avoiding the supposed necessary trade-off between system capacity and QoS. The queuing aspect is taken into consideration as well as higher layer requirements. Frequency diversity in addition to time and multi-user diversity are also exploited in a cross layer design and allow to significantly improve opportunistic scheduling approach. This concept can be used in order to increase system throughput, fairness, QoS and QoE but also to provide energy efficient radio communication or increase network connectivity [6].

Study of MIMO channel matrices correlation to optimize resource allocation algorithms in multi-users 5G

[KH95] R. Knopp, P. Humblet, "Information capacity and power control in single-cell multiuser communications", *in : Proc. IEEE Int. Conf. on Communications (ICC)*, *1*, p. 331 – 335, June 1995.

[WC99] C. Y. Wong, R. S. Cheng, "Multiuser OFDM with Adaptive Subcarrier, Bit, and Power Allocation", *IEEE J. Sel. Areas Commun. 17*, 10, Oct. 1999, p. 1747 – 1757.

Resource allocation is a major research field in wireless networks. The main challenge is to find the most suitable user for each time and frequency resource to reach the quality of service requirements. The necessity to always increase the capacity of wireless networks leads to systems using more and more antennas. Namely, the use of Massive-MIMO (Multiple Input Multiple Output) allows to simultaneously schedule several users on the same frequency resource. This is a new paradigm for resource scheduling. In this context, resource allocation algorithms have to include in their decision mechanism the choice of users association on the same time and frequency resource. A possible strategy, seen in the state of the art, is to base this user grouping on their channel-matrix correlation to minimize the interference level. In [18, 19] we shown the limited efficiency of this approach in a system using block diagonal precoder leading to non-optimal resource allocation solutions. Currently, we study more appropriated parameters in order to build more efficient MIMO schedulers.

Opportunistic routing

In [8], we proposed a new multihop wireless routing protocol inspired by opportunistic resource allocation strategies that take into account the variability of the radio conditions due to path loss, shadowing and multipath fading. Thanks to this knowledge, the proposed solution dynamically adapts the selected path accross time. The adaptation is function of each link state and the amount of channel information available. This allows to improve system performance in terms of delay and throughput. This solution can be used in all multihop wireless contexts but can have a special interest in wireless coverage zone extension context. Results show that the proposed routing protocol greatly outperforms the other existing protocols such as Ad-hoc On-demand Distance Vector (AODV), Optimized Link State Routing (OLSR) and Extremely Opportunistic Routing (ExOR) protocols reducing mean packet delays by more than 50% in several scenarii.

LSA spectrum auctions for 5G networks.

Licensed shared access (LSA) is a new approach that allows Mobile Network Operators to use a portion of the spectrum initially licensed to another incumbent user, by obtaining a license from the regulator via an auction mechanism. In [7], different truthful auction mechanisms have been proposed for LSA. These mechanisms differ in terms of allocation (who gets the spectrum) but also on revenue. Since those mechanisms could generate an extremely low revenue, we extend them by introducing a reserve price per bidder which represents the minimum amount that each winning bidder should pay. Since this may be at the expense of the allocation fairness, for each mechanism we find by simulation the reserve price that optimizes a trade-off between expected fairness and expected revenue. Also, for each mechanism, we analytically express the expected revenue when valuations of operators for the spectrum are independent and identically distributed from a uniform distribution.

Energy management and base station switching in green mobile networks.

In 5G wireless networks, specific requirements are defined on the periodicity of Synchronization Signaling (SS) bursts. This imposes a constraint on the maximum period during which a Base Station (BS) can be deactivated. In [16], we propose a distributed algorithm based on Reinforcement Learning (RL) that controls the states of the BSs while respecting the requirements of 5G. By considering different levels of Sleep Modes (SMs), the algorithm chooses how deep a BS can sleep according to the best switch-off SM level policy that maximizes the trade-off between energy savings and system delay. The latter is calculated based on the wake-up time required by the different SM levels. Results show that our algorithm performs better than the case of using only one type of SM. Furthermore, our simulations show a gain in energy savings up to 90% when the users are delay tolerant while respecting the periodicity of the SS bursts in 5G. In [22], we consider cellular networks powered by both renewable energy and the Smart Grid. We study the problem of minimizing the cost of on-grid energy while maximizing the satisfaction of users with different requirements. We use Q-learning algorithm to extract a common pattern of renewable energy generation as well as to decide the number of radio resource blocks activated to maximize the users' satisfaction and minimize the on-grid energy cost. Results show that using Q-learning achieve a good tradeoff with a reduction of cost more than 75% and negligible degradation in users' satisfaction. Management of energy savings and sleep strategies for energy-efficient 5G BSs can be coupled with managing the Quality of Service (QoS) resulting from waking up sleeping BSs. Our work in [15] focuses on multi-level SM environment, where the BS can switch to several SM levels. We propose a Q-Learning algorithm that controls the state of the BS depending on the geographical location and moving velocity of neighboring users in order to learn the best policy that maximizes the tradeoff between energy savings and delay.

Ali El Amine defended with success his PhD on 12 nov. 2019. This thesis [3] focused on studying the role of energy and its behavior while designing and operating wireless 5G cellular networks. We considered different and complementary approaches and parameters, including energy efficiency techniques (i.e., radio resource management and sleep schemes), renewable energy sources, smart grid and tools from machine learning, to bring down the energy consumption of these complex networks while guaranteeing a certain quality of service adapted to 5G use cases.

Device-To-Device transmission for Machine-Type Communications.
Reducing energy consumption is a key requirement for Massive Machine-Type Communication (mMTC) devices operating on battery power. Device-to-Device (D2D) communication is a promising technology that can be used in 5G networks for this purpose. In our previous publications, we identified in which conditions relaying spares some energy compared to a direct transmission and quantified the interest of using Hybrid Automatic Repeat reQuest (ARQ) with Chase Combining (CC-HARQ). In this studies, we assumed that the relay is already chosen. In [25] we propose a simple joint relay-selection and access mechanism that enables any device to discover UEs in its neighborhood. Our numerical and simulation results confirm that when using the proposed discovery mechanism, the total device energy consumption can be significantly reduced depending on the data packet size and the location of the device with respect to the base station.

Mobile ad hoc wireless networks are characterized by the absence of central administration and any network element may be very mobile. It may exist no fixed element within an ad hoc network. In fact, within these networks, all elements must cooperate so as to create a temporary network topology which enables communication. To create this topology and carry data, ad hoc networks must use efficient routing protocols. In [13], we propose a multipath routing protocol with low energy consumption in order to improve the performance of mobile ad hoc wireless networks. Our protocol ESMR (Energy aware and Stable Multipath Routing Protocol) uses a path selection strategy which is based on energy constraint and link stability. It is designed on a realistic mobility model, contrary to most existing protocols which are based on random mobility models with some unrealistic behaviors such as sudden stop, abrupt acceleration. Simulation results demonstrate that ESMR has better performance in terms of energy consumption and network reliability.

Energy-efficient M2M cellular coverage.

In previous studies, we quantified the capacity gain brought by the use macro-diversity in ALOHA-based network, which is the technique used by Lower Power Wide Area Networks (LPWAN) to handle M2M traffic. We analysed selection combining at the base station. In [10], we consider maximum-ratio-combining and we use stochastic geometry to analyze the packet loss probability when Maximum Ratio Combining (MRC) is implemented for both pure and slotted Aloha and obtain a closed formula when the path loss exponent is 4. However, the formula is valid when all base stations on an infinite plane participate in the MRC procedure, which gives an optimistic evaluation. We developed simulations to get the performance when a finite number of receivers in the MRC is considered and focus on the case with only 2 receivers. We use a curve-fitting approach based on the simulation results to get a closed-form formula of the packet loss probability with 2 receivers. The formula is easy to use and accurate enough when the loss probability is greater than 0.5%. The system capacity for a 10% packet loss probability is increased by a factor greater than 1.2 compared to a simple scheme in which each base station independently decodes packets.

3.6 Wireless network monitoring

Participants: Alberto Blanc, Maha Mdini, Gwendal Simon.

Root Cause Diagnosis in Large-Scale Networks.

With the evolution of automation and artificial intelligence tools, mobile networks have become more and more machine reliant. Today, a large part of their management tasks runs in an autonomous way, without human intervention. The latest standards of the Third Generation Partnership Project (3GPP) aim at creating Self-Organizing Network (SON) where the processes of configuration, optimization and healing are fully automated. Many researchers design expert systems and applied Machine Learning (ML) algorithms in order to automate the healing process. However, a large part of the

network troubleshooting still rely on human experts.

For this reason, the thesis of Maha Mdini [4] focuses on taking advantage of data analysis tools such as pattern recognition and statistical approaches in order to automate the troubleshooting task and carry it to a deeper level. The troubleshooting task is made up of three processes: detecting anomalies, analyzing their root causes and triggering adequate recovery actions. We focus on the two first objectives: anomaly detection and root cause diagnosis. The first objective is about automatically detecting issues in the network without including expert knowledge. To meet this objective, we have created an Anomaly Detection System (ADS) that learns autonomously from the network traffic and detects anomalies in real time in the flow of data. The algorithm we propose, Watchmen Anomaly Detection (WAD), is based on pattern recognition. The second objective is automatic diagnosis of network issues, that is identifying the root cause of issues without any prior knowledge about the network topology and services. To address this question, we have designed an algorithm, Automatic Root Cause Diagnosis (ARCD) that identifies the roots of network issues [9]. ARCD is composed of two independent threads: inefficiency-Major-Contributor identification and Incompatibility detection. As monitoring systems collect a large number of logs from the different devices in their networks, it is possible to determine which connections resulted in a poor user experience and apply a failed/successful label. Our solution analyzes labeled connection logs to identify the major contributors to the network inefficiency (e.g., a faulty core device) as well as the incompatibilities between different elements (e.g., make and model of a phone not being able to access a service). We evaluated the effectiveness of our solution by using logs from three different real cellular networks. In each case, ARCD was able to identify the major contributors and the most widespread incompatibilities. In the three cases, the precision (detection accuracy) and the recall (detection rate) are higher than 90%.

WAD and ARCD have been proven to be effective. However, many improvements of these algorithms are possible. The thesis does not address fully the question of self-healing networks. Nevertheless, it contributes to the understanding and the implementation of this concept in production cellular networks.

3.7 Blockchain as a Software Connector for Distributed Services

Participants: Romaric Ludinard.

For two years, blockchain has become omnipresent in the media. Blockchain refers to the technology behind Bitcoin cryptocurrency, allowing participants to perform currency transfers without a trusted third party. This goal is achieved by enforcing nodes to collectively maintain a replicated tamper proof history of ever executed transactions, the so called blockchain. Every participant can thus check this history to validate new transactions. However, this data structure, as well as protocols to share, update and leverage this structure are currently understudied and the set of guaranteed properties vary with these protocols.

In [27, 11], we model the behavior of different blockchains in an abstraction called Blockchain Abstract Data Type. The goal of this abstraction is allow reasoning about consistency guarantees provided by such blockchains and the associated requirements

in term of communication abstractions as well as consensus number.

The work [14] focuses on the design of a scalable permissionless blockchain in the proof-of-stake setting. In particular, it uses a distributed hash table as a building block to set up randomized shards, and then leverage the sharded architecture to validate blocks in an efficient manner. The combination of verifiable Byzantine agreements run by shards of stakeholders and a block validation protocol to guarantee that forks occur with negligible probability along with induced churn makes shards robust to eclipse attacks. Relying on the UTXO coin model guarantees that any stake-holder action is securely verifiable by anyone. This protocol works against adaptive adversary, and makes no synchrony assumption beyond what is required for the byzantine agreement.

4 Software development

4.1 360-Transformations

Participants: Hristina Hristova, Gwendal Simon.

Omnidirectional videos, or 360-degree videos, are captured from all directions so that the frames can apply on a sphere. However, the encoding of videos and most of the video management techniques take a video that is on a flat 2-dimensional rectangular area. The spherical video must thus be projected into a map before being encoded and manipulated. The mapping of a spherical surface onto a rectangular area has been studied for centuries. Various mappings have been proposed, including equirectangular, cube map, and pyramidal.

360-Transformation is a software that enables the mapping from one projection to another for any omnidirectional video. The software, which is released under an MIT free software license, manipulates the different frames of a video to re-project them on another mapping. It also enables to encode the projected video with different encoding parameter settings, in particular to have a region of interest encoded at high quality and other parts of the video encoded at a lower quality.

360-Transformation follows the main concepts that have been adopted by the MPEG experts for the Omnidirectional Media Application Format (OMAF). It is available at `https://github.com/xmar/360Transformations`.

5 Contracts and collaborations

5.1 International Initiatives

5.1.1 Dynamic Distribution of On-demand and Live Videos in Mobile Network

Participants: Gwendal Simon.

- Title: Dynamic Distribution of On-demand and Live Videos in Mobile Network

- Framework: National Natural Science Foundation of China
- Duration: 01/10/2016 to 31/09/2019 (36 months)
- Partners: Xidian University
- Abstract: The objective of the project is to provide the theoretical fondations for content delivery of novel interactive applications baesd on live video streaming.

5.1.2 Inclusive Radio Communications

Participants: Bernard Cousin, Ahmad Fadel.

- Title: Inclusive Radio Communications (IRACON)
- Framework: European Cooperation in Science and Technology (COST)
- Duration: 2016 to 2019
- Partners: numerous European research institutions
- Abstract: The European Cooperation in Science and Technology (COST) provides funding for the creation of research networks, called COST Actions. These networks offer an open space for collaboration among scientists across Europea and thereby give impetus to research advancements and innovation. The Inclusive Radio Communications (IRACON) concept defines those technologies aimed to support wireless connectivity at any rates, for any communicating units, and in any type of scenarios. Indeed the Wireless Internet of Things beyond 2020 will require revolutionary approaches in Radio Access technologies, networks and systems. Some theoretical foundations have to be revisited and breaking technologies are to be discovered during the coming decade. IRACON Action aims at scientific breakthroughs by introducing novel design and analysis methods for the 5th-generation (5G) and beyond-5G radio communication networks. Challenges include i) modeling the variety of radio channels that can be envisioned for future inclusive radio, ii) capacity, energy, mobility, latency, scalability at the physical layer and iii) network automation, moving nodes, cloud and virtualization architectures at the network layer, as well as iv) experimental research addressing Over-the-Air testing, Internet of Things, localization and tracking and new radio access technologies.

5.2 National Initiatives

5.2.1 5M project at IRT B<>COM

Participants: Bernard Cousin, Cédric Gueguen, Xavier Lagrange, Malo Manini.

- Title: 5G Massive-MIMO Mm Waves Multi-User plateform

- Framework: IRT
- Duration: January 2017- December 2019 (36 months)
- Partners : Mitsubishi Electric R&D Centre Europe, Orange Labs, B<>com, University of Rennes 1, IMT Atlantique, INSA Rennes
- Abstract: The 5M project deals with the increase of the number of antennas in wireless communication systems, called Massive MIMO system, according to its network dimension. He is particularly interested in: the optimization of their capacity by increasing the number of transmitting antennas and the use of millimeter frequency bands, the combination and pooling of radio interfaces (multi-RAT) optimizing the overall network, the reduction of the energy consumption of network, the physical implementation to prove the technological feasibility and validate the expected contributions.

5.3 Bilateral industry grants

5.3.1 CIFRE Thesis with Orange

Members of ADOPNET have numerous research projects in cooperation with Orange.

- CIFRE thesis (2016-2019) on the new protocol stack of the Internet for content delivery (Gwendal Simon)
  - Some novel proposals have been studied, implemented and deployed in the Internet although the understanding of their impact on the network performance are still largely unknown. It is especially the case of HTTP/2 and also QUIC. We want to analyze the impact of these protocols on the content delivery with respect to the other competing traffic flows.
- CIFRE thesis (2017-2020) on game theoretic studies for new dynamic spectrum access mechanisms in the 5G context (Patrick Maillé, Loutfi Nuaymi, Isabel Amigo)
  - Different dynamic spectrum access mechanisms are considered in the context of 5G networks. These mechanisms will dramatically change how spectrum is managed and their associated business models. This thesis studies the different dynamic spectrum access mechanism from a mathematical and economic point of view. The objective is to evaluate opportunities and risks for operators in these new contexts.
- CIFRE thesis (2017-2020) on the use of D2D communication for optimized IoT-connectivity (Xavier Lagrange)
  - The objective is of the thesis is to provide an energy-efficient connectivity to a very large number of devices by using terminals connected to cellular networks as relays.
- CIFRE thesis (2019-2022) on the optimization of Ultra-Reliable Low Latency communications (URLLC) (Xavier Lagrange)

– The objective of the thesis is, through a cross-layer approach, to identify the combination of transport protocols, scheduling algorithms, congestion control and buffer management that allows to ensure a very low latency in 5G networks and to achieve an open implementation.

5.3.2 Control distribution in an SDN architecture

Participants: Géraldine Texier.

- Title: Control distribution in an SDN architecture
- Framework: CIFRE Thesis
- Duration: December 2016- December 2019 (36 months)
- Partners: TDF
- Abstract: The SDN architecture specifies a "logically" distributed control but most of the solution are currently defined for a centralized control. We want to propose an architecture and algorithms for the distribution of the control with a focus on the management of Quality of Service in the SDN architecture.

5.3.3 Immersive Video Delivery

Participants: Hristina Hristova, Gwendal Simon.

- Title: Immersive Video Delivery in 5G Networks
- Framework: direct contract
- Duration: February 2018- April 2019 (1 year)
- Partners: Huawei
- Abstract: The objective of this project is to develop new approaches for the delivery of immersive media in 5G networks.

5.3.4 Live Network Anomaly

Participants: Alberto Blanc, Maha Mdini, Gwendal Simon.

- Title: Live Network Anomaly by Massive Collection of Data in Mobile Networks
- Framework: CIFRE framework
- Duration: February 2016- February 2019 (3 years)
- Partners: Astellia (now Exfo)

- Abstract: The objective of this project is to enhance the capacity of Astellia to analyze the cause of anomaly in the network they constantly monitor. Big data technologies and algorithms based on statistics can provide the essential components of new approaches, for live implementation of anomaly detection systems.

5.3.5 Hybrid Broadcast-Unicast Cellular Networks

Participants: Xavier Lagrange, Juan-Carlos Vargas.

- Title: Integration of Multicast and Unicast for Highly Efficient Video Delivery in Cellular Networks
- Framework: CIFRE framework
- Duration: December 2019- December 2022 (3 years)
- Partners: Enensys
- Abstract: The objective of the thesis is to analyze the performance of unicast and multicast/broadcast modes and to study how to combine them in a really hybrid mode in order to maximize the quality of service while limiting the radio resource that is used.

5.3.6 Optimisation of mobile relays for LTE

Participants: Xavier Lagrange,.

- Title: Optimization of mobile relays for LTE
- Framework: Industrial Contract
- Duration: January 2019- December 2019 (12 months)
- Partners: SGP (Société du Grand Paris)
- Abstract: Even with dense base station deployments, public transport users often have a low quality for mobile services. Due to the insulation of the vehicle, passengers experience little to no connectivity on their end devices and low data bit rate. The objective of the project is to propose a mobile relay architecture for LTE and to study how it can be adapted and optimized for 5G.

5.4 Collaborations

5.4.1 International forum

Bernard Cousin is IRISA's representative to the Traffic Management forum (TM Forum). TM Forum is an international association for digital business, connecting talented individuals, leading companies, and diverse ecosystems to accelerate digital business transformation.

5.4.2 Cooperation with universities

We have very good and long-lasting ties with some international universities, namely Tunisia (Tunis university, Sfax University and Manouba University), Lebanon (Lebanese University, Saint Joseph University, Ivory Coast (Houphouet-Boigny University and INPHB) and Algeria (Oran university and Mascara university). Two of these international cooperations are supported by formal agreements where Bernard Cousin is the collaboration leader :

- between University of Rennes 1 and Institut National Polytechnique Félix Houphouet-Boigny (Ivoiry Coast), signed in 2012, and renewed in 2017.
- between University of Rennes 1 and University Saint Joseph (Lebanon), signed in 2011.

5.4.3 Visiting researchers

- Ferdinand ATTA stays at our research laboratory for a duration of 9 months. Its mobility has been funded by two research grants from Rennes Metropole grant (6 months) and French government (3 months). Ferdinand ATTA works with the professor Souleymane Oumtanaga at Institut National Polytechnique Félix Houphouet-Boigny in Ivoiry Coast.

6 Dissemination

6.1 Awards

Xavier Corbillon won on 27 march 2019 the Best 2018 Thesis Award from Institut Mines-Télécom, France. Under the supervision of thesis advisor Gwendal Simon, Xavier Corbillon studied methods for the efficient streaming of 360-video.

6.2 Promoting scientific activities

6.2.1 Scientific Events Selection

Member of Conference Program Committees Bernard Cousin is member of IEEE Communications Society (ComSoc) Technical Committee on Information Infrastructure and Networking (TCIIN).
He served, in 2019, in the Program Committee of the following conferences:

- FNC 2019, International Conference on Future Networks and Communications
- ICN 2019, The Eighteenth International Conference on Networks
- ICNC 2019 OGC, International Conference on Computing, Networking and Communications: Optical and Grid Computing
- IJDSN, International Journal of Distributed Sensor Networks

- Nature & Technology Journal
- OPAL 2019, International Conference on Optics, Photonics and Lasers
- OPTICS 2019, International Conference on Optical Communication Systems
- SCS 2019, Smart Cities Symposium

Xavier Lagrange serves in the Program Committee of the following conferences:

- IEEE ICC 2019, IEEE International Conference on Communications, Mobile and Wireless Networks Symposium
- PIMRC 2019, 2019 IEEE 30th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC) - Track 2: MAC and Cross-Layer Design

Loutfi Nuaymi served in the Program Committee of the following conferences:

- ISCC 2019, IEEE Symposium on Computers and Communications
- PIMRC 2019, 2019 IEEE 30th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)
- WCNC 2019, IEEE Wireless Communications and Networking Conference

Romaric Ludinard serves in the Program Committee of the following conferences:

- Algotel 2019, a french conference gathering the netwetork and distributed system community
- NCA 2019 : 18th IEEE International Symposium on Network Computing and Applications (NCA 2019)
- WBD 2019 : Second International Workshop on Blockchain Dependability
- SERIAL 2019 : 3rd Workshop on Scalable and Resilient Infrastructures for Distributed Ledgers

Gwendal Simon serves in the Program Committee of the following conferences:

- ACM Multimedia 2019, ACM flagship conference on Multimedia

Géraldine Texier has served in the Program Committee of the following conferences:

- IEEE DIPI 2019, the first international workshop on Data Distribution in Industrial and Pervasive Internet
- CoRes 2019, a french conference gathering the french community around issues related to the design, modeling, performance evaluation and experimentation of communication networks
- INTERNET 2019 the Eleventh International Conference on Evolving Internet
- AdHoc-Now 2019, the 18th International Conference on Ad Hoc Networks and Wireless

6.2.2 Journals

In 2019, Bernard Cousin was member of the Editorial Boards for:

- Wireless Communication & Mobile Computing journal (Wiley)
- International Journal of Communication Networks and Information Security
- Smart Control and Management of Networks (ISTE)

Loutfi Nuaymi is regular reviewer for Wiley Editions books proposals.

Gwendal Simon is in the editorial board of the IEEE MMTC R-letters related to Multimedia ACM SIG chapter.

6.2.3 Scientific Expertise

Xavier Lagrange was member of the expert committee for the evaluation of the LIG laboratory by HCERES (Haut Conseil de l'évaluation et de la recherche et de l'enseignement supérieur) in 2019.

Bernard Cousin was member of the expert committee for the promotion of university members of the King Saud University in 2019.

7 Bibliography

Major publications by the team in recent years

[1] R. Aparicio Pardo, K. Pires, A. Blanc, G. Simon, "Transcoding Live Adaptive Video Streams at a Massive Scale in the Cloud", *in : MMSys 2015 : 6th ACM Multimedia Systems Conference*, p. 49–60, 2015.

[2] X. Corbillon, R. Aparicio, N. Kuhn, G. Texier, G. Simon, "Cross-Layer Scheduler for Video Streaming over MPTCP", *in : ACM MMSys*, 2016.

[3] X. Corbillon, G. Simon, A. Devlic, J. Chakareski, "Viewport-adaptive navigable 360-degree video delivery", *in : 2017 IEEE international conference on communications (ICC)*, IEEE, p. 1–7, 2017.

[4] M. El Helou, M. Ibrahim, S. Lahoud, K. Khawam, D. Mezher, B. Cousin, "A network-assisted approach for RAT selection in heterogeneous cellular networks", *IEEE Journal on Selected Areas in Communications 33*, 6, 2015, p. 1055–1067.

[5] C. Gueguen, M. Ezzaouia, M. Yassin, "Inter-cellular scheduler for 5G wireless networks", *Physical Communication*, 2016, `https://hal.archives-ouvertes.fr/hal-01293199`.

[6] C. Gueguen, A. Rachedi, M. Guizani, "Incentive scheduler algorithm for cooperation and coverage extension in wireless Networks", *IEEE Transactions on Vehicular Technology 62*, 2, January 2013, p. 797–808, `https://hal-upec-upem.archives-ouvertes.fr/hal-00740058`.

[7] X. Lagrange, "Very Tight Coupling between LTE and Wi-Fi for Advanced Offloading Procedures", *in : WCNC 2014 : IEEE Wireless Communications and Networking Conference*, 2014.

[8] Z. Li, M. K. Sbai, Y. Hadjadj-Aoul, D. Alliez, G. Simon, K. D. Singh, G. Madec, J. Garnier, A. Gravey, "Network Friendly Video Distribution", *in : NoF 2012 : 3rd International Conference on the Network of the Future*, 2012.

[9] U. Mir, L. Nuaymi, "LTE Pricing Strategies", *in : VTC Spring 2013: Vehicular Technology Conference*, 2013.

[10] L. Suarez, L. Nuaymi, J.-M. Bonnin, "Energy-efficient BS switching-off and cell topology management for macro/femto environments", *Computer Networks 78*, 2015, p. 182 – 201, Special Issue: Green Communications, https://doi.org/10.1016/j.comnet.2014.10.028.

[11] L. Yang, L. Gong, F. Zhou, B. Cousin, M. Molnár, Z. Zhu, "Leveraging light forest with rateless network coding to design efficient all-optical multicast schemes for elastic optical networks", *Journal of Lightwave Technology 33*, 18, 2015, p. 3945–3955.

Doctoral dissertations and "Habilitation" theses

[1] M. Ben Yahia, *Low latency video streaming solutions based on HTTP/2*, Theses, Ecole nationale supérieure Mines-Télécom Atlantique, May 2019, https://tel.archives-ouvertes.fr/tel-02179028.

[2] R. Corbel, *Évolution des protocoles de transport du point de vue de l'équité*, Theses, Ecole nationale supérieure Mines-Télécom Atlantique, December 2019.

[3] A. El Amine, *Radio resource allocation in 5G cellular networks powered by the smart grid and renewable energies*, Theses, Ecole nationale supérieure Mines-Télécom Atlantique, November 2019.

[4] M. Mdini, *Anomaly detection and root cause diagnosis in cellular networks*, Theses, Ecole nationale supérieure Mines-Télécom Atlantique, September 2019, https://tel.archives-ouvertes.fr/tel-02304602.

[5] G. Texier, *Vers un Internet programmable offrant des garanties de qualité de service*, Habilitation à diriger des recherches, Université de Rennes 1 [UR1], December 2019, https://hal-imt-atlantique.archives-ouvertes.fr/tel-02464389.

Articles in referred journals and book chapters

[6] M. Ben Yahia, Y. Le Louedec, G. Simon, L. Nuaymi, X. Corbillon, "HTTP/2-Based Frame Discarding for Low-Latency Adaptive Video Streaming", *ACM Transactions on Multimedia Computing, Communications and Applications*, February 2019, https://hal-imt-atlantique.archives-ouvertes.fr/hal-02463331.

[7] A. Chouayakh, A. Bechler, I. Amigo, L. Nuaymi, P. Maillé, "Auction mechanisms for Licensed Shared Access: reserve prices and revenue-fairness trade offs", *ACM SIGMETRICS Performance Evaluation Review*, January 2019, https://hal.archives-ouvertes.fr/hal-02456364.

[8] C. Gueguen, P. Fabian, X. Lagrange, "Link state opportunistic routing for multihop wireless networks", *Wireless Networks 25*, October 2019, p. 3983–3998, https://www.springerprofessional.de/en/link-state-opportunistic-routing-for-multihop-wireless-networks/16462302.

[9] M. Mdini, G. Simon, A. Blanc, J. Lecoeuvre, "Introducing an Unsupervised Automated Solution for Root Cause Diagnosis in Mobile Networks", *IEEE Transactions on Network and Service Management*, 2019, p. 1–1, https://hal-imt-atlantique.archives-ouvertes.fr/hal-02377865.

[10] Q. Song, L. Nuaymi, X. Lagrange, "Analysis of Macro Diversity based on Maximum Ratio Combining in Long Range ALOHA Networks *", *Telecommunications Systems*, May 2019, https://hal-imt-atlantique.archives-ouvertes.fr/hal-02140290.

Publications in Conferences and Workshops

[11] E. Anceaume, A. Del Pozzo, R. Ludinard, M. Potop-Butucaru, S. Tucci-Piergiovanni, "Blockchain Abstract Data Type", *in : SPAA 2019 - 31st ACM Symposium on Parallelism in Algorithms and Architectures*, ACM, p. 349–358, Phoenix, Arizona, United States, June 2019, https://hal-cnrs.archives-ouvertes.fr/hal-02380364.

[12] I. Ben Dhia, M. Bouhtou, T. En Najjary, S. Lahoud, X. Lagrange, "Dynamic Access Point Selection and Resource Allocation in Multi-Technology Wireless Network", *in : IEEE Wireless Communications and Networking Conference*, Marrakech, Morocco, April 2019, https://hal.archives-ouvertes.fr/hal-02159844.

[13] S. E. Benatia, O. Smail, M. Boudjelal, B. Cousin, "ESMRsc: Energy Aware and Stable Multipath Routing Protocol for Ad Hoc Networks in Smart City", *in : 2nd International Conference on Artificial Intelligence in Renewable Energetic Systems (ICAIRES'2018)*, Springer (editor), *Lectures Notes in Networks and Systems: Renewable Energy for Smart and Sustainable Cities*, *62*, p. 31–42, Tipasa, Algeria, January 2019, https://hal.archives-ouvertes.fr/hal-01950397.

[14] A. Durand, E. Anceaume, R. Ludinard, "STAKECUBE: Combining Sharding and Proof-of-Stake to build Fork-free Secure Permissionless Distributed Ledgers", *in : International conference on networked systems (NETYS)*, Marrakesh, Morocco, June 2019, https://hal.archives-ouvertes.fr/hal-02078072.

[15] A. El Amine, H. Al Haj Hassan, M. Iturralde, L. Nuaymi, "Location-Aware Sleep Strategy for Energy-Delay Tradeoffs in 5G with Reinforcement Learning", *in : 2019 IEEE 30th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Istanboul, Turkey, September 2019, https://hal-imt-atlantique.archives-ouvertes.fr/hal-02168390.

[16] A. El Amine, M. Iturralde, H. Al Haj Hassan, L. Nuaymi, "A Distributed Q-Learning Approach for Adaptive Sleep Modes in 5G Networks", *in : 2019 IEEE Wireless Communications and Networking Conference (WCNC) (IEEE WCNC 2019*, Marrakech, Morocco, April 2019, https://hal-imt-atlantique.archives-ouvertes.fr/hal-01988226.

[17] a. Fadel, A. Nimr, H. L. Chiang, M. Chafii, B. Cousin, "Cross-Layer Multi-User Selection in 5G Heterogeneous Networks Based on Hybrid Beamforming Optimization for Millimeter-Waves", *in : IEEE 30th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC). , September 8-11, 2019.*, Istanbul, Turkey, September 2019, https://hal.archives-ouvertes.fr/hal-02180396.

[18] M. Manini, C. Gueguen, X. Lagrange, R. Legouable, "Etude de la Corrélation des Canaux Massive MIMO pour l'Optimisation d'Algorithmes d'Allocation de Ressources Multi-Users 5G", *in : CORES2019*, Saint Laurent de la Cabrerisse, France, June 2019, https://hal.archives-ouvertes.fr/hal-02127083.

[19] M. Manini, C. Gueguen, R. Legouable, X. Lagrange, "Study of MIMO Channel Matrices Correlation to Optimize Resource Allocation Algorithms in Multi-Users 5G", *in : 2019 12th IFIP Wireless and Mobile Networking Conference (WMNC)*, p. 162–166, Sep. 2019.

[20] C. Morin, G. Texier, C. Caillouet, G. Desmangles, C.-T. Phan, "VNF placement algorithms to address the mono- and multi-tenant issues in edge and core networks", *in : CloudNet 2019 - IEEE International Conference on Cloud Networking*, Coimbra, Portugal, November 2019, https://hal.archives-ouvertes.fr/hal-02313403.

[21] S. Petrangeli, G. Simon, H. Wang, V. Swaminathan, "Dynamic Adaptive Streaming for Augmented Reality Applications", *in : 21st IEEE International Symposium on Multimedia (ISM)*, San Diego, United States, December 2019, https://hal-imt-atlantique.archives-ouvertes.fr/hal-02377856.

[22] H. Sayed, A. El Amine, H. Al Haj Hassan, L. Nuaymi, R. Achkar, "Reinforcement Learning for Radio Resource Management of Hybrid-Powered Cellular Networks", *in : 2019 Twelfth International Workshop on Selected Topics in Mobile and Wireless Computing (STWiMob'2019)*, IEEE, Barcelona, Spain, October 2019, https://hal-imt-atlantique.archives-ouvertes.fr/hal-02294149.

[23] G. Simon, S. Petrangeli, N. Carr, V. Swaminathan, "Streaming a Sequence of Textures for Adaptive 3D Scene Delivery", *in : 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, IEEE, p. 1159–1160, Osaka, France, March 2019, https://hal-imt-atlantique.archives-ouvertes.fr/hal-02276617.

[24] G. Texier, V. Issarny, "La puissance du crowdsensing au service de la durée de vie des réseaux IoT urbains", *in : ALGOTEL 2019 - 21èmes Rencontres Francophones sur les Aspects Algorithmiques des Télécommunications*, Saint Laurent de la Cabrerisse, France, June 2019, https://hal.archives-ouvertes.fr/hal-02118074.

[25] C. Vargas Anamuro, N. Varsier, J. Schwoerer, X. Lagrange, "Energy-efficient discovery process for mMTC applications", *in : 12th IFIP Wireless and Mobile Networking Conference*, Paris, France, September 2019, https://hal.archives-ouvertes.fr/hal-02100252.

[26] M. Xiao, S. Wang, C. Zhou, L. Liu, Z. Li, Y. Liu, S. Chen, L. Sassatelli, G. Simon, "Companion Paper for "MiniView Layout for Bandwidth-Efficient 360-Degree Video"", *in : ACM Multimedia Conference*, Nice, France, October 2019, https://hal-imt-atlantique.archives-ouvertes.fr/hal-02276620.

Miscellaneous

[27] E. Anceaume, A. Del Pozzo, R. Ludinard, M. Potop-Butucaru, S. Tucci-Piergiovanni, "POSTER: Blockchain Abstract Data Type", 24th ACM SIGPLAN Annual Symposium on Principles and Practice of Parallel Programming (PPoPP 2019), ACM, February 2019, Poster, https://hal.archives-ouvertes.fr/hal-01988364.

[28] A. F. Atta, B. Cousin, J. C. Adepo, S. Oumtanaga, "Sub-tree Pair Selection for Reconfiguration of a Light-tree Pair", working paper or preprint, November 2019, https://hal.archives-ouvertes.fr/hal-02374828.