UMR IRISA

Activity Report 2020

Team ADOPNET

Advanced Technologies for Operated Networks

D2 – RESEAUX, TELECOMMUNICATIONS et SERVICES

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1 Team composition

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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 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 (PON). 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: Xavier Lagrange, Bruno Stévant, Juan-Carlos Vargas.

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.

Though a lot of effort is put on content delivery based on unicast transmissions (fixed or cellular), wireless broadcast should still be considered because of its simplicity and its property to reach a lot of terminals with a moderate cost and a limited infrastructure. This is particularly interesting in emergency situations.

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),

- 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, Géraldine Texier, Tania Alhajj, Ahmad Fadel, Cédric Morin, Masoud Taghavian, Flavien Ronteix–Jacquet, Cesar 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 ef-

ficient. 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 Software Defined Networking (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.

3 Scientific achievements

3.1 Content delivery in wireless networks

Participants: Juan-Carlos Vargas, Xavier Lagrange.

Video is an important factor of the load in cellular networks due to the growing popularity of streaming and linear services. In unicast transmission mode, the same data is transmitted as many times as the number of receivers demanding the same video content. Conversely, in broadcast transmissions using the Single Frequency Network

(SFN) technique, a set of base stations perform synchronized transmission of the same waveform to a potentially infinite number of users. In [22], we compared the performance of unicast and broadcast. More precisely, we determined the minimum number of users downloading the same data for which a broadcast transmission is more efficient than multiple unicast transmissions. The analysis is based on a model to calculate the Signal-to-Interference-plus-Noise Ratio (SINR) in unicast and broadcast modes, considering Poisson distributed base stations, path loss, fading, shadowing, trisectored antennas, SFN with a different number of base stations and beamforming in unicast mode. Results show that even when an SFN is formed by just 2 base stations and unicast transmissions are performed using beamforming with 8 antennas per sector, broadcast outperforms unicast when there are at least 8 users per cell demanding the same content.

3.2 Function and Service Placement in Networks

Participants: Alberto Blanc, Bruno Stévant, Géraldine Texier, Cédric Morin.

Placement of Micro-Services on Edge Infrastructure.

In order to avoid 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. 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. We defined a model of the application response-time 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.

In [21], we extended this work by addressing the case of micro-services deployed on actual devices hosted by volunteers. In this real-life test environment, the response time of the application may vary due to concurrent traffic on the network between devices. We proposed an adaptation framework that modify the placement of the micro-services in order to limit these variations.

This work is done as part of Bruno Stévant thesis under supervision of Jean-Louis Pazat, from MYRIADS team, advised by Alberto Blanc.

Placement of network services using network virtual functions.

The advent of 5G offers opportunities to define network services with higher speeds and very low latencies. Software Defined Networking (SDN) and Network Function Virtualization (NFV) paradigms that pave the way for automating the instantiation of

network services and dynamically adapting their provisioning.

These architectures make it possible to fine-tune the allocation of network resources but therefore require the ability to adapt quickly to changing demands. Public cloud computing providers offer individuals and businesses the ability to rent IT resources to meet their needs without investing in their own hardware. At the same time, the NFV concept promotes the migration of network operators from expensive and poorly-scalable hardware network devices to virtual softwarized network functions. In order to embed those functions, network operators may decide to subscribe to public cloud offers. However, their diversity, both in terms of resource capacity and price, makes it difficult to find the optimal combination of offers that meets all needs at the lowest cost.

In [19] and [18] we propose to solve this issue with an algorithm designed to help a network operator to select the best combination of offers (in terms of price) to reserve the virtual machines needed to support a set of network services. We analyze the computation time of our solution against various metric, and estimate the cost savings compared to a traditional resource provision scheme or an unplanned resource rental strategy. Finally we evaluate the opportunity for a network operator to build its own datacenter, considering the existence of public clouds offers.

This work is done as part of Cédric Morin thesis under supervision of Géraldine Texier, co-advised with Gilles Desmangles, from TDF.

3.3 Advanced management of optical networks

Introduction of virtualization technologies (SDN/NFV) in the optical access network.

Participants: Loutfi Nuaymi.

We proposed and verified experimentally a dynamic traffic management [23]. This is done for both backhaul and service ports of an Optical Line Termination (OLT) by using a switch, some smart SFP (Small form-factor pluggable) and SDN abstraction. We successfully demonstrate dynamic traffic management between PON ports and backhaul ports thanks to a probe and the algorithm implemented in our SDN controller. In addition to efficient management, energy savings can be obtained.

3.4 QoS management in fixed and mobile networks

Participants: Cédric Morin, Masoud Taghavian, Géraldine Texier, Xavier Lagrange.

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 [17], 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.

Mobile relay and Quality of Service.
Assuring an uninterrupted high Quality of Service (QoS) of railway communications between on-board terminals and base stations creates challenges for the provider. This is partly explained by the inherent mobility and the high penetration loss of carriages. Deploying mobile relays in public transportation is possible with a 100%-compatible LTE/EPC architecture. This effectively ensures that the electromagnetic insulation is kept to a minimum as QoS on board can be dramatically affected and worsened within the railway vehicles. However, the radio backhaul link gathers the traffic of all users and should accommodate extra packet-overhead and signaling messages that are usually transmitted on fixed links.

In [8] we analyze the performance of mobile relays in loaded conditions and to compare it with a standard direct mode. We propose an analytical model to compute the signaling rate. We parametrize it with experiments done on a testbed with real radio transmissions and show that signaling has no major impact on performance. We also evaluate the QoS experienced by passengers by means of simulations for two representative services: web browsing and voice communications.

In [12], we consider the uplink of the railway communication system. Each onboard relay communicates with two cooperating base stations at the ends of the section along which the train is moving. Each carriage is equipped with two distinct antenna arrays. We designe transmit coding schemes distributed between the antenna arrays and we apply reception macrodiversity. Simulations show that the proposed schemes enable to maintain transmission quality and throughput as the carriage moves along the section.

3.5 Radio Resource Management

Participants: Bernard Cousin, Cédric Guéguen, Xavier Lagrange, Loutfi Nuaymi, Ahmad Fadel, Malo Manini, Christopher Merlhe, 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 Resource Management in 5G networks.

One of the most important issues in the efficient use of radio resource spectrum for multiuser multiple-input/multiple-output (MU-MIMO) systems is the selection of users to achieve the maximum system throughput. The optimal user selection algorithm, which requires exhaustive search, is prohibitive due to its high computational complexity. Moreover, fairness among the users cannot generally be achieved with such a scheme. Therefore, we propose to use Jain's fairness index to assure that each user can achieve a required data rate, as in a system with quality of service guarantees. In [15], we formulate an optimization problem for user selection based on angle-of-arrival (AoA), in a HetNET aiming to jointly maximize the total system throughput and the spectrum efficiency. Notably, we use a well-known beamforming technique to eliminate inter-users interference. Simulation results validate that the proposed algorithm achieves almost the same system throughput than a capacity-based algorithm under a high SNR regime with a considerable reduction in complexity.

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 [7, 16, 10].

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 5G networks, new spectrum sharing concepts such as Licensed Shared Access (LSA) will be implemented in order to optimize spectrum usage: a Mobile Network Operator can access temporarily to other incumbent's spectrum after obtaining a license. The LSA concept guarantees to the incumbent and the LSA licensee a certain level of QoS according to the LSA license.

In [5], we review the existing mechanisms taking into account such radio interference constraints, propose new ones, and compare their performance. We show how to increase the revenue, while maintaining truthful-telling, of all-or-nothing auction mechanisms by introducing a reserve price per bidder. We also investigate extensions of those mechanisms, namely when the management of interference among base stations is more subtle than partitioning base stations into groups of non-interfering base stations. For each mechanism, we show how to optimize a trade-off between expected fairness, expected revenue and expected efficiency by carefully working with groups and reserve prices. Simulations suggests that the extension of those mechanisms may lead to increase an indicator combining allocation fairness, social welfare and seller's revenue by more than 20%.

In [25], we investigate extensions of those mechanisms, when the management of interference among base stations is more subtle than partitioning base stations into groups, and when several base stations are controlled by a common entity. For those extended contexts, we show that we can maximize social welfare and preserve the truthfulness

[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.

by properly applying Vickrey-Clarke-Grove auction scheme. In this context, different auction schemes were proposed, however they are all one-shot auctions. In [13], we propose an ascending implementation of the well-known Vickrey-Clarke-Groves mechanism (VCG) when the regulator has K identical blocks of spectrum to allocate. The implementation is based on the clinching auction.

Ayman Chouayakh defended with success his PhD on 10 march 2020. In this thesis [1], the auction mechanisms proposed in the literature for the LSA context are studied. First we show how to increase the performances of those auctions (in terms of revenue, efficiency and fairness of the allocation)- while preserving truthful bidding- by splitting spectrum and converting single block auctions to multi-block auctions. Then, we show how to convert one-shot mechanisms to equivalent ascending mechanisms (in terms of allocations and payments) so that we add transparency and privacy to the auction.

Radio Access Network evolution for Ultra-Reliable Low latency communications.

Many use cases are meant to be supported by the fifth generation (5G) wireless technology. The one which is occupying the research area for its challenging requirements is the Ultra Reliable Low Latency Communications (URLLC). Hybrid Automatic Repeat reQuest (HARQ) protocol is used to ensure reliability but it induces delay. Furthermore, the transmission in the Radio Access Network (RAN) should be taken into account in the delay budget. In [11], we jointly analyzed the reliability and the delay with two RAN architectures: the legacy one where only one radio unit receives the packet from a terminal and a Centralized-RAN (C-RAN) architecture where several radio units can decode a packet. We proposed to combine these approaches in a flexible architecture. The observed enhancement is a division by 850 of the packet erasure rate compared to the legacy architecture with a latency of 3 milliseconds. We further extended the work in [24] to consider the case where the signal received by different radio units are combined. We found an analytical formula to compute the packet loss probability. This result will be used in a future study.

Energy management and base station switching in green mobile networks.

In 5G networks, specific requirements are defined on the periodicity of Synchronization Signaling (SS) bursts. This imposes a constraint on the maximum period a Base Station (BS) can be deactivated. In addition, BS densification in 5G architecture will cause a drastic increase in the network energy consumption followed by a complex interference management. In [14], we study the Energy-Delay-Tradeoff (EDT) problem in a Heterogeneous Network (HetNet) where small cells can switch to different sleep mode levels to save energy while maintaining a good Quality of Service (QoS). We propose a distributed Q-learning algorithm controller for small cells that adapts the cell activity while taking into account the co-channel interference between the cells. Our numerical results show that multi-level sleep scheme outperforms binary sleep scheme with an energy saving up to 80% in the case when the users are delay tolerant, and while respecting the periodicity of the SS bursts in 5G.

Device-To-Device transmission for Machine-Type Communications.
Massive machine-type communication (mMTC) is one of the main services delivered by the 5G mobile network. mMTC represents a major challenge for 5G network since it is characterized by a large number of low complexity devices thats end small data packets. Moreover, mMTC devices are often battery-powered, and the battery is expected to operate for long periods without being recharged or replaced. Traditional cellular networks, which are designed for human communications, are not energy efficient for this type of service.

To address this problem, in the thesis of Cesar Vargas defended in 2020 [2], we studied the use of Device-to-Device(D2D) relaying as a complementary transmission. In this approach, the mMTC device can transmit its data using a nearby UE as a relay.

First, we calculated the energy consumed in each phase of the communication process for a device located at the cell border that uses LTE-Mtechnology. Then, using a simple model, we compared the energy consumption of cellular and D2D transmission modes, and we determined the optimal relay location.

Through the use of stochastic geometry, we analyzed the performance of D2D communication with ARQ and CC-HARQ with regard to the transmission success probability, the average number of transmissions, and MTD energy consumption. Finally, we proposed an energy-efficient D2D relaying mechanism suitable for mMTC applications thanks to its easy implementation. This mechanism used a distributed relay selection approach, which prioritizes the selection of the user equipments (UEs) with the best channel qualities. Moreover, we present a tractable model to evaluate the performance of our mechanism.

Energy Efficiency in Wireless Ad Hoc Networks.

Ad hoc wireless mobile networks are characterized by a lack of central administration and the fact that any element of the network is very mobile and susceptible to disappear. In an Ad hoc network, all the elements must cooperate in order to establish a temporary network to communicate. This communication is affected by the links stability mainly in a restricted environment such as a city and the depletion of the batteries energy of the nodes. These factors degrade the ad hoc networks performance. We propose in [3] a stable routing protocol with low energy consumption for urban areas in order to improve these performances. The proposed solution is a multipath protocol named ESMRua (Efficient energy aware and Link Stable Multipath Routing Protocol in urban areas). ESMRua uses a path selection scheme based on energy constraint, signal quality and link stability. For the link stability, three calculation variants are used. ESMRua will be designed for realistic mobility, contrary to the main existing protocols which are designed for the random mobility models; these models have unrealistic behaviors such sudden accelerations and stops. Simulation results show that our multipath protocol enhance the performance of the ad hoc networks, mainly in terms routing overhead, energy consumption and network reliability.

Opportunistic routing

Since the last few years, the Internet of Vehicles (IoV) has gained more interest from the community because of the rapid development of autonomous vehicles, the growing amount of data generated by vehicles'sensors, and the motivation to use this data for different purposes. Given the very dynamic nature of fast moving vehicles, building a network that guarantees the Quality of Service (QoS) is still a challenge. This is why we have developed in [6] an original architecture and a programmable objective function to improve QoS on the ever-changing networks present in the IoV. Simulation results show that the proposed solution adapts better to mobility by providing better packet delivery ratio up to five times, achieving three times less packet losses and greatly reducing the energy consumption by a factor 10 compared with state of the art solutions, without compromising delay nor throughput usage.

In [4] we address the problem induced by the frequent variations of the topology and

the nature of the radio links that have a negative impact on the stability of the links. To overcome these problems, new forms of routing protocols are used as the MultiPath routing that change the behavior of Ad-Hoc On demand Multi-path Distance Vector (AOMDV) routing protocol by considering the density of the nodes as well as the interference of the neighboring nodes. This selection of paths goes through two stages. In the first step, we study the impact of the neighbor discovery process to select a set of paths having a minimum number of neighboring nodes to diminish contention problems and interference rate. In the second step, the Interference Ratio (IR) metric is used to select the paths in which the nodes are surrounded by a minimum of interference. Extended simulations shown that networks performances are clearly enhanced.

3.6 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. Beyond the questions related to the properties guaranteed by the different blockchain architectures, cryptocurrencies are often attacked on the legality of the transactions that are recorded in the ledger. In [9, 20] we investigate stochastic models to classify transactions according to their legality. The proposed approach provides the same quality of classification as those provided by different blackbox classifiers. In addition, we studied the graph structure from the transaction set of the blockchain from its inception. Both temporal and graph metrics were used to improve the classification.

4 Contracts and collaborations

4.1 International Initiatives

4.1.1 AI4Green Celtic European project

Participants: Loutfi Nuaymi.

- Title: Artificial Intelligence for green networks
- Framework: Celtic European project
- Duration: October 2019- September 2022 (36 months)

- Partners : KTH (Coordinator), Allbesmart, BI Nordic, Canaima Communications, Celfinet, Instituto Politecnico de Castelo Branco, Instituto Superior de Engenharia de Lisboa, Orange SA, P.I. Works, Tele2 , Turkcell, Turkgen, University of Oulu, Verkotan Oy, VTT Technical Research Centre of Finland, Institute Mines Telecom,

- Abstract: Artificial Intelligence and Machine learning have been successfully applied to various domains. This success suggests that these techniques could be successfully applied in the context of wireless networks to improve the overall performance and efficiency. AI4Green is built around the need to build comprehensive, sophisticated and energy-efficient algorithms and solutions at both radio access and core networks, but also on data centres and storage while keeping in mind the emergence of new architectures and the development of smart grids.

4.2 National Initiatives

4.2.1 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- September 2020 (45 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.

4.2.2 Maya project at IRT B<>COM

Participants: Bernard Cousin, Cédric Gueguen, Xavier Lagrange.

- Title: Réseau MAIllés et Intelligence Artificielle

- Framework: IRT

- Duration: October 2020- September 2023 (36 months)

- Partners : Airbus Defence & Space, Nokia, Centrale Supélec, INSA Rennes, Secure-IC, Orange Labs, University of Rennes 1, IMT Atlantique
- Abstract: The Maya project deals with the optimisation of meshed wireless networks when there is no infrastructure (natural disaster, desert zone). The approach is to use learning methods when possible.

4.2.3 WEC-UP project at IRT B<>COM

Participants: Géraldine Texier, Cédric Morin, Masoud Taghavian.

- Title: Wireless Edge Computing and User Plane
- Framework: IRT
- Duration: Novembre 2019- October 2022 (36 months)
- Partners : Orange, TDF, Nokia, Mitsubishi Electric, Enensys, Aviwest, Exfo, University of Rennes 1, University UBO and IMT Atlantique
- Abstract: The WEC-UP project proposes to build optimized, cooperative and coordinated Networks and Edge Clouds for verticals. The architecture enables the network to evolve into an E2E Cloud Native infrastructure that integrates 5G NR RAN, 5G Core network and EDGE computing.

  The project hosts the thesis of Cédric Morin, that was defended on the 18^{th} of November 2020 and the thesis of Masoud Taghavian that started in September 2020, under supervision of Géraldine Texier, co-advised by Géraldine Texier and Philippe Bertin, from IRT B-Com. The goal is to study and propose mechanisms for the instantiation of VNF/CNF in the edge, for services with high QoS needs and potentially a short lifespan.

4.3 Bilateral industry grants

4.3.1 CIFRE Thesis with Orange

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

- 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.

- CIFRE thesis (2019-2022) on the Introduction of virtualization technologies (SDN/NFV) in the optical access network (Loutfi Nuaymi, Isabel Amigo)

  - The thesis aims to study the evolution of the optical network access due to the introduction of virtualization in the access: characteristics required for the SDN controller, need for an abstraction layer between the controller and the network equipment (such as offers in the literature), choice of protocols and their limits, choice of data models and their limits, limits of the management architecture (failures, latency, etc.), choice of functions to be virtualized (e.g. bandwidth allocation) and associated constraints, integration of the SDN/NFV architecture chosen in the global network context, other equipment, other controllers.

4.3.2 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.

4.3.3 Optimisation of mobile relays for LTE

Participants: Xavier Lagrange.

- Title: Optimization of mobile relays for LTE

- Framework: Industrial Contract
- Duration: January 2020- December 2020 (12 months)
- Partners: SGP (Société du Grand Paris)
- Cooperation with IMT-Atlantique/Lab-STICC (Karine Amis)
- 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.

4.4 Collaborations

4.4.1 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.

4.4.2 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.

We have also cooperation with Facultad Ingeniera de Telecomunicaciones of Universidad Santo Tomas and Pontificia Universidad Javeriana in Bogota, Columbia. Xavier Lagrange is the international advisor of the PhD thesis of Monica Espinosa Buitrago on "Cognitive Radio Architecture for Massive Internet of Things services with Dynamic Spectrum Access".

4.4.3 Visiting researchers

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

5 Dissemination

5.1 Promoting scientific activities

5.1.1 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 2020, in the Program Committee of the following conferences:

- CSnet 2020, Cyber Security in Networking Conference
- FNC 2020, International Conference on Future Networks and Communications
- ICC 2020 NGNI, IEEE International Conference on Communications: Next-Generation Networking and Internet Symposium
- ICN 2020, The Eighteenth International Conference on Networks
- ICNC 2020 OGC, International Conference on Computing, Networking and Communications: Optical and Grid Computing
- IJDSN, International Journal of Distributed Sensor Networks
- Nature & Technology Journal
- OPAL 2020, International Conference on Optics, Photonics and Lasers
- OPTICS 2020, International Conference on Optical Communication Systems
- VEHITS 2020, 6th International Conference on Vehicle Technology and Intelligent Transport Systems

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

- IEEE ICC 2020, IEEE International Conference on Communications, Mobile and Wireless Networks Symposium

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

- ISCC 2020, the 25th IEEE Symposium on Computers and Communications
- ICCT 2020, International Conference on Telecommunications

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

- NCA 2020 : 18th IEEE International Symposium on Network Computing and Applications (NCA 2020)
- SSS 2020 : 22nd International Symposium on Stabilization, Safety, and Security of Distributed Systems (SSS 2020)

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

- ISCC 2020, the 25th IEEE Symposium on Computers and Communications
- Agotel 2020, a french conference gathering the french community around issues related to distributed systems and communication networks

5.1.2 Journals

In 2020, Bernard Cousin was member of the Editorial Boards for:

- Wireless Communication & Mobile Computing journal (Wiley): academic editor
- International Journal of Communication Networks and Information Security

Loutfi Nuaymi is regular reviewer for Wiley Editions books proposals.

Romaric Ludinard was reviewer for Transactions on Dependable and Secure Computing.

Géraldine Texier is regular reviewer for Internet Technology Letters, Computer Networks, Transactions on Emerging Telecommunications Technologies, Computer Communications.

5.1.3 Scientific Expertise

Bernard Cousin was member of the expert committee for the promotion of university members of the King Saud University in 2020. He was also member of the expert committee for the CIFRE grants, in 2020.

Loutfi Nuaymi was named opponent of the PhD Thesis of Olli Apillo, entittled "Energy efficiency analysis and improvements of MIMO cellular communications" and defended at the University of Oulu in december 2020.

Romaric Ludinard was member of the expert committee for Airbus Defense and Space in 2020.

5.2 MOOCs

A new MOOC on 5G networks was launched in 2020 on France Université Numérique https://www.fun-mooc.fr/fr/cours/explorer-la-5g/. More than 7500 people registered to the first session, among which 11% got the success attestation

The MOOC "Objectif IPv6" ran its fifth session in 2020 on France Université Numérique. This MOOC counts more than 25,000 registrations in total and 1200 success attestations. A new version of the MOOC is planned including contributions from Véronique Vèque (Université Paris-Saclay) and Pascal Anelli (Université de la Réunion).

5.3 Popularization

In 2020, the first 5G commercial networks were launched. In this context, several members of Adopnet (L. Nuaymi and X. Lagrange) were interviewed to answer the questions raised by this new technology:

- Technical presentation of 5G systems to non-scientific audience on website "The Conversation" [26]
- Presentation of 5G to individuals involved in rural emergency services. A video was recorded and is available [27]
- Interview in Ouest France newspaper about 5G issues: https://www.ouest-france.fr/bretagne/rennes-35000/5g-ce-chercheur-de-rennes-propose-de-brider-les-debits-pour-reduire-l-empreinte-ecologique-6994091
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