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Activity Report 2021

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, is 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.

Though there are very different requirements regarding the Quality of Service, 5G can be considered as the main *convergence* technology as well as an enabler to accommodate the various types of heterogeneity.

Convergence does not mean a monolithic network but a multifaceted and agile network. Virtualization of the network functions and the concept of slicing, which are possible in 5G, make it the dominant technology for the next decade. Furthermore, wireless transmission is the most used access technology.

The spectrum used for mobile services keeps increasing: in addition to the traditional bands between 700 and 2600 MHz, higher frequencies are being deployed (3.4 GHz) or planned (26 GHz) to eventually reach THz in 6G. This evolution does not only concern radio transmissions but has an influence on the network because the very low coverage resulting from very high frequencies leads to multi-layer networks (mixing small and large cells). This paradigm shift identified more than 20 years ago has not yet been translated into reality because the layers interact weakly. The virtualization of radio functions makes it possible to have agile networks whose radio resources are adapted to demand and where the traditional notion of a cell disappears, as a terminal is connected to several access points that vary over time.

5G is characterized by two aspects at the network level: it is a configurable distributed system that can be deployed in multiple slices, each providing a certain quality of service, and it is based on an increasingly sophisticated integration of software technologies in the network (virtualization of network functions, Software-Defined Networking (SDN) approach). The combination of these two aspects leads to the possibility of an agile network, whose configuration evolves according to needs.

Among the quality criteria, latency is an element that was little taken into account by previous technologies and is vital for many applications (haptics, interactive 360-degree videos). The electrical consumption of the terminals and the network is also an essential issue. The two constraints are often contradictory: minimizing latency leads to placing

the processing as close as possible to the terminals (Edge Computing) but reduces the possibilities of mutualization and consequently increases energy consumption.

Ensuring compliance with quality of service criteria requires optimizing each protocol, but with a holistic approach that takes into account all the layers and elements of the network. The challenge is also to set up and optimize an agile network whose capacities adapt to demands, relying among other things on artificial intelligence techniques but also on operational research. Generally speaking, the relevance of learning mechanisms depends closely on the available data and requires good data engineering, i.e., the set of techniques that allow the capture and the collection of data disseminated in a network and their formatting in order to allow their processing (the data can be observations of the network).

The ADOPNET team will contribute to the specification of architectures, protocols, control mechanisms for next-generation networks. Our goal is to design flexible networks that adapt in real-time to the exact demand and typology of services in order to provide to each user or application an adapted level of service while minimizing the operation cost (including the energy footprint) of both the network and the terminals.

We identify two research axes: control of radio networks and control of edge networks.

2.2 Scientific foundations

Since the objective of a network is to interconnect various types of devices and to share different types of resources (information, storage capacity, computing power), studying a network is, by nature, a multi-disciplinary activity. Furthermore, it requires a holistic approach because the global optimization of the 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 Stochastic systems

Keywords: Queuing systems analysis, Markov chains, stochastic geometry.

Traffic is an object of study 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 resources 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.

2.3 Application domains

2.3.1 Control of radio networks

Participants: Bernard Cousin, Cédric Gueguen, Xavier Lagrange, Loutfi Nuaymi, César Viho, Tania Alhajj, Ahcene Boumhand, Ahmad Fadel, Chourouk Ghodhbane, Sid Ali Hamideche, Malo Manini, Christopher Merlhe, Amath Ndao, Flavien Ronteix–Jacquet, Julien Saint-Martin, El Hadj Mohamed Traore, Cesar Vargas, Juan-Carlos Vargas.

The radio access network is no longer a set of base stations, each one working independently from each other, but a group of radio units controlled by a central unit with the advent of Cloud/Centralised Radio Access Networks (C-RAN). Furthermore, the multi-layer aspect should be used to provide a network with both high-capacity and energy efficiency. Massive Multi-Input Multiple-Output (MIMO) transmissions and more generally all multi-antenna techniques give the possibility to limit the co-channel interference and to increase the capacity but they require intensive processing and high-data bit rates between the radio units and the central unit (fronthaul links). In exceptional circumstances including natural disaster and low-density environment, the fronthaul links are based on radio transmission. Furthermore, a high degree of reliability is required, possibly at the expense of lower capacity.

Our aim is to contribute to the definition of new radio-access architectures and associated control procedures that are able to adapt to the varying load conditions

regarding both the time dimension, the space and the type of services. This axis includes studies on

- Radio Resource management (scheduling with service differentiation, power-control, MIMO modes, energy saving),
- Functional split between the radio units and the central unit for different fronthaul types.
- Terminal-access point association in a multi-layer context,
- Hybrid networks that combine device-to-device and device-to-network transmissions or radio-based fronthaul,

All these questions can be seen as multi-objective optimization problems. The objective can include the total capacity, the latency, the fairness, the energy consumption and the resiliency.

2.3.2 Control of edge networks

Participants: Alberto Blanc, Bernard Cousin, Nicolas Huin, Romaric Ludinard, Loutfi Nuaymi, Bruno Stévant, Géraldine Texier, Ferdinand Atta, Zahraa El Ataar, Pierre-Marie Lechevalier, Menuka Perera, Masoud Taghavian.

Network Function Virtualization (NFV) is a strong trend in networks. It is adopted for example for all Network Functions (NF) of a 5G network. A service is defined by a composition of elementary functions, called VNF (Virtual Network Functions), which can be deployed at different locations on the network, potentially operated by different actors. It thus allows the emergence of virtualized or non-virtualized service providers and their composition.

In addition, network slicing allows operators to define several virtual networks dedicated to specific use cases. The slices are implemented with different levels of isolation on the same physical infrastructure, which is potentially complex and operated by different actors. Depending on the type of use case they address, slices must respect a set of properties that can range from properties of availability, quality of service (latency, jitter, ...) to properties related to energy consumption or security. Fulfilling constraints on these properties is challenging, especially for use-cases implying dynamic “edge-to-edge" communications. Therefore, enabling slicing requires mechanisms to ensure their dynamic adaptation to the network conditions involving self-configuration, monitoring, analysis and planning. However, the objective is not to design fully self-organized networks but to put these mechanisms at the service of the implementation of a global strategy. An important issue is to determine when auto-adaptation actions should be performed in a distributed way or require a centralized approach and to which extent hybrid approaches can be used.

There are several research issues to address.

- The first question is how to define the slices, where to locate the involved virtual network functions in order to provide the expected quality of the global network

service especially in term of latency and throughput while minimizing the energy consumption of the system and ensuring a minimum resiliency against failures. We will consider automatic scaling and placement of these functions as part of the solution to dynamically adapt the slicing to changes in the initial conditions.

- The second question is related to reliability when the service involves several actors. The different actors can be all kinds of IT systems, not necessarily sharing the very same objectives nor being designed to achieve security or more generally reliability at system scale. In a context that is highly distributed by nature, and without any real trust, composing the services while respecting the constraints imposed by it is a real challenge. Distributed trusts solutions like blockchains can be a solution to this problem.

3 Scientific achievements

3.1 Radio Resource Management

Participants: Bernard Cousin, Cédric Guéguen, Xavier Lagrange, Loutfi Nuaymi, Ahmad Fadel, Malo Manini, Christopher Merlhe, Juan-Carlos 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 [2], 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. The main challenge is to find the most suitable user for each time and frequency resource to ensure the Quality of Service (QoS) requirements. The use of Massive Multiple-Input-Multiple-Output (MIMO) makes it possible to simultaneously schedule several users on the same time and frequency resources. This is a new paradigm for resource scheduling. In this context, resource allocation algorithms have to account for the choice of users served on the same time and frequency resource in their decision mechanism. In [22, 3] we analyze the impact of different group sizes on system capacity using several user selection algorithms and we propose a new user selection algorithm which performs closer to the optimal algorithm proposed in the literature.

Multi-Point Coordination for Inter-Cell Interference Management.

As previously explained, in wireless networks, the transmission efficiency is highly impacted by attenuations such as: path-loss, shadowing, multi-path fading and interference. At cell edges, mobiles are far from their access point and close to neighboring cells, leading to high path-loss and high magnitude of interference. Consequently, ensuring high spectral efficiency is necessary to guarantee an appropriate Quality of Service (QoS), especially at edges. To cope with this crucial issue, this work investigates the benefits of the Joint Transmission Coordinated Multi-Point (JT-CoMP) clustering to mitigate Inter Cell Interference (ICI). In [23] we propose the Hybrid Joint-Transmission Coordinated MultiPoint algorithm (H-JT-CoMP). This solution dynamically performs its ICI management according to the Chanel State Information (CSI). This allows to make a wise CoMP usage according to the magnitude of interference received. Performance evaluation highlights an increased QoS and system capacity with a better fairness between inner and edges of the cell.

Pre-Scheduler for Multi-Cell Wireless Networks.

With the constant increase of throughput demands, maximizing the wireless network capacity has always been a crucial issue. Network densification becomes one of the adopted strategies to guarantee a high Quality of Experience (QoE). These new access points are included in the traditional 5G coverage scheme and offload the network

[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.

in dense areas where the demand is high. A mobile may be located in the coverage area of several base stations which implies the need to extend traditional scheduling to a multicell context. This leads to the emergence of new issues concerning resource allocation strategies. When one user is suitable to receive resources from different cells, a well designed users' distribution is essential to limit unbalanced and overloaded cells. The main contribution of [12] is to propose a pre-scheduler called Multi-Cell Pre-Scheduler (MCPS) that adequately allocates user traffic between different access points, intervening before the scheduling application. Compatible with any type of simple cell existing schedulers, MCPS adapts schedulers to multi-cell context and improves their performance by delaying the system congestion and making the system more robust to unexpected traffic peaks. Performance evaluations show that the use of MCPS solution allows to increase the throughput capacity and energy efficiency while improving QoE fairness between users.

Resource management optimisation with delay tolerant users.
In [15], we analyze the impact of delaying delay-tolerant calls under certain conditions in cellular networks. We propose to queue the call if the user agrees when the terminal has bad radio conditions and the system is loaded. The call is served as soon as radio conditions become good or the current load goes below a given threshold. We model the system as a continuous-time Markov chain, which allows us to compute the blocking probability, the mean waiting time and the mean service time. Numerical results show that when the proportion of users with delay tolerance is 20%, the system can bear 16% more calls with the same blocking probability, and 113% more calls if 80% of users are delay tolerant.

Transmission Mode for Mission Critical communications.
Mission Critical Communication (MCC) Services are currently provided through secure and reliable Professional Mobile Radio (PMR) dedicated networks. These services include voice, data and video delivery. During an emergency, timely access to video streaming can increase situational awareness and enhance life-saving operations. Therefore, to improve the capabilities of PMR networks and benefit from the advantages of mutualization, standard cellular technologies based on 4G and 5G were adopted for MCC. In particular, the evolved Multimedia Broadcast Multicast Service (eMBMS) is suitable for the transmission of group communication services. There are two broadcast transmission modes proposed in eMBMS: Multicast Broadcast Single Frequency Network (MBSFN) and Single-Cell Point-to-Multipoint (SC-PTM). In [26], we compare MBSFN, SC-PTM and Unicast (UC) in Mission Critical (MC) scenarios from a resource use perspective. More precisely, we calculate the system spectral efficiency in each mode and estimate the number of users per square kilometer demanding the same MC service from which MBSFN and SC-PTM become more efficient than UC. Results show that SC-PTM is the best solution for locally restricted and small-scale emergencies while MBSFN is more suitable for emergencies during massive events or wide-area scenarios.

3.2 Resource Allocation and Radio Access Network architecture

Participants: Bernard Cousin, Cédric Guéguen, Xavier Lagrange, Loutfi Nuaymi, Tania AlHajj, Flavien Ronteix–Jacquet.

Integrated Access and Backhaul (IAB) in 5G Networks.
Integrated Access and Backhaul (IAB) allows to ease the deployment of gNodeBs (gNBs) in a 5G network by connecting them using usual cellular connectivity. The radio frequencies to achieve such a result can be the same as the ones used to connect User Equipment (UE) (in-band) or specific ones can be reserved (out-of-band). Both sub 6 GHz and millimeter wave (mmWave) frequencies can be used. IAB is relatively new and several contributions have been studying the lower layers (i.e. physical and link) in order to improve performance in scheduling and resource allocation. However, performance results are also very dependent on how the routing is implemented at the network layer which is an aspect that is not much studied in the state of the art. In this work ([19]), we evaluate the performance of several IAB topologies against a topology without IAB-nodes. Results confirm the conclusions of the state of the art by showing that adding IAB- nodes significantly improve performance in terms of delay (more than 90 ms shorter delay) and Packet Delivery Ratio (PDR) (by up to 15%), and also allows to extend the coverage area. These results reveal the high potential of IAB that could be improved even more using efficient routing.

Low-Impact Latency Measurement.

Amongst the appealing features of 5G, ultra low latency is perhaps the most attractive one, as it unleashes a wealth of disruptive services. However, meeting such a challenging goal requires a thorough understanding of latency in the 5G prevailing bottleneck, that is, the Base Station. For this purpose, in [24] we propose LatSeq, an open-source tool for fine-grained analysis of latency inside a software Base Station (BS), and implement it on the OpenAirInterface platform. LatSeq tackles each packet's sequence of successive delays across the layers of a Base Station, which reveals enlightening causal links. We demonstrate the low impact of LatSeq on the observed system, and the relevance of statistics based on individual packet tracing inside the base station.

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

In fifth generation (5G) wireless technology, the centralization of some base station functions will be possible using the new radio access network (RAN) architecture: centralized-RAN (C-RAN). The most challenging type of service to be served by 5G is ultra reliable low latency communication (URLLC), which requires high reliability and low latency simultaneously. In [16], we compare three RAN architectures. The first has all the processing close to the user and involves single reception. The second and the third architectures have some centralized BS functions, allowing multiple-cell coordination and thus multiple reception points. We study the impact of architecture

and macro-diversity both on the reliability of uplink (UL) packet transmission and on latency. It is shown that receiving from the best BS induces less latency and higher reliability than receiving from the nearest BS. Macro-diversity had a positive impact on reliability and latency compared to a single reception with architecture A. The main finding of the study is the importance of the Maximum Ratio Combining when both high reliability and low latency are required.

Energy management and base station switching in green mobile networks.

Answering energy challenges requires complex energy frameworks that consider Smart Grid, renewable energy, battery systems and employs efficient management of radio as well as energy resources. Lithium batteries present very good performance indicators (e.g., high energy density, large service life and environmental friendliness) but can also have very poor use duration when the energy management system is not suitable. In ([9]), the use of Lithium batteries is studied with the important consequences of radio resource allocation on energy consumption and operational cost. We study and propose energy and radio allocation mechanisms for cellular networks supplied with hybrid energy sources (grid and renewable). We propose a Battery Aging and Price-Aware (BAPA) algorithm that brings down the grid energy consumption of the operator while including battery degradation constraints. We decompose the problem into three subproblems: radio resource allocation problem, grid energy purchase problem and power allocation problem. We show that our algorithm performs very close to the optimal solution and outperforms a benchmark algorithm, allowing more efficient battery use, energy savings and network operation cost reduction with no impact on the QoS of users. Finally, we provide some insights into how the advancement in base station technology will help reducing the investment cost in future cellular networks.

Auctions for Effective 5G Licensed Shared Access, LSA.

Licensed Shared Access (LSA) is a new concept proposed by the radio spectrum policy group in order to optimize spectrum usage: a Mobile Network Operator (MNO) can access temporarily to other incumbent's spectrum after obtaining a license. The licensing process is made via an auction mechanism. The mechanisms proposed in the literature for the LSA context are oneshot auction mechanisms which allocate all the available spectrum as a unique block. In ([7]), we first show how to increase the performance 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 into multi-block auctions. Simulation results illustrate how appropriately choosing the number of blocks allows to increase the aforementioned metrics. Second, 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.

In the LSA framework, in order to determine how to bid, each MNO has to estimate his valuation for spectrum i.e., how much he is willing to pay for spectrum. In ([18]), we propose a model for estimating that valuation. The model is based on Markov chain modeling of user behavior, to compute the MNO satisfaction as a function of the

obtained spectrum. We then illustrate our method by applying it to real operator data.

Reliable Multipath Routing for MANETs.

A mobile ad hoc network (MANET) is a set of mobile and self-organizing nodes that cooperate to create dynamic network architecture to establish communications. Its characteristics present critical challenges: limited residual energy of nodes and transmission range, wireless links sensitivity to environmental effects, and the mobility aspect, which leads to frequent link failure and rapid changes in the network topology. In this work ([5]), we propose a new multipath routing protocol RMQS-ua (Reliable Multipath Routing Protocol based on Link Quality and Stability in Urban Areas). Our objective is to select the path that has better link quality and more stable links to guarantee reliable data transmission. We consider a combination of signal to noise ratio SNR and an enhanced packet reception ratio PRR to evaluate link quality, and the exponential moving average (EMA) to estimate the link stability. RMQS-ua is designed for an urban area that includes shadowing effect and background noise which deteriorates the link quality. Simulation results show that RMQS-ua improves network performance, and provides more reliability compared to some recent existing protocols.

Access architecture for IoT services overs TV white space.

In [10], we paper propose a novel radio access mechanism for massive Internet of Things (IoT) services over TV White Spaces (TVWS). The proposal considers TVWS as the suitable frequency bands for facing the limited-spectrum problem in massive IoT services. Our radio access mechanism is compliant with regulatory policies by interacting with a TVWS Geolocation Database and with the IETF Protocol to Access White-Space (PAWS). It uses several Master Devices (MD), which act as access points. With this approach, IoT devices require neither geolocation receiver in the deployments, nor different frequency bands for the PAWS initialization process. Regarding the evaluation of the radio access mechanism, we explore different types of deployments and coverage areas. This paper also describes the optimization process to obtain the maximum service area, while maintaining an outage probability below a given objective. Moreover, we evaluate the performance of a loaded network with the maximum service area, with respect to a reference case with one MD. We evidence that the average packet loss probability is reduced by 26% compared to a single reception architecture when the load is equal to 80% in our proposal.

3.3 Hybrid Access

Participants: Cédric Guéguen, Xavier Lagrange, Cesar Vargas.

Device-To-Device transmission for Machine-Type Communications.

Massive machine-type communications (mMTC) is one of the main services delivered

by the fifth Generation (5G) mobile network. The traditional cellular architecture where all devices connect to the base station is not energy efficient. For this reason, the use of device-to-device (D2D) communications is considered to reduce the energy consumption of mMTC devices. The main idea is to use nearby user equipment (UE) as a relay and establish with it D2D communication. However, the relay selection process also consumes energy, and this consumption can be significant compared to the energy consumed during the data transmission phase. In [14], we propose a distributed energy-efficient D2D relaying mechanism for mMTC applications. This mechanism favors the selection of the UEs with low path loss with the mMTC device. Through mathematical analysis and simulations, we show that our mechanism allows a reduction of the total energy consumption of mMTC devices (up to 75% compared to direct transmission) when they have an unfavorable link budget. Moreover, our mechanism achieves almost constant energy consumption for a large range of UE densities and distances between the mMTC device and the base station.

Routing for Wireless Mesh Networks.

Providing a high level of Quality of Service (QoS) is essential for future wireless networks. In [6] we present a new multihop wireless routing protocol that opportunistically takes profit from variations of radio conditions in terms of path loss, shadowing and multipath fading to maximize the system capacity. However, guaranteeing high system capacity should not evade the packet delay minimization objective. Consequently, the best path should not only be considered as the path with best throughput but a combination of a good link throughput and, in addition, low router buffer occupancy load. Taking into account the available router buffer occupancy in its path selection, our proposal uses queuing theory information in order to also provide an efficient load balancing solution that adequately distributes the traffic load in the whole network. Exploiting this information, our solution dynamically adapts the selected path across time avoiding overexploited efficient links as well as low throughput link usage. This adaptation is performed considering each link state and the amount of channel information available. This improves the throughput and delay with only small marginal overhead cost. Our proposal applies to all wireless multihop networks, with increased benefit for extending cell coverage. We demonstrate through our simulation study that our solution raises the system capacity by more than 50 percents in several scenarii as well as reduces packet delays compared to state-of-the-art protocols such as Ad-hoc On-demand Distance Vector (AODV), Optimized Link State Routing (OLSR) and Link State Opportunistic Routing (LSOR).

Internet of Things (IoT) is an other context. The ever increasing amount of connected mobile devices and users in the Internet of Vehicles (IoV) and the fact bicycles, electric scooters and users' smartphones are also connected poses a real challenge in terms of ensuring Quality of Service (QoS). The constantly changing topology due to the high-mobility of devices and users greatly impacts its stability and the connectivity of devices. Furthermore, to ensure safety of people in the case of autonomous vehicles it is of paramount importance to ensure excellent reliability. This is why we have developed a solution that is based on Machine Learning (ML) to classify devices according to their mobility profile and that uses a scoring system to select the best candidates to act

as Mobile Relays (MR) amongst devices with a suitable mobility profile. The scoring system allows to find critical locations in terms of user density. In [11] we propose a solution that not requires a dedicated infrastructure such as Road Side Units (RSUs). Simulations results will show the proposed solution increases the packet delivery ratio by up to 6 percents, reduces the energy consumption by up to 30 percents and increases the efficiency of bandwidth usage without sacrificing the end delay of users and devices compared to the state of the art.

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 or 5G 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 [17], we investigate downlink interference management schemes that avoid channel state information (CSI) knowledge at the transmitter side. Assuming reconfigurable antennas at both ends of each train, we apply the dark-blind interference alignment principle. Simulations show that compared to considered orthogonal multiple access techniques, the proposed scheme achieves an efficient trade-off between maximum achievable throughput and error rate.

3.4 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 [26], 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.

3.5 Function and Service Placement in Networks

Participants: Géraldine Texier, Masoud Taghavian.

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 pave the way for automating the instantiation of network services with respect to a set of given constraints.

To satisfy the expectations of NFV, sophisticated algorithms are required to allocate the physical resources in an optimal way, within a fair time constraint. Resources are allocated by determining the suitable placements of the service requests over the Substrate Network (SN). The placement problem is classified as an NP-Hard problem in terms of complexity, as it is a generalization of the Virtual Network Embedding (VNE) problem.

In [25], we address the placement problem, proposing a fast reliable solution for systematically placing network services based on a Branch and Bound (BB) method, which allows us to evaluate different artificial intelligence search strategies (especially A*). The BB approach is well suited because of the large number of different types of constraints in this problem (the more constraints we have, the more we can prune the tree and limit the branches, which speeds up the search procedure). Another advantage of BB is the guarantee of not producing infeasible placements in any circumstance. It also guarantees the respect of all of the constraints as the search advances and avoids to progress in non-promising constraints-violating areas. Our objective is to find theoretically proven optimal results (usually obtained with ILP-based methods), while maintaining the scalability of a heuristic-type strategy. It is suitable for on-line scenarios that we need to conform to a time constraint.

This work is done as part of Masoud Taghavian's thesis under supervision of Géraldine Texier, co-advised with Philippe Bertin from IRT b<>com and Yassine Hadjadj-Aoul from University of Rennes.

3.6 Advanced management of optical networks

Participants: Bernard Cousin, Loutfi Nuaymi.

Multicast routing in optical networks.

Our work ([8]) deals with the problem of multicast routing and the allocation of wavelengths in a WDM network with optical splitters and converters. We present an exact formulation in integer linear programming (ILP) to find a set of optical structures connecting a source to a set of destination nodes. We use a new optical structure called hierarchical. In hierarchical structure, an optical signal can pass more than

once through the same optical node and an intermediate node can belong to the set of destinations; this is a generalization of light trails). The problem of multicast routing with sparse wavelength conversion and sparse splitting using the hierarchical structure has not yet been studied. So, our main contribution consists of introducing new optical constraints of wavelength converters with the hierarchical structure. The objective is to focus on the benefits and performances of using wavelength converters in a WDM network. Simulation results show that the hierarchical structure gets better results in terms of overall link cost and number of wavelengths in the case of WDM network sparse wavelength converters than the WDM network without converters.

Multicast reconfiguration in optical networks.

Network reconfiguration is an important mechanism for network operators to optimize network performance and optical flow transfer. It concerns unicast and multicast connections. Multicast connections are required to meet the bandwidth requirements of multicast applications, such as Internet Protocol-based TeleVision (IPTV), distance learning, and telemedicine. In optical networks, a multicast connection is made possible by the creation of an optical tree-shaped path called a light-tree. The problem of light-tree pair reconfiguration is addressed in this study ([4], [1]). Given an initial light-tree used to transfer an optical flow and a new (final) light-tree that is computed by the network operator to optimize network performance, the goal is to migrate the optical flow from the initial light-tree to the final light-tree without flow interruption. Flow interruption is not desirable for network operators because it forces them to pay financial penalties to their customers. To solve this problem, existing methods use a branch approach that is inefficient if some network nodes do not have wavelength conversion capability. Therefore, we proposed in this study a sub-tree-based method. This approach selects and configures sub-tree pairs from the light-tree pair (initial light-tree, final light-tree) to be reconfigured. Then, we produce a sequence of configurations. The performance evaluation confirms that our method is efficient in solving the problem of light-tree pair reconfiguration because our method does not cause flow interruption.

Virtualization in optical networks.

In [27], we propose a Software Defined Network-based (SDN) Passive Optical Network (PON) Radio Access Networks (RAN) protection scheme. We experimentally assess the performance by implementing it through a testbed including an SDN controller, Small form-factor pluggable transceiver PON (SFP+/PON), a layer 2 switch, and several SFP+ Point-to-Point (SFP+/PtP) in lieu of a traditional OLT chassis. We compared our proposition with a PtP scheme based on legacy layer 2 redundancy protocol solution with respect to different metrics such as recovery time, latency, power consumption, CAPEX and flexibility/scalability. We show that a trade-off exists among those metrics and that while the SDN-based solution is outperformed by the legacy-based one in terms of recovery time, the proposed solution still provides a remarkable improvement with respect to nowadays practices in protection, while allowing for cost and energy reduction. Such solution scheme can thus be used as a protection scheme for non-time-critical services.

We experimentally assessed 5G backhaul traffic over an OVS-DPDK based vOLT in a generic server [28]. Our SDN solution provides the flexible residential and 5G-mobile converged PON for different scenarios such as 5G self-healing in optical access network by means of dynamic SLA coordination.

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 Beyond 5G

Participants: Amath Ndao, Nicolas Huin, Xavier Lagrange, Pierre-Marie Lechevalier, Romaric Ludinard, Loutfi Nuaymi, Géraldine Texier.

- Title: Beyond 5G
- Framework: Strategic Sector Committee (CSF) for Digital Infrastructure: Sovereignty in Telecommunications Networks
- Duration: November 2020 - Jan 2024 (38 months)

- Partners: Thales SIX GTS France, Ericsson France, Eurecom, Institut Mines-Telecom
- Abstract: The participants in the "Beyond 5G" program will work together for three years to design technical solutions for the development of sovereign and secure next-generation 5G networks, while developing innovative uses for the industry of the future. The project goes far beyond a simple technical improvement by paving the way for a wide range of industrial uses based on new cognitive, predictive and contextual capabilities in order to provide an unprecedented experience. The project teams will also focus on post-5G developments, which will be driven by the introduction of disruptive technologies with severe constraints in terms of digital security.

4.2.2 SPIDER project at IRT b<>com

Participants: Romaric Ludinard.

- Title: SPIDER: Self-managing Programmable Intelligent Network DEtection and Response
- Framework: IRT
- Duration: June 2021- Mai 2024 (36 months)
- Partners: Orange, Nokia, Secure-IC, b<>com, IMT Atlantique, University UBO, University Rennes 1 and CentraleSupélec
- Abstract: The main objective of SPIDER is to develop an Autonomous cyber defense against Internet threats for 5G private networks. In order to reach this aim, 4 main drivers will be considered:
  - Proactive threat hunting based on threat intelligence and contextual correlations
  - Autonomous decision making and action orchestration for Incident Response
  - Security as PaaS offering
  - Federated solution across domains

The project hosts the thesis of Antoine Rebstock under supervision of Yann Busnel, co-advised by Romaric Ludinard and Yann Busnel, from IMT Atlantique and Stéphane Paquelet from IRT b<>com. The goal is to study and propose mechanisms for the correlation of alerts and prediction attacks scenarios in the context of SOC.

4.2.3 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, CentraleSupélec, 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.

4.2.4 WEC-UP project at IRT b<>com

Participants: Géraldine Texier, 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 Masoud Taghavian that started in September 2020, under supervision of Géraldine Texier, co-advised by Géraldine Texier and Philippe Bertin from IRT b<>com and Yassine Hadjadj-Aoul from University of Rennes 1. 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 (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.
- CIFRE thesis (2021-2024) on the use of D2D communication for industrial IoT (Xavier Lagrange)
  - The objective of the thesis is to propose innovative solutions for the integration of D2D communications in the 5G new-radio (NR) interface for Industrial IoT (IIoT) applications, with a strong focus on the emergence of new use cases.

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, Julien Saint-Martin.

- Title: Optimization of mobile relays for LTE
- Framework: Industrial Contract
- Duration: January 2021- December 2021 (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 foreign 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". The thesis was defended on 2021 October 11th.

4.4.3 Visiting researchers

- Adopnet was happy to welcome Professor Oriol Sallent, full professor at UPC for a 1-month visit in July 2021. Oriol Sallent has participated in a wide range of European projects and contributed to standardization bodies such as 3GPP, IEEE, and ETSI. He has published 200+ papers, mostly in IEEE journals and conferences. His research interests include self-organizing networks, radio network optimization, and QoS provisioning in heterogeneous wireless networks.

- Due to Covid-19, some expected visits have been canceled.

5 Dissemination

5.1 Promoting scientific activities

5.1.1 Scientific Events Selection

Member of Conference Program Committees Bernard Cousin is member of IEEE Technical Committee on Information Infrastructure and Networking (TCIIN). He served, in 2021, in the Program Committee of the following conferences:

- FNC 2021, International Conference on Future Networks and Communications
- Globecom 2021 NGNI, IEEE Global Communications Conference: Next-Generation Networking and Internet Symposium
- ICN 2021, The Eighteenth International Conference on Networks
- OPAL 2021, International Conference on Optics, Photonics and Lasers

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

- IEEE ICC 2021, IEEE International Conference on Communications, Mobile and Wireless Networks Symposium
- MWN PIMRC 2021, Mobile and Wireless Networks Symposium in the framework of 2021 IEEE 32th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications
- WCNC 2021, IEEE Wireless Communications and Networking Conference
- HiPNet 2021, Worskhop on High-Precision, Predictable, et Low-Latency (HiPNet)

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

- ISCC 2021, the 26th IEEE Symposium on Computers and Communications
- WCNC 2021, Wireless Communications and Networking Conference
- ICT 2021 International Conference on Telecommunications

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

- NCA 2021: 19th IEEE International Symposium on Network Computing and Applications (NCA 2020)
- FAB 2021: Fourth International Symposium on Foundations and Applications of Blockchain 2021 (FAB 2021)

Géraldine Texier has served in the Program Committee of ICIN 2021, the 24th Conference on Innovation in Clouds, Internet and Networks. She was also the co-chair of CORES 2021's program committee, the 6th conference on Protocol Design, Performance Evaluation and Experimentation of Communication Networks. This conference gathers the french community around issues related to distributed systems and communication networks.

5.1.2 Journals

In 2021, Bernard Cousin was member of the Editorial Boards for:

- Wireless Communication & Mobile Computing journal (Wiley): academic editor

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 and Computer Networks.

5.2 Continuing Education

Xavier Lagrange participated on 19 october 2021 to a panel discussion organised by "Pôle Doctoral de Rennes" on the formation and supervision of PhD students.

5.3 Popularization

Launched in 2020, 5G commercial networks were still debated in 2021. In this context, several members of Adopnet (L. Nuaymi and X. Lagrange) were interviewed to answer the questions raised by this new technology:

- Participation of Xavier Lagrange to a panel discussion on 5G and its role for embedded systems in the framework of "Assises de l'embarqué 2020" organised in January 2021 (due to the pandemic situation) (video record)
- Participation of Loutfi Nuaymi in March 2021 to a webconference on 5G and logistics organised by "Le Monde Informatique", (video record)
- Interview of Loutfi Nuaymi in March 2021 by France Bleu Armorique in "invité de 7h45" (podcast).

6 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] P. Fabian, A. Rachedi, C. Gueguen, "Programmable objective function for data transportation in the Internet of Vehicles", *Transactions on emerging telecommunications technologies*, January 2020, `https://hal.archives-ouvertes.fr/hal-02463677`.

[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] D. Renga, H. A. H. Hassan, M. Meo, L. Nuaymi, "Energy management and base station on/off switching in green mobile networks for offering ancillary services", *IEEE Transactions on Green Communications and Networking 2*, 3, 2018, p. 868–880.

[8] Q. Song, X. Lagrange, L. Nuaymi, "Evaluation of macro diversity gain in long range ALOHA networks", *IEEE Communications Letters 21*, 11, 2017, p. 2472–2475.

[9] 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`.

[10] 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] F. Atta, *Reconfiguration du routage multicast dans les réseaux optiques WDM ayant la propriété de conversion partielle de longueur d'onde*, Theses, Institut National Polytechnique Félix Houphouët Boigny, December 2021.

[2] A. Fadel, *Management of Radio Resources in a 5G Heterogeneous Network using Beamforming Technique and Millimeter Waves*, Theses, Université de Rennes 1, October 2021.

[3] M. Manini, *Resource allocation and scheduling in 5th generation networks*, Theses, Université Rennes 1, January 2021, `https://tel.archives-ouvertes.fr/tel-03223084`.

Articles in referred journals and book chapters

[4] A. F. Atta, J. C. Adépo, B. Cousin, S. Oumtanaga, "Sub-Tree-Based Approach for Reconfiguration of Light-Tree Pair without Flow Interruption in Sparse Wavelength Converter Network", *Information 12*, 5, May 2021, p. 211–230, https://hal.archives-ouvertes.fr/hal-03228311.

[5] S. Benatia, O. Smail, B. Meftah, M. Rebbah, B. Cousin, "A reliable multipath routing protocol based on link quality and stability for MANETs in urban areas", *Simulation Modelling Practice and Theory 113*, 2021, p. 102397, https://hal.archives-ouvertes.fr/hal-03337275.

[6] J.-B. Bordier, C. Merlhe, P. Fabian, S. Baey, D. Garnaud, K. Bussereau, E. Livolant, C. Gueguen, "Buffer Occupancy and Link State Opportunistic Routing for Wireless Mesh Networks", *Wireless Networks*, August 2021, https://hal.archives-ouvertes.fr/hal-03315089.

[7] A. Chouayakh, A. Bechler, I. Amigo, L. Nuaymi, P. Maillé, "Multi-Block Ascending Auctions for Effective 5G Licensed Shared Access", *IEEE Transactions on Mobile Computing*, March 2021, https://hal-imt-atlantique.archives-ouvertes.fr/hal-03197729.

[8] A. Dafeur, B. Cousin, R. Ziani, "Multicast routing and allocation of wavelengths in a WDM network with splitters and converters", *International Journal of Internet Protocol Technology 14*, 2, 2021, p. 120, https://hal.archives-ouvertes.fr/hal-03300560.

[9] A. El Amine, H. A. H. Hassan, L. Nuaymi, "Battery-Aware Green Cellular Networks Fed By Smart Grid and Renewable Energy", *IEEE Transactions on Network and Service Management 18*, 2, June 2021, p. 2181–2192, https://hal-imt-atlantique.archives-ouvertes.fr/hal-03271482.

[10] M. Espinosa, M. Perez, T. Zona, X. Lagrange, "Radio Access Mechanism for Massive Internet of Things Services Over White Spaces", *IEEE Access 9*, 2021, p. 120911 – 120923, https://hal.archives-ouvertes.fr/hal-03338604.

[11] P. Fabian, A. Rachedi, C. Guéguen, "Selection of relays based on the classification of mobility-type and localized network metrics in the Internet of Vehicles", *Transactions on emerging telecommunications technologies 32*, 4, April 2021, https://hal.archives-ouvertes.fr/hal-03190430.

[12] N. Guérin, M. Manini, R. Legouable, C. Gueguen, "High System Capacity Pre-Scheduler for Multi-Cell Wireless Networks", *Wireless Networks 27*, 2021, p. 13–25, https://hal.archives-ouvertes.fr/hal-03125029.

[13] J. Henry, N. Montavont, Y. Busnel, R. Ludinard, I. Hrasko, "A Geometric Approach to Noisy EDM Resolution in FTM Measurements", *Computers 10*, 3, March 2021, p. 33, https://hal-imt-atlantique.archives-ouvertes.fr/hal-03167978.

[14] C. Vargas Anamuro, N. Varsier, J. Schwoerer, X. Lagrange, "Distance-aware relay selection in an energy-efficient discovery protocol for 5G D2D communication", *IEEE Transactions on Wireless Communications 20*, 7, 2021, p. 4379 – 4391, https://hal-imt-atlantique.archives-ouvertes.fr/hal-03160591.

[15] F. Yan, P. Maillé, X. Lagrange, "Performance Analysis of Cellular Networks with Delay Tolerant Users", *Telecommunication Systems 77*, 2021, p. 241–253, https://hal.archives-ouvertes.fr/hal-03124581.

Publications in Conferences and Workshops

[16] T. Alhajj, X. Lagrange, "Impact of the RAN Architecture and Macro-diversity Techniques on Latency", *in : IEEE VTC2021-Fall*, virtual conference, France, September 2021, https://hal-imt-atlantique.archives-ouvertes.fr/hal-03436783.

[17] K. Amis, T. Galezowski, X. Lagrange, "Dark Blind Interference Alignment for Downlink of Future Railway Communication Systems", *in : 2021 IEEE 32nd Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, IEEE, p. 666–671, 2021.

[18] A. Chouayakh, A. Bechler, I. Amigo, L. Nuaymi, P. Maillé, "Estimation of spectrum valuation for 5G dynamic frequency allocation and auctions", *in : VTC2021-Spring: IEEE 93rd Vehicular Technology Conference*, Helsinki (Online), Finland, April 2021, https://hal-imt-atlantique.archives-ouvertes.fr/hal-03197693.

[19] P. Fabian, G. Z. Papadopoulos, P. Savelli, B. Cousin, "Performance Evaluation of Integrated Access and Backhaul in 5G Networks", *in : IEEE Conference on Standards for Communications and Networking (CSCN 2021)*, En ligne, Greece, December 2021, https://hal.archives-ouvertes.fr/hal-03487105.

[20] J. Henry, Y. Busnel, R. Ludinard, N. Montavont, "Ranging and Location attacks on 802.11 FTM", *in : PIMRC 2021: IEEE 32nd Annual International Symposium on Personal, Indoor and Mobile Radio Communications*, IEEE, p. 1–6, Oulu, Finland, September 2021, https://hal-imt-atlantique.archives-ouvertes.fr/hal-03265600.

[21] J. Henry, Y. Busnel, R. Ludinard, N. Montavont, "Reducing FTM ranging and location attack exposure with crowd-wisdom", *in : 9th International Conference on Indoor Positioning and Indoor Navigation (IPIN 2021)*, Lloret de Mar, Spain, November 2021, https://hal-imt-atlantique.archives-ouvertes.fr/hal-03515297.

[22] M. Manini, C. Gueguen, R. Legouable, X. Lagrange, "Efficient System Capacity User Selection Algorithm in MU-MIMO", *in : VTC2021-Spring : IEEE 93rd Vehicular Technology Conference*, Helsinki, Finland, April 2021, https://hal.archives-ouvertes.fr/hal-03265005.

[23] C. Merlhe, C. Gueguen, X. Lagrange, "Hybrid Joint-Transmission Multi-Point Coordination for Inter-Cell Interference Management", *in : VTC2021-Spring : IEEE 93rd Vehicular Technology Conference*, Helsinki, Finland, April 2021, https://hal.archives-ouvertes.fr/hal-03260374.

[24] F. Ronteix-Jacquet, A. Ferrieux, I. Hamchaoui, S. Tuffin, X. Lagrange, "LatSeq: A Low-Impact Internal Latency Measurement Tool for OpenAirInterface", *in : 2021 IEEE Wireless Communications and Networking Conference (WCNC)*, IEEE, p. 1–6, 2021.

[25] M. Taghavian, Y. Hadjadj-Aoul, G. Texier, P. Bertin, "An Approach to Network Service Placement using Intelligent Search Strategies over Branch-and-Bound", *in : GLOBECOM 2021 - IEEE Global Communications Conference*, IEEE, p. 1–7, Madrid, Spain, December 2021, https://hal.inria.fr/hal-03510057.

[26] J.-C. Vargas, T. Cedric, X. Lagrange, "Comparison of MBSFN, SC-PTM and Unicast for Mission Critical Communications", *in : WPMC 2021*, virtual conference, France, November 2021.

[27] M. Wang, G. Simon, I. Amigo, L. A. Neto, L. Nuaymi, P. Chanclou, "SDN-based RAN Protection Solution for 5G, an Experimental Approach", *in : 2021 International Conference on Optical Network Design and Modeling (ONDM)*, IEEE, p. 1–6,

Gothenburg, France, June 2021, https://hal-imt-atlantique.archives-ouvertes.fr/hal-03513270.

[28] M. Wang, G. Simon, L. A. Neto, A. Bella, I. Amigo, L. Nuaymi, P. Chanclou, "SDN-oriented Disaggregated Optical Access Node for Converged 5G Mobile and Residential Services", *in: 2021 European Conference on Optical Communication (ECOC)*, IEEE, p. 1–4, Bordeaux, France, September 2021, https://hal-imt-atlantique.archives-ouvertes.fr/hal-03513275.

Internal Reports

[29] M. L. Koma, S. Assié, A. Bouabdallah, L. Dorso, X. Lagrange, G. Papadopoulos, "Mobilité réseau robuste pour service de téléexpertise vétérinaire par lunettes connectées", *Research Report number RR-2021-01-SRCD*, IMT ATLANTIQUE, June 2021, https://hal-imt-atlantique.archives-ouvertes.fr/hal-03274500.