



Advanced Technologies for Operated Networks

ADOPNET

Rennes, Brest

Activity Report

2016

1 Team

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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 3G 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.

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.

2.2 Key Issues

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.

3 Scientific Foundations

3.1 Introduction

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 performance. However, when the analysis is focused on a particular mechanism, several scientific tools can be used like stochastic analysis or discrete optimization.

3.2 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 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.

As traffic is more and more heterogeneous in nature and as the applications have different needs in terms of Quality of Service it is important for operators to monitor and classify the traffic per category of applications. This can be based on port analysis or Deep Packet Inspection (DPI) but these methods have drawbacks, such as applications changing port numbers or using dynamic port numbers and the widespread deployment of encryption that prevents access to packet payload. Another approach to the traffic classification problem is to use pattern recognition methods such as Support Vector Machine (SVM) in order to classify flows on the basis of descriptors such as the length of packets.

It is important to detect anomalies in traffic and to be able to do so with a low false alarm rate and a low delay. Sequential decision theory provides a rigorous framework to deal with real-time traffic anomaly detection problems. These methods are useful in the context of anomaly based Intrusion Detection Systems (IDS). The anomalies that one can discover in the traffic if one works on coarse traffic aggregates such as aggregated volumes of traffic are not useful in the framework of IDS. On the contrary rich anomalies can be discovered if one observes the traffic at a finer time scale on a per flow basis. As the cardinality of the state space of IP addresses is very large it is necessary to design data stream mining methods to maintain in real time some traffic statistics at flow level.

The economical context that network operators have to face is considered to be very difficult. Indeed, the emergence of bandwidth demanding services are putting operators under pressure since they generate a lot of traffic that consumes capacities deployed by operators. But on the other hand these services generate revenues for service providers mainly (i.e. OTT) rather than for network operators. Economical models must therefore be rethought in order to permit a fair share of the revenues between the different stakeholders. The interactions between the stakeholders in this ecosystem can be analyzed with a game theoretic approach.

3.3 Hardware and software traffic processing

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

A major challenge for network operators is to be able to process traffic at very high bit

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

3.4 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.

Within the vast field of operations research, discrete optimization is one of the most fascinating branch, which still encompasses many open fundamental problems. In particular, the impossibility to develop fast algorithms that computes optimal solutions for discrete problems have conducted network scientists to find trade-offs between performances and computability.

From a scientific standpoint, network scientists are interested in developing fast approximate algorithms, where the performances are bounded with respect to the optimal solution, or exact algorithms that lever some relaxed version of problems. Meta-heuristics have also gained some interests since they allow significant progresses in problem solving at relatively low development costs.

3.5 Protocol Design for Optical Networks

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

Introducing optical technologies into network architecture implies designing new protocols for both transfer and control planes. This is mostly true for *transparent* or *translucent* optical

technologies, that do not rely at all (or rely only partially) on Optical to Electronic (OE) conversions.

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

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

The optical control plane has to be integrated with existing control planes.

This can be done either by designing a new Ethernet transport network (similarly to EPON in an FTTH access network). An alternative is to build a new multi-client optical transport layer that could be integrated in a global GMPLS framework (GMPLS is the current framework used in operators' networks to globally command their networks). This is facilitated by generalizing label switching in technologies used for transport networks. In both cases, SDN can be used to configure the network.

4 Application Domains

4.1 Content Delivery

Participants: Alberto Blanc, Bernard Cousin, Annie Gravey, Gwendal Simon, Géraldine Texier, Sandrine Vaton, Mariem Ben Yahia, Xavier Corbillon, Alica Devlic, Kuhn He.

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

Today's multimedia services offer some interactive features, where the end-users can control the video consumption to some extent. Multimedia services have more stringent requirements related to interactivity. For example, cloud gaming requires an overall response time below

120 ms for an acceptable Quality of Experience (QoE). This trend is expected to be even stronger in the next years due to the popularity of haptic controllers. The latency of today's cloud architecture is not low enough to guarantee QoE for users of such interactive services. To address the needs in content delivery with ultra-low response time, the most appealing architecture is a Content Delivery Network (CDN) with servers that are very close to the end-users, in other words at the edges of the network. It is thus natural that network operators develop their ability to leverage devices close to the end-users.

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

The objective of ADOPNET is twofold:

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

4.2 Network Control

Participants: Alberto Blanc, Bernard Cousin, Annie Gravey, Cédric Gueguen, Xavier Lagrange, Samer Lahoud, Loutfi Nuaymi, Iaad Ben Dhia, William David Diego Maza, Jialong Duan, Souheir Eido, Ali El Amine, Mahdi Ezzaouia, Mohamad Kanj, Younes Khadraoui, Soha Farhat, Najmeddine Majed, Pratibha Mitharwal, Alassane Samba, Qipeng Song, Farah Slim, Mohamad Yassin.

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

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

of service. From a pure radio point of view, it also extends the possibility of developing multi-radio-access-technology (RAT) selection algorithms and opportunistic energy efficient radio resource management procedures.

- *Virtualization of optical networks.* Transmissions on optical fibers have unique features: large bandwidth, low loss, low cost, light weight, immunity to electromagnetic interference and corrosion resistance. However, the management of optical network is a very challenging task. Network virtualization can provide a very efficient management and thus, a very efficient use of available network resources. By using network virtualization solutions, network resources can be managed as logical services, rather than physical resources. Due to the high degree of manageability provided by network virtualization, network operators can improve network efficiency and maintain high standards of flexibility, scalability, security, and availability. As a result, it reduces capital and operational costs for network operators.
- *Advanced optical networks.* Several forecasts have emphasized that distribution/aggregation networks, also called Metro Area Networks (MAN), are particularly impacted by traffic evolution. Future MANs should fulfill several requirements: quick adaptation to varying traffic demands, efficient support of both fine granularity and large volumes of traffic demands, possible isolation of different clients' flows, together with an excellent QoS, energy efficiency and low Operational Expenditures (OPEX). Optical packet/burst switching (OPS/OBS) combines sub-wavelength granularity, optical transparency and is thus energy efficient. The challenge is to achieve a high multiplexing gain together with a QoS similar to the one provided by electronic switching and to develop efficient MAC (Medium Access Control mechanisms) with contention avoidance. In the context of Fixed-Mobile Convergence, fiber-based access technologies can be used for fronthauling and backhauling traffic generated by mobile users. Our objective is to propose a dynamical and adaptive control of interfaces and routes to allow an efficient use of available resources in access and aggregation networks.
- *Multiple Access Technology Selection.* Different RATs, including 3GPP families and IEEE ones, are now widely deployed. A key feature will be an increased integration of both the fixed access and the different RATs. Our objective is to consider two aspects: i) the optimization of the architecture to allow a better integration of the different access technologies in a convergence perspective, ii) the optimization of the selection algorithms.
- *Radio Resource Management.* Radio Resource Management (RRM) algorithms or heuristics are a key element for providing high system throughput and high mobile user satisfaction. We focus on two aspects of RRM: power allocation and scheduling. We work on RRM issues in cellular networks where part of the energy comes from renewable sources such as wind and solar. We also consider RRM proposals for cellular M2M with different QoS requirements and according to different criteria, starting with energy efficiency. We propose opportunistic scheduling techniques, which take advantage of multi-path fading and multi-user diversity to provide high throughput. Our specific approach is to take into account the variability of the traffic and the queuing aspects. We propose scheduling

algorithms for hybrid networks where a terminal can relay the traffic of some others and propose to combine it with opportunistic routing.

4.3 Network Monitoring

Participants: Alberto Blanc, Gwendal Simon, Sandrine Vaton, Antoine Saverimoutou, Maha Mдини, Serge Romaric Tembo, Santiago Ruano Rincon.

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

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

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

- *Traffic monitoring acceleration for flexible and very high capacity traffic monitoring probes.* We develop the concept of traffic monitoring acceleration in order to reach bit rates of dozens to hundreds of Gb/sec. We develop different approaches, some are based on hardware acceleration on FPGA and others are based on specific capture engines and optimization mechanisms in software.
- *Detection/localization of failures in access networks.* Failures in access networks trigger hundreds of alarms and it is very difficult to find the root causes of these alarms with rule based methods. Indeed the number of rules to maintain in order to take into account any possible case is very large. It is interesting to complement rule based approaches with probabilistic approaches that model the dependencies between failures, alarms and signal levels on the network equipments. In particular we develop an approach based on Bayesian network modelling in order to locate failures in GPON-FTTH networks.
- *Traffic anomaly detection for network security.* Anomalies in traffic can reveal ongoing attacks such as flooding attacks. Traffic anomaly detection involves building traffic models, continuously monitoring traffic in order to extract appropriate traffic descriptors and triggering an alarm when the observed behavior significantly diverges from the model.

- *New metrics and methods to measure the quality of web navigation.* It is important to understand which are the different factors that contribute to the quality of experience of web navigation, to monitor this QoE and to identify the reasons of a degradation. Network performance but also the performance of web browsers and the way web sites are designed have an impact the quality of navigation. New metrics have been defined by the W3C but differences in their implementation lead to unreliable results. New protocols such as QUIC must also be taken into account since many monitoring methods are made obsolete by ciphering. Our objective is to design new metrics and methods to measure the quality of web navigation in this changing landscape.
- *Big Data technologies for network management.* One of our objectives is to conceive a mechanism that allows the gathering of fine-tuned data about the QoS actually perceived by the end-users in (almost) real time. Moreover, a related objective is to identify whether the cause of a QoS degradation is internal to the network operator or due to an actor out of the scope of the network operator. A consequence of such approach is that the network operator would be able to manage their network based on the client-perceived QoS (or QoE) rather than on the traditional network equipment QoS. This objective requires to analyze data from a huge number of sources, and thus to develop statistical tools that group data flows and find correlations in subset of data.

5 Software

5.1 Wi2me

Participants: Alberto Blanc, Xavier Lagrange¹.

The WiFi technology becomes more and more popular and the the density of access points is very high in urban areas. Several community networks, which are based on sharing WiFi residential access points, are now available. They can provide locally a wireless access at a high speed rate but show uncontrolled performance. In this scenario, the goal for a user is to have multiple interfaces, and exploit them the best he/she can, by always selecting the best matching between flows and interfaces. In order to have real traces and to evaluate the performance, the availability and the potentiality of these networks, OCIF team have developed a new mobile sensing tool, called Wi2Me Traces Explorer. It is an Android-based application that performs network discovery, automatic authentication and TCP traffic generation through WiFi and 3G.

ADOPNET team is involved in Wi2me project. It studies in cooperation with OCIF how to analyse the gross results given by the platform in order to characterize the performance and the quality of service of the community networks.

¹Only participants in ADOPNET are listed.

5.2 360-Transformations

Participants: Xavier Corbillon, Alisa Devlic, Gwendal Simon.

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

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

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

5.3 gGalop - Generates and Analyses Lots Of Packets

Participants: Santiago Ruano Rincon, Sandrine Vaton.

gGalop is a suit of tools, built on top of commodity hardware and high-performance networking software frameworks, that makes it possible to generate and process Domain Name System (DNS) packets at 10GbE wire-rate.

We have developed gGalop as the main component of a flexible testbed for research on methods to countermeasure flooding attacks against DNS infrastructure. From one side, gGalop can reproduce different kinds of flooding attacks against or using the DNS, and it is able to scale, saturating several 10GbE ports depending on the hardware it runs on. At the reception side, we have developed different script prototypes to analyse network streams on-the-fly, and to identify elements common to anomalies or abuse sources.

6 New Results

6.1 New technologies to enhance multimedia delivery

Participants: Chiheb Ben Ameer, Mariem Ben Yahia, Alberto Blanc, Xavier Corbillon, Bernard Cousin, Alisa Devlic, Xavier Lagrange, Gwendal Simon, Géraldine Texier.

Adaptive Multimedia Multicast Services in Networks.

Video broadcast technologies are essentially not designed to address a heterogeneous population of end-users. The same content is delivered, without regard to the characteristics of the receiving devices (e.g., display size and hardware capabilities) and to the quality of the support

network. Yet, the heterogeneity of the devices that are used to consume video has increased, ranging from HDTV to smartphones. The specification of video broadcast technologies for the latest generation (Long Term Evolution, LTE) and the next generation (5G) of cellular networks opens new opportunities to address the limitations of video broadcasting.

In classical approaches, there are two types of networks : broadcast networks are used to send content to a large number of terminals without any guarantee of delivery, cellular networks are used with unicast transmission in which the content is sent to a given terminal and retransmitted in case of reception errors. We work on hybrid multicast/broadcast transmission protocols. In [26], we present new adaptive automatic repeat request (ARQ) schemes for wireless broadcast/multicast combining erasure coding (EC) and packet retransmission. Traditional approaches rely on retransmitting the lost packets in a point-to-point or point-to-multipoint mode. The main idea behind the presented protocols is to retransmit adaptive combinations of the lost packets using EC, which can help several receivers to recover the lost information with fewer retransmission attempts. We propose two versions of EC-based ARQ protocols, and investigate theoretically the corresponding transmission bandwidths in different contexts. We showed through simulation results the efficiency of the proposed protocols with respect to conventional ARQ strategies and new published ARQ works for broadcast/multicast.

Large scale delivery of live video streams.

The delivery of multimedia applications has become a major concern for network operators because these applications have stringent requirements, which are sometimes difficult to accommodate with the underlying protocols and infrastructure of Internet.

Rate-adaptive streaming technologies, such as the Dynamic Adaptive Streaming over HTTP (DASH) standard, provides an efficient and easy solution to stream multimedia in a heterogenous context. However, it reinforces the streaming capacity problem in the core Content Delivery Network (CDN) infrastructure since delivering one video means delivering an aggregation of multiple representations. In particular, for live rate-adaptive streaming, a large set of non-divisible data streams need to be either delivered in whole, or not delivered at all. Previous theoretical models that deal with streaming capacity problems are based on elastic bit rates, and do not capture the emerging features of today's CDNs. In a series of papers, we have addressed various problems and provided various solutions:

- In [16, 44], we identify a new, discretized streaming model. We formulated a general optimization problem and show that it is NP-complete. Then we study two fundamental scenarios that occur in real CDNs. For each of these scenarios, we presented a fast, easy to implement, and near-optimal algorithm with performance approximation ratios that are negligible for large networks. These are the first sets of results for the discretized streaming model, and have both practical and theoretical importance in a topic that has become critical.
- In [39], we address the problem of ultra-low latency. End-users in online video services are sensitive to the overall quality of the video at screen, but also, and more importantly, to other factors, including the latency between the video generation and the playback for live videos. So far, the impact of delay, latency, and re-buffering has not received a significant

attention. Adaptive streaming technologies contribute to this lack of consideration since vendors usually recommend the introduction of significant extra-latency. We proposed an implementation of multi-path video delivery at the applicative level, which exploits the information provided in the latest version of the video delivery standards. We presented an implementation of a video player, which takes advantage of multi-path networking to enable video playback using TCP with a latency below 100 ms. By initiating the multi-path delivery from the client side, our mechanism is compatible with current network equipments and does not require any change neither at the server nor in the middleboxes.

- In [33], we have also used multi-path for live streaming. Transport protocols that can exploit multiple paths, especially MPTCP, do not match the requirements of video streaming: high average transmission delay, too strict reliability, and frequent head-of-line phenomenons resulting in abrupt throughput drops. We addressed this mismatch by introducing a cross-layer scheduler, which leverages information from both application and transport layers to re-order the transmission of data and prioritize the most significant parts of the video. Our objective is to maximize the amount of video data that is received in time at the client. We showed that current technologies enable the implementation of this cross-layer scheduler without much overhead. We then demonstrated the validity of our approach by studying the performance of an optimal cross-layer scheduler. The gap between the performance of the traditional scheduler versus the optimal scheduler justifies our motivation to implement a cross-layer scheduler in practice. We proposed one implementation with basic cross-layer awareness. To evaluate the performance of our proposal, we aggregated a dataset of real MPTCP sessions and we used video stream encoded with HEVC. Our results show that our cross-layer proposal outperforms the traditional scheduler. Viewers not only benefit from the inherent advantages of using MPTCP (such as a better resilience to path failure) but also get a better QoE compared to the traditional scheduler.
- In [34], we deal with dropping some of the video frames to cope with bandwidth deficit. Indeed, When the video bit-rate is greater than the available network bandwidth, the video stream suffers from packet loss due to packets that need to be dropped. A streaming server (or a network proxy) can implement a proactive packet filtering strategy, which is to voluntarily block (not forward) some packets in the event of such bandwidth mismatch. The challenge is to decide which packets to block so that the quality of the video at the client side is maximized with regards to the available bandwidth. Previous proposals aimed to use meta-information from the video encoding or to pre-process the multimedia data. Our goal is to design a lightweight strategy, which only uses video metadata available from the video file container. We demonstrated on a set of HEVC videos that our lightweight packet filtering algorithm performs as well as more complex strategies. Moreover, the video quality remains high despite a large number of blocked packets, while a random selection of dropped packet leads to a significant quality drop.

TCP Congestion Control and Shaping Methods for HTTP Adaptive Streaming.

HTTP Adaptive Streaming (HAS) is a streaming video technique commonly employed over best-effort networks (aka Internet). However, it is characterized by some issues that harm users' quality of experience (QoE) in cases of daily use. The main use case of the present investigation involves HAS clients competing for bandwidth inside the same home network. Based on related works, we found that one of the most convenient solutions for this use case is to define a bandwidth manager. Studies have shown that managing the bandwidth between HAS clients using traffic shaping methods improves the QoE. Additionally, the TCP congestion control algorithm in the HAS server may also impact the QoE because every congestion control variant has its own method to control the congestion window size. We describe two traffic shaping methods, the Hierarchical Token Bucket shaping Method (HTBM) and the Receive Window Tuning Method (RWTM), as well as four popular congestion control variants: NewReno, Vegas, Illinois, and Cubic. In [10], our objective is to provide a detailed comparative evaluation of combining these four congestion control variants with these two shaping methods. The main result indicates that Illinois with RWTM offers the best QoE without causing congestion. Results were validated through experimentation and objective QoE analytical criteria

Economic Considerations related to Multimedia Delivery.

We have also addressed the problem of content delivery from the perspective of network economics. We have in particular dealt with the question of network neutrality.

Network neutrality has been topic of discussion for the past 25 years, with current legislation/ regulation in the United States and Europe targeting the ISPs or "common carriers." But the reality of the Internet in the 2010s is that various actors contribute to the delivery of data, with sometimes contradictory objectives. In [17], we highlight the fact that neutrality principles can be bypassed in many ways without violating the rules currently evoked in the debate; for example, via CDNs, which deliver content on behalf of content providers for a fee, or via search engines, which can hinder competition and innovation by affecting the visibility and accessibility of content. We therefore call for an extension of the net neutrality debate to all the actors involved in the Internet delivery chain. We particularly challenge the definition of net neutrality as it is generally discussed. Our goal is to initiate a relevant debate on net neutrality in an increasingly complex Internet ecosystem, and to provide examples of possible neutrality rules for different levels of the delivery chain, this level separation being inspired by the OSI layer model.

We also addressed the question of the vertical integration of CDN and ISP in a same company. Indeed, while CDN services were initially offered by independent entities, some large ISP now develop their own CDN activities to control costs and delivery quality. But this new activity is also a new source of revenues for those vertically integrated ISP-CDNs, which can sell those services to content providers. In [47], we investigated the impact of having an ISP and a vertically-integrated CDN, on the main actors of the ecosystem (users, competing ISPs). Our approach is based on an economic model of revenues and costs, and a multilevel game-theoretic

formulation of the interactions among actors. Our model incorporates the possibility for the vertically-integrated ISP to partially offer CDN services to competitors in order to optimize the trade-off between CDN revenue (if fully offered) and competitive advantage on subscriptions at the ISP level (if not offered to competitors). Our results highlighted two counterintuitive phenomena: an ISP may prefer an independent CDN over controlling (integrating) a CDN, and from the user point of view vertical integration is preferable to an independent CDN or a no-CDN configuration. Hence, a regulator may want to elicit such CDN-ISP vertical integrations rather than prevent them.

6.2 Advanced management of optical networks

Participants: Bernard Cousin, Mohamad Kanj.

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

Management of flex-grid optical networks.

The exponential traffic growth in optical networks has triggered the evolution from fixed-grid to flex-grid technology. This evolution allows better spectral efficiency and spectrum usage over current optical networks in order to facilitate huge dynamic traffic demands. The promise of flex-grid technology in terms of increasing the number of optical channels established over optical links, however, may not be sustainable because of the associated increase in optical amplification power. In these works [13, 40, 4], we detail a power control process that takes advantage of link optical power and channel optical signal-to-noise ratio (OSNR) margins to allow network operators to support this optical power increase while maintaining the use of legacy optical amplifiers. New generalized multiprotocol label switching (GMPLS) protocol extensions are proposed on which to integrate the optical power control process in the control plane. The performance of the process is evaluated in terms of the blocking ratio and network throughput over fixed-grid and flex-grid networks. Results show that controlling optical power

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

benefits from the flex-grid technology in terms of spectrum and capacity gain and reduces optical connection blocking.

In [8], we show that flex-grid technology is an effective mean to improve the spectral efficiency of optical communications. For a given amplifier spectral bandwidth, it gives rise to the increase of the number of optical channels as it reduces the channel spacing. Therefore, in order to reap full benefits from flex-grid saved spectrum, further amplification power is required with respect to conventional fixed grid. This is a strong limitation when the legacy amplifiers cannot meet this new requirement due to their optical power limits. In this work, we demonstrate that exploiting the link margins allows supporting this increase while maintaining in use legacy amplifiers.

Protection of Optical Networks.

To ensure service continuity, for instance in optical networks, even after failures, primary paths should be protected by pre-computed and generally configuring backup paths. Upon a failure occurrence, only backup paths protecting against that failure are activated to repair the affected primary paths. As a result, the backup paths protecting against different failures should share their resources to save them. Two strategies of resource sharing are proposed in literature to provide protection while saving resources: (1) restrained sharing which applies the resource sharing to the backup paths only and (2) global sharing which extends the resource sharing to the primary and backup paths. In this work ([52]), we compared the two strategies of resource sharing when the primary paths correspond to the shortest ones according to a strictly positive and static metric. Even when the amount of resources that can be shared between the primary and the backup paths is unbounded, we proved that the maximum number of backup paths is still bounded. Besides, our simulations showed that the resource sharing between the primary and backup paths has very slight impact on the backup path rejection, i.e. the two strategies of resource sharing have very close performances.

Reconfigurable Optical Switch Management with SDN

Optical networks are well known to offer high rate bandwidth by sending data over light wavelengths. Those optical networks are composed of fiber optics, amplifiers, optical switches, Reconfigurable optical add drop multiplexer (ROADM), etc. Nowadays, we wish to manage and monitor that type of networks, especially the ROADMs, flexibly and intelligently by integrating Software Defined Networking (SDN) in optical networks. Unfortunately, legacy ROADMs are not SDN compatible yet. They have all the basic optical functionalities we wish to deploy (offered via the Simple Network Management Protocol (SNMP) in our case). However, we are not always able to update hardware or software in the ROADMs to adapt legacy ROADMs to SDN architecture. In [29] we propose an architecture with a proxy that translates OpenFlow messages sent by ONOS system into SNMP messages to configure the ROADMs and conversely. This solution allows not only to flexibly monitor and manage an optical network via SDN architecture, but also to recover and reroute wavelengths when a link is down. It is also the most adapted solution to legacy networks because it does not require any upgrade on the optical network elements.

Congestion Management of Multicast Traffic in Carrier Ethernet technology.

Carrier Ethernet is an extension to Ethernet to enable telecommunication network providers to provide Ethernet services to customers and to utilize optical Ethernet technology in their networks. It is mainly provided using optical fibers interconnected by Ethernet switches. Quantized Congestion Notification (QCN) is a Layer 2 congestion control scheme for Carrier Ethernet networks used in data centers, for instance. The QCN has been standardized as an IEEE 802.1Qau Ethernet Congestion Notification standard. In [20] and [21] we study QCN with multicast traffic and propose an enhancement to QCN. In fact, in order to be able to scale up, the feedback implosion problem has to be solved. Therefore, we resorted to the representative technique, which uses a selected congestion point (i.e., the switch with the most overloaded queue in the path tree), to provide timely and accurate feedback on behalf of the congested switches in the path of multicast traffic. This paper evaluates the rate variation, the feedback overhead, the loss rate, the stability, the fairness, and the scalability performance of the standard QCN with multicast traffic and our enhanced QCN solution for multicast traffic. This work compares their performance criteria. The evaluation results show that our enhanced proposition on QCN for multicast traffic gives better results than the standard QCN with multicast traffic. Indeed, the feedback implosion problem is mitigated by decreasing the feedback rate.

6.3 Advanced optical networks

Participants: Annie Gravey, Ahmed Triki.

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. Flexibility, facilitating a quick adaptation to varying traffic demands, in terms of supported protocols and traffic profiles, is mandatory. An efficient support of both fine granularity and large volumes of traffic demands, for uplink and downlink traffic, is necessary, as MANs have to interconnect both low activity nodes (e.g., small DSLAMs, eNodeBs) and high activity nodes (e.g., data centers, pools of RRH). MANs should provide methods for isolating different clients' flows, together with an excellent QoS, including high reliability and fast protection.

In the framework of the SASER project, together with Orange Labs, we furthered our investigations of the Time-domain Wavelength Interleaved Network (TWIN) technology, an optical burst switching technology for transport networks with active edge nodes, passive core nodes, and time slotted operation.

- In [22], we studied several alternatives of protection for TWIN. The main difference between those alternatives concerns the degree of resource sharing (transmitters, receivers and wavelengths). We distinguished three main protection schemes: totally shared protection, partially shared protection and dedicated protection. The obtained results show that the totally shared protection scheme outperforms the other schemes in terms of

resource utilization with non significant degradation of the performance, and a prompt recovery time.

- In [59] we compared the resource requirements of three different transport technologies (optical packet switching, opaque circuit switching and transparent circuit switching) within two architecture scenarios (the current hub-and-spoke architecture and the next generation distributed architecture). The comparison study considered the predicted traffic growth from 2014 to 2019 and the potential traffic decentralization due to content replication. For the optical packet switching, we focused on Time-domain Wavelength Interleaved Network (TWIN) solution which achieves passive switching at the intermediate nodes thanks to the precomputed optical packet emission schedule. Results showed that TWIN outperforms the other transport technologies in terms of number of transmitters and receivers with a high ability to cope with scalability issues.

We also pursued our studies regarding the implementation of Optical Packet Switching (OPS) architectures.

- In [50] We proposed a new optical transport solution, TSAN, based on variable bit rate packet transmission and passive fast switching. We addressed the expected TSAN CAPEX and OPEX savings using scenarios inspired from the current and the next generation network architectures. This work has been carried out in collaboration with KDDI.
- In [25] we considered a new receiver architecture for coherent detection in slotted optical packet switching rings with elastic (rate adaptive) optical transponders. The new receiver can detect more than a single packet per time slot and consequently has higher flexibility (translating into higher supported capacity, or, equivalently, lower end-to-end latency, or a combination of both), at the cost of a moderate increase in the transponder complexity and energy consumption (less than 10%). Theoretical modelling together with network planning and traffic engineering simulation tools were used to quantify the increase in network capacity and latency reduction that can be achieved thanks to the use of the new receivers. The reported study was carried out in the framework of a long running collaboration with Nokia Bell Labs.
- A new collaborative project with Nokia Bell Labs as a leader (and participation by Université Versailles Saint Quentin, Telecom Sud Paris et Telecom ParisTech) was accepted by ANR, and is intended to study a WDM OPS technology, similar to POADM, but which multiplexes a single data packet on 10 wavelengths. The project N-GREEN has been launched in January 2016. Simulators have been developed to assess the data plane performance, and to dimension N-GREEN rings.

6.4 Segment Routing

Participants: Géraldine Texier, Samer Lahoud, Rabah Guedrez.

Segment Routing (SR) is a new architecture aiming to simplify the management of traffic in core networks and in particular traffic engineering. It leverages the source routing mechanism to

enhance packet forwarding in networks. Segment routing received a lot of attention especially from Service Providers as it reduces the operation and management overhead and can easily be combined with Software Defined Networks (SDN). Segment routing deployment is very straight forward as it can be deployed with a software upgrade. Therefore, service providers are not required to invest in new hardware. Segment routing is designed to operate over either an MPLS or an IPv6 control plane. Currently, the standardization efforts are directed by the service provider's use cases. Specifically, an important focus on the SR-MPLS, given the amount of work conducted by the IETF working groups (the focus on SR-IPv6 comes from content distribution actors such Google and Facebook). SR-MPLS, its instantiation over MPLS, encodes a path as a stack of labels inserted in the packet header by the ingress node.

The instantiation of segment routing over the MPLS control plane requires to encode a path as a stack of labels that will be inserted in the packet header by the ingress node. In [38], we show that this overhead may in most cases violate the Maximum SID Depth (MSD), the equipment hardware limitation which indicates the maximum number of labels an ingress node can push onto the packet header. Currently, the MSD varies from 3 to 5 depending on the equipment manufacturer. Therefore, the MSD value considerably limits the number of paths that can be implemented with SR-MPLS. The consequence may be an inefficient network resource utilization and may also lead to congestion. We propose and analyze SR-LEA, an algorithm for an efficient path label encoding that takes advantage of the existing IGP shortest paths in the network. The output of SR-LEA is the minimum label stack to express SR-MPLS paths according to the MSD constraint. Therefore, SR-LEA substantially slackens the impact of MSD and restores the path diversity that MSD forbids in the network.

6.5 QoS and mobility management in mobile networks

Participants: Alberto Blanc, Bernard Cousin, Souheir Eido, Annie Gravey, Xavier Lagrange, William Diego Maza, Najmeddine Majed, Pratibha Mitharwal, Alassane Samba, Gwendal Simon.

Management of QoS in LTE networks.

LTE/EPC is an all-IP mobile system which provides higher data rates and lower latency. Nevertheless guaranteeing the QoS is a real challenge since the LTE/EPC QoS model inherits many characteristics of circuit oriented legacy standards. Contrary to usual QoS models of the fixed internet (IP networks), additional signalling procedures are required in order to establish a dedicated bearer for each desired QoS level. In [35] we proposed an analytical model to evaluate the impact of such a QoS model in terms of Processing Load. We showed that this cost is important in most cases. As an alternative, we introduced an IP-centric QoS model mainly inspired by IP policies commonly found in fixed networks. We compared the performance of this proposal compared to various implementations of the 3GPP QoS model using the ns-3 simulator in realistic scenarios. Some good properties of our IP-centric proposal compared to the standardized QoS model have been brought into evidence [2].

Call Admission Control with Classes of Service in LTE network.

In [30], we introduce a new call admission control (CAC) mechanism for Long Term Evolution (LTE) networks supporting multimedia services with different classes of traffic. Our CAC mechanism classifies calls into real time and non-real time users, then estimates the channel quality based upon the received signal strength (RSS) value, and finally identifies the call as either new call (NC) or handoff call (HC) before performing admission control decision. We also use a simple preemption technique in order to allocate the resources to high priority bearer requests. We show through extensive simulation analysis that our CAC mechanism provides high number of accepted users with higher priorities while providing high system throughput.

Throughput Prediction in Mobile Networks

In [53], we addressed statistical approaches for the prediction of throughput without history. Throughput has a strong impact on user experience in cellular networks. The ability to predict the throughput of a connection, before it starts, bring new possibilities, particularly to the Internet service providers. They could adapt contents to the quality of service really reachable by users, in order to enhance their experience. First our paper [53] highlighted the prediction capabilities thanks to different algorithms and data gathered at different network levels. Then we proposed a simple approach based on machine learning to predict the throughput using a few data related to the context of use.

Distributed Mobility Management.

Data traffic in mobile networks is likely to exceed data traffic in fixed networks in the near future. Mobility management is going to take considerable importance. Today, the principle is to concentrate the traffic from and to mobile devices on a single gateway (which is called an anchor) in the mobile core network. By use of tunnelling mechanisms, the traffic is forwarded to the location of the mobile terminal. Such a mechanism is used in Mobile IP, Proxy Mobile IP and GTP (LTE mobility). This architecture concentrates the traffic in a single entity and merges mobility signaling and data traffic. It is necessary to develop new mechanisms for mobility management that are more distributed and that are activated only when the user or the service really need it: these are called Distributed Mobility Management (DMM). In [7], we consider one of the DMM approaches (dynamic mobility anchoring) and study the usage of session initiation protocol (SIP) for providing reachability support. After defining different SIP-based location update modes, we carried out a comparative cost analysis considering new performance metrics related to the processing loads at each network entity. We considered the location update loads on the location server as well as the context, signaling, and tunneling loads on a mobility anchor. We investigated the different modes in several scenarios, allowing the mobile network operator to adopt the preferred mode depending on their architecture.

Network Mobility.

In the framework of Pratibha Mitharwal's thesis [6] defended in September 2016, we stud-

ied how to support network mobility. In particular, in [48], we focused on the quantitative and qualitative performance analysis of Network Mobility (NEMO). It compared the original NEMO architecture with an architecture in which NEMO is enhanced with Multi-Path TCP (MPTCP). This quantitative and qualitative analysis was done by plotting theoretical and experimental results using a local testbed implementation. It was shown that the novel combination of NEMO and MPTCP performs significantly better, in terms of routing efficiency and of throughput, compared to a classical implementation of NEMO.

6.6 Multiple Access Technology Selection

Participants: Iaad Ben Dhia, Bernard Cousin, Soha Farhat, Annie Gravey, Cédric Guéguen, Xavier Lagrange, Samer Lahoud, Younes Khadraoui.

Along with the rapid growth of mobile broadband traffic, different Radio Access Technologies (RATs), including 3GPP families and IEEE ones, are being deployed. A key feature will be an increased integration of both the fixed access and the different radio access technologies (RAT). A typical mobile device today can support 3G, numerous releases of 4G LTE, possibly including LTE-Unlicensed, several types of WiFi (possibly with access points owned by home users), all this across several large spectral bands. Our objective is to consider two aspects: i) the optimization of the architecture, ii) the optimization of the selection algorithms.

In the framework of the FP-7 COMBO project (CONvergence of fixed and Mobile BrOadband access/aggregation networks), we participated to the definition of the concept of Universal Access Gateway and a unified approach for authentication. We focused on the convergence of the data paths, we proposed new convergent architectures and analysed their performance. The convergence can be made i) at the IP level and above or ii) at layer 2 and below [5]. In the first case, the problem is related to multi-attachment and multi-homing and is widely addressed by the scientific community. The very-tight coupling concept, which we proposed, is an example of layer-2 convergence solutions in which residential Wi-Fi APs are connected to LTE base stations. This represents an interesting solution to offload the LTE networks even for fast-moving terminals because a dual connection (Wi-Fi and LTE) is kept. Unlike other coupling solutions (tight coupling at the SGW (Serving Gateway) level or loose coupling at the Internet level), very-tight coupling naturally guarantees session continuity of the application because the IP address is kept in all mobility scenarios. We analysed the performance of very tight-coupling from a theoretical point of view [41]. We also implemented the concept of very tight coupling on a testbed based on OpenAir Interface (see <http://http://www.openairinterface.org/>), proved its interest and measured the performance for different scenarios [42, 62, 43]. In particular, we found that aggregating WiFi and LTE simultaneously does not always increase the bit rate when there are a large difference regarding the latency of each network and that implementing packet reordering mechanisms below TCP does not bring any increase of the user bit rate.

In [14], we consider the downlink of a heterogeneous network with two broadband RATs: a primary RAT such as LTE, and a secondary RAT such as WiFi. We start by formulating a centralized approach for the RAT selection as an optimization problem. Then, two distributed approaches are proposed for adequate RAT selection: first, we put forward distributed heuristic

algorithms based on the peak rate perceived by users from available RATs. Second, we devise a distributed RAT selection scheme portrayed as a non-cooperative game with a learning-based algorithm to reach the Nash Equilibriums of the RAT selection game. Extensive simulation results show that the proposed distributed algorithms give efficient results compared to the centralized optimal approach. The analysis of the simulation results enables to define pertinent use cases that delimit the scope of the proposed optimal centralized and distributed approaches.

In [11] we propose a hybrid decision framework for RAT selection that dynamically integrates operator objectives and user preferences. Mobile users are assisted in their decisions by the network that broadcasts cost and QoS information. Our hybrid approach involves two inter-dependent decision-making processes. The first one, on the network side, consists in deriving appropriate network information so as to guide user decisions in a way to meet operator objectives. The second one, where individual users combine their needs and preferences with the signaled network information, consists in selecting the RAT to be associated with in a way to maximize user utility. We first focus on the user side and present a satisfaction-based multi-criteria decision-making method. By avoiding inadequate decisions, our algorithm outperforms existing solutions and maximizes user utility. Further, we introduce two heuristic methods, namely the staircase and the slope tuning policies, to dynamically derive network information in a way to enhance resource utilization. The performance of each decision-making process, on the network and user sides, is evaluated separately through extensive simulations. A comparison of our hybrid approach with six different RAT selection schemes is also presented.

When in presence of multiple operators, the access technology selection needs special attention. In our recent works, we adapt the Simple Additive Weighting (SAW) and Nearest Performance Handover (NPH) algorithms for the access selection in a multi-operator environment [3]. We also compare different pricing scenarios for the transaction cost of the inter-operators agreement in a cooperative environment. This enables us to highlight how network conditions and operator's strategy for service price may affect the profitability of the cooperation. Further, a best pricing scenario can be decided depending on the deployed capacity for sharing and the user's service price settings. Finally, we investigate the access selection and joint pricing problem in multi-operator wireless networks. The problem is formulated as a Stackelberg game, where cooperating service operators first set the service price to maximize their revenue. Then, the home operator of the mobile user performs the access selection process among the service operators, in order to maximize its own profits and its client satisfaction, in terms of perceived QoS.

6.7 Radio Resource Management

Participants: Alberto Blanc, Bernard Cousin, Cédric Guéguen, Xavier Lagrange, Samer Lahoud, Loutfi Nuaymi, Hussein Al Haj Hassan, Jialong Duan, Ali El Amine, Mahdi Ezzaouia, Soha Farhat, Qipeng Song, Mohamad Yassin,.

Radio Resource Management (RRM) algorithms or heuristics are a key element for providing high system throughput 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 (RRM): Inter-Cell Interference Coordination, scheduling, energy-efficient power control and selection strategies.

Multi-Cell Interference Coordination and Power Allocation.

One major concern for operators of Long Term Evolution (LTE) networks is mitigating inter-cell interference problems. Inter-Cell Interference Coordination (ICIC) techniques are proposed to reduce performance degradation and to maximize system capacity. It is a joint resource allocation and power allocation problem that aims at controlling the trade-off between resource efficiency and user fairness ^[Yas15].

In [16], we provided a comprehensive survey on Inter-Cell Interference Coordination (ICIC) techniques, and study their performance while putting into consideration various design parameters. This study was implemented throughout intensive system level simulations under several parameters such as different network loads, radio conditions, and user distributions. Simulation results showed the advantages and the limitations of each technique compared to frequency reuse-1 model. Thus, we were able to identify the most suitable ICIC technique for each network scenario.

In [60] building on the results of the above survey, we made a contribution on power allocation for multiuser Orthogonal Frequency Division Multiple Access (OFDMA) networks, such as Long Term Evolution networks. OFDMA uses the frequency reuse-1 model to face the tremendous increase of mobile traffic demands, and to increase network capacity. However, inter-cell interference problems are generated, and they have a negative impact on cell-edge users performance. Resource and power allocation should be managed in a manner that alleviates the negative impact of inter-cell interference on system performance. In this work, we formulate a novel centralized multi-cell resource and power allocation problem for multiuser OFDMA networks. The objective is to maximize system throughput while guaranteeing a proportional fair rate for all the users. We decompose the joint problem into two independent problems: a resource allocation problem and a power allocation problem. We prove that each of these problems is a convex optimization problem, and that their optimal solution is also an optimal solution to the original joint problem. Lagrange duality theory and subgradient projection method are used to solve the centralized power allocation problem. We study the convergence of our centralized approach, and we find out that it reduces inter-cell interference, and increases system throughput and spectral efficiency in comparison with the frequency reuse-1 model, reuse-3 model, fractional frequency reuse, and soft frequency reuse techniques.

In [45], we tackle the joint power control, user association and scheduling problems. Despite the relevance of the addressed problem, it has remained largely unsolved, mainly due to its non-convex and combinatorial nature. We address this multifaceted challenge in a distributed fashion for reduced complexity. We assume that proportional fairness among UEs boils down to time fairness and we solve the joint UE association and power control in a distributed fashion. Accordingly, the UE association and power control schemes are portrayed as non-cooperative

[Yas15] M. YASSIN, *Inter-Cell Interference Coordination in Wireless Networks*, Theses, Rennes 1, November 2015.

games that can lead to a substantial complexity reduction. In our case, eNBs and UEs optimize their local parameters by making use of signaling messages already present in the networks. Notably, a fully distributed algorithm for the UE association scheme based on reinforcement learning is applied by UEs to attain the Nash Equilibriums (NE) of the game.

Resource Allocation in Centralized Radio Access Networks.

Centralized/Cloud Radio Access Network (C-RAN) is a promising future mobile network architecture which can ease the cooperation between different cells to manage interference. However, the feasibility of C-RAN is limited by the large bit rate requirement in the fronthaul. In [37] we considered the uplink channel (from a terminal to the network) and studied several split strategies of signal processing functions (e.g Fourier transform) between the remote radio head and the base band unit and their impact on the load on the fronthaul. In [36] we studied the maximum throughput of different transmission strategies in a C-RAN cluster with transmission power constraints and fronthaul capacity constraints. Both transmission strategies without cooperation (e.g. "no cooperation transmission") and with cooperation (e.g. "distributed MIMO") between different cells are considered. Simulation results show that "distributed MIMO" has a better performance than "no cooperation transmission" with high RRH power constraint, high fronthaul capacity constraint and when the UEs are located at cell edge area.

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 increase network connectivity [6] or provide energy efficient radio communication. Currently we work in order to increase the efficiency of these solutions. These activities can lead to many other subjects, such as dynamic inter-cellular bandwidth Fair Sharing and energy allocation in smart grid.

[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.

Inter-cellular bandwidth Sharing.

Enhancing the Quality of Experience (QoE) in wireless networks is a crucial issue. Many acknowledged works focus on intra-cellular scheduling. They have shown that when the channel impairment is taken into consideration by the opportunistic scheduling approaches, it allows to reach higher throughputs and, for the most efficient ones, a higher fairness. However, if some of these works provide results near to optimum considering a single cell, high QoE cannot be guaranteed for scenarios where the cells are overloaded. In [12], we proposed a new intercellular scheduler called Inter-cellular Bandwidth Fair Sharing Scheduler (IBFS) able to help the overloaded cells thanks to a dynamic cell bandwidth allocation. Our resource allocation technique is based on an adequate emergency parameter called Mean Cell Packet Delay Outage Ratio (MCPDOR). This metric is used to select the best candidate cell to receive additional bandwidth from its neighbors. The logical metric could be to base our approach on the global cell traffic load, but we have shown that it is not the optimal metric. Indeed, cell's mobiles have no reason to use the same data rate profiles (less or more elastic) or the same applications with the same delay constraints. Intra-cellular schedulers of the cells with more elastic traffic profile or more restrictive QoS constraints have a more difficult task to ensure QoS. They could require more bandwidth than the schedulers of other cells with higher global throughput but less restrictive QoS constraints or lower peak data rate demands. Consequently, the IBFS scheduler should be based on a reliable metric, which is a crucial issue for its performance. Thanks to the new introduced metric MCPDOR that measures the cell emergency to access to more radio resources, IBFS is able to always select the appropriate cell to help. Performance evaluation shows that the proposed scheduler widely outperforms existing solutions in various scenarios. A variant of our solution that does not consider MCPDOR is also proposed and evaluated.

Trade-off between spectrum efficiency and energy efficiency.

One of the used strategies to increase the spectral efficiency (SE) of cellular network is to reuse the frequency bandwidth over relatively small areas. The major issue in this case is higher interference, decreasing the energy efficiency (EE). In addition to the higher bandwidth, densification of the networks (e.g. small cells or multi-user multiple input single output, MU-MISO) potentially increases the area spectral efficiency (ASE). The total energy consumption of the wireless networks increases due to the large amount of circuit power consumed by the dense network structures, leading to the decrease of EE. There is thus a trade-off between spectrum efficiency and energy efficiency [49]. In [46] we consider the Signal-to-leakage-and-noise ratio (SLNR) approach, which is a promising criterion for linear precoder design in multiuser multiple-input multiple-output systems. We derived an expression of a precoder maximizing the SLNR based on the generalized Rayleigh quotient theorem. Compared with the conventional SLNR precoders, we considered the non-homogeneous average received signal-to-noise ratio (SNR) condition due to the random network geometry and the leakage to other cells. Simulation results demonstrate the superiority of the SLNR precoder over zero-forcing (ZF) precoder in terms of EE-ASE tradeoff. Our contribution lies in the analysis of the performance of SLNR precoder in PPP networks in terms of tradeoff between EE and SE, and in

the comparison between the well known ZF precoder and SLNR precoder, when static power consumption is considered.

In [15], we address energy efficient resource management in downlink Orthogonal Frequency Division Multiple Access (OFDMA) networks. The focus is targeted towards multi-cell networks, which are composed of multiple Base Stations (BSs) sharing the available radio resources. Consequently, greater emphasis is given to techniques that take inter-cell interference into account. Resource management in our context refers to the task of allocating the radio resources in order to maximize energy efficiency. We devise resource management techniques that jointly tackle the problems of scheduling and power control. Accordingly, we adopt two different approaches: a centralized approach where BSs coordinate in order to reach a globally optimal energy efficient solution; and a distributed approach where BSs selfishly strive to maximize their own energy efficiency. We portray the centralized approach as a convex optimization problem; whereas, we have recourse to non-cooperative game theory to model the distributed approach. Particularly, we show that the non-cooperative game converges to a unique Nash equilibrium in low and high interference scenarios. We perform thorough numerical simulations to quantify the discrepancy between the centralized and distributed approaches, and identify the conditions where they have precedence over the state-of-the-art. Moreover, the simulation results highlight the fast convergence of our algorithms, which is a precious asset for realistic deployments.

Energy-efficient power control and selection strategies.

In [28], we study the trade-off of user satisfaction and grid energy consumption associated to the usage of renewable energy, considering different types of traffic. User satisfaction of each type of traffic is represented by a utility function, as this allows for a better trade-off between energy consumption and user satisfaction. The problem is formulated as a weighted sum of two objectives, power demand and average users utility. We analyze the efficient use of small cells in a renewable energy context and considering real-time price of grid energy. This is typically the case when the mobile network is powered by the Smart Grid, in addition to renewable energy when available. We study the use of an algorithm adapted for this context and analyze it in simulation [27]. Our results show that a suitable number or density of small cells gives better cost and energy savings performance, if we take grid energy cost into account.

The significant growth in the number of access points deployed in WLAN stimulates research efforts to focus on finding solutions to reduce the power consumed by their components. One promising approach is to put the access points (or at least its radio interface) into sleep mode when no activity is detected on the channel. In this paper we designed and implemented a measurement platform which can automatically send repeated sleep/wake up request to an access point (see Section 5.1), and measure the energy it consumes in each state. We define and conduct several experiments to evaluate four different techniques to control and manage the sleep/wake up procedure of an access point. We compare their performance in terms of the time needed to complete the wake up, the energy consumed, and the changes, if any, needed in the mobile terminals. [54].

Energy Efficiency and Routing in Wireless BAN.

Body area network (BAN), also referred to as a wireless body area network (WBAN) or a body sensor network (BSN), is a wireless network of wearable computing devices. This new generation of networks is designed to operate autonomously, to connect various medical sensors and appliances located on or inside a human body. Mobile WBANs have been designed, offering numerous practical and innovative services so that health care and quality of life can be improved. Thus, the equipment used in WBAN is usually mobile and autonomous which imposes high constraint on energy. That is, the energy efficiency must be taken into account as one of the objectives of the routing protocol. Although mobile nodes may cause link breaks, most of studies ignore the link stability. In this work ([55]), we propose a stable, reliable, energy efficient routing protocol for mobile Wireless Body Area Networks. It preserves the residual energy of nodes with an increase network lifetime. To achieve this goal, we use an objective model to select the most energy-efficient path with stable set of links. Simulation results demonstrate that our protocol improves the state of the art in terms of energy consumption and routing overhead.

Energy-efficient M2M cellular coverage.

In [23], we propose a survey providing a global view of the network technologies previewed for cellular M2M. In this survey, we study the existing classifications of M2M applications according to different criteria in the literature. The comparison of traffic characteristics between M2M and human-to-human is also proposed. Quality of service (QoS) requirements for typical M2M applications are resumed. The advance of reference M2M network architectures proposed by the Standard Development Organization (SDO) is investigated. We identify two possible effort directions to improve the energy efficiency for cellular M2M. The first one is to evolve the current existing 3rd Generation Partnership Project (3GPP) Consortium cellular networks to effectively support MTC (Machine Type Communication). The other direction is to design M2M-dedicated networks from scratch, which are often called low-power wide-area (LPWA) networks.

We evaluate the power efficiency, energy efficiency and system capacity for uncoordinated CDMA and coordinated FDMA [56]. Through numerical results, we conclude that coordinated FDMA is more resistant to various packet lengths of M2M devices packets in terms of power efficiency and is not influenced by imperfect power control. Thus coordinated multiple strategies, especially FDMA, are more suitable for the future M2M-included cellular networks and deserve further optimization works. With respect to uncoordinated CDMA, although its performance is affected by BS load intensity and power control, it is still a considerable choice due to its simplicity and no signaling overhead, when the BS load intensity is not high and the power control policy is suitable.

Energy allocation in smart grid.

In [19, 18] we proposed a real-time Neighborhood Energy Management approaches that aims to manage real-time residential energy. The introduced approaches allow first to decrease

the energy cost by optimally choosing between locally generated energy, neighborhood energy surplus, or grid supplied energy. Second, they maximize the producer's gains by selling the excess energy not only to the utility companies but also to neighbors at a more profitable price. Our proposed energy selling price is flexible and adequately adapted to the user's excess energy. Simulation results proved the effectiveness of our proposed approaches. The results show that our energy sharing pricing models satisfy requirements of each user (minimizing energy cost, maximizing gain) which will effectively motivate and encourage users to share energy and invest in renewable energy.

6.8 Revenue Sharing in Multi domain Alliances

Participants: Sandrine Vaton, Isabel Amigo.

Alliances arise in a wide variety of domains, when a group of countries, political parties, people or other entities agree to work together because of shared interests or aims. They make sense, if the output obtained is somehow better than the outcome of acting individually. Revenue or cost sharing is key when determining if individuals are better off by contributing to an alliance or not.

In our alliance each member owns a unique resource –or set of resources–, which is given to the alliance . The alliance sells services, which are supported thanks to one or a set of these resources. We focus on alliances that sell services in such a way that the total revenue of the alliance is maximized. We have shown that this kind of problems can be modeled through a Network Utility Maximization problem. We have explored the problem of revenue sharing among the members of the alliance. Such a problem is a complex one since the interests of all participants must be ensured and correct incentives must be provided. We formally formulate the members' interests through a set of properties the revenue sharing method should verify. We have explored existing methods for revenue sharing and conclude that none of them verify the needed properties for the case of a revenue maximizing alliance. We finally propose a revenue sharing method based on projecting the contributions of each member of the alliance into an economic stable set [9]. We have followed a numeric approach to explore our solution which was shown to provide, in addition to economic stability, fairness among members and the right incentives to them. Our general framework is applicable, for instance, to Network Service Provider alliances, which sell quality-assured data transport services, are considered as an application example.

6.9 Network Monitoring

Participants: Isabel Amigo, Sandrine Vaton, Santiago Ruano Rincón, Serge Romaric Tembo Mouafo.

Software-based tools to reproduce DNS 10Gbps flooding attacks.

Recently the Domain Name System (DNS) has become a privileged medium to threaten the resilience of Internet. Every single Internet service uses the information about domain

names provided by the DNS, what makes it an attractive target for malicious users.

At the same time, the constantly increasing Internet traffic rate challenges DNS operators and their attack detection methods to handle legitimate queries while being flooded by tens of millions of malicious requests per second. Moreover, state of the art on hostile actions evolve fast. DNS administrators continuously face new kinds of attacks and they regularly need to evaluate their detection systems.

We have studied different approaches to develop a tool able to reproduce state-of-the-art attacks, aiming to make it easy to evaluate countermeasure strategies. To develop highly flexible tools, we have focused on commodity-hardware, DPDK and MoonGen to build a fully-random request generator.

The described tool can saturate a 10Gbps link, sending more than 12 million attack-like random DNS requests per second. This tool is described in [51].

Application of probabilistic modeling and machine learning to the diagnosis of FTTH GPON networks.

Detecting, isolating and correcting primary faults related to network connectivity and network performance should be automatized as much as possible using tremendous amounts of data generated by network components and services as source of information on the observed network anomalies.

We have investigated the possibilities offered by probabilistic modeling and machine learning for fault diagnosis in optical access networks [57] [58][24].

A Bayesian inference engine, called Probabilistic tool for GPON-FTTH Access Network self-Diagnosis (PANDA), has been developed and applied to fault diagnosis of Gigabit capable Passive Optical Networks (GPON). PANDA approach has been assessed on real diagnosis data, showing very satisfactory alignment with an operational rule-based expert system. Furthermore, it provides diagnosis conclusions for all tested cases, even if some monitoring data are missing or incomplete. Finally, an Expectation Maximization algorithm allows to finely tune the probabilistic model.

Monitoring and Routing in Overlay Networks.

It is now broadly admitted that the performances of individual Internet flows could be improved by selecting alternate paths to those provided by IP routing protocols. Unfortunately, the routing infrastructure of the Internet has become resistant to major changes, preventing even necessary changes to take place.

An alternative approach for shielding distributed services from path outages and performance degradations of the Internet is to use a routing overlay. The overlay nodes correspond to end hosts, which are deployed over the Internet, and cooperate with each other to forward data on behalf of any pair of communicating nodes. This approach has been used to create self-healing and self-optimizing routing overlays that are able to monitor the quality of Internet paths between their nodes and to adapt their routing schemes according to application-specific metrics and to what is observed from the underlying network. However, most routing overlays use all-pairs probing, resulting in a costly $O(n^2)$ probing overhead as the number of partici-

pating nodes n increases. Evidence indicates that such an $O(n^2)$ approach is able to scale to approximately 50 overlay nodes. We are working on the proposal of a routing overlay that can be widely deployed over a sizable population of routers. We have designed an active measurement method providing an accurate estimation of the quality of overlay links without overloading the network (i.e. keeping a low monitoring effort).

We have proposed an SDN-based architecture able to support such overlay network [31] and are currently working on a test-bed. We have performed active measurements campaigns using the RIPE Atlas measurement infrastructure which allowed us to have a model for RTT in the Internet paths. Our findings show that RTTs can be suitably modelled as Markov chains (MC) or as noisy Markov chains, so called Hidden Markov Models (HMM). Our approach for accurately estimate the delay on a path without loading the network builds on these models. Our future work in this direction includes extending our approach to a more generalized scenario.

7 Contracts and Grants with Industry

7.1 Contracts with Orange

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

- A grant (Contrat de Recherche, 2014-2016, 150 kE, holder: Gwendal Simon) on the study of the impact of Content Delivery Networks on the network neutrality. This grant targets the development of new strategies for network operators to operate their content delivery networks.
- CIFRE thesis (2013-2016) on detection and correction of faults in networks (Sandrine Vaton)
 - Application of swarm intelligence to the detection, isolation and correcting of multiple faults in telecommunication networks.
- CIFRE thesis (2013-2016) on traffic engineering for mobile networks (Xavier Lagrange).
 - The objective of the work is to propose in 4G mobile networks IP centric mechanisms that can be both simple and cheap to deploy and efficient enough to provide several levels of QoS.
- CIFRE thesis (2013-2016) Smart Management of Optical Networks (Bernard Cousin)
 - Smart management of flex-grid optical networks could revolutionize telecommunication networks. It remains to be seen whether advanced optical functionalities (as, for instance, advanced grooming functionalities, advanced optical modulation formats, differentiated optical services, optical power management) can be efficiently managed on flex-grid WDM networks.
- CIFRE thesis (2014-2017) on Traffic Monitoring and Forecasting based on Big Data (Alberto Blanc and Gwendal Simon)

- The idea here is to leverage big data technologies to implement traffic forecasting strategies and to detect in advance traffic troubles.
- CIFRE thesis (2014-2017) on the definition of programmable algorithm for connectivity in a segment routing network (Géraldine Texier).
 - Segment routing is a new but promising mechanism to optimize the forwarding of packets in networks that implement predefined segments. The objective of the work is to study and to propose algorithms to enable traffic engineering and quality of service by reservation or traffic prioritization with segment routing.
- CIFRE thesis (2015-2018) on QoS management for mobile voice over IP services (Alberto Blanc and Xavier Lagrange)
 - After decades of voice communications with circuit-switch technology, voice over IP is the only way to provide a telephone service in 4G cellular networks. Furthermore, new codecs like EVS (Enhanced Voice Service) are available. Offering an excellent quality of service (QoS) is a key point for operators. The aim of this PhD is to design new algorithms to improve audio quality control in mobile voice over IP services. The work includes the identification of key areas for improvement, the design and development of new algorithms for QoS control and the experimental evaluation of the proposed algorithms.
- CIFRE thesis (2015-2018) on content delivery for 5G networks (Loutfi Nuaymi and Gwendal Simon)
 - The design of 5G networks considers not only the development of new wireless technologies but also the conception of new architectures and protocols to support the novel generation of applications, mainly multimedia and interactive to enable immersion. The thesis aims at addressing these questions altogether.
- CIFRE thesis (2015-2018) on the study and implementation of algorithms for managing resource in a cloudified network (Annie Gravey).
 - Resource management in a cloudified network is not yet well known. This is typically true in the well-known OpenStack framework. The objective of the present thesis is to design resource management algorithms (e.g. task scheduling and resource allocation in a virtualized network), to mathematically analyse them and to test them within Orange Labs.
- CIFRE thesis (2015-2018) on the joint optimisation of resource allocation and access network selection (Xavier Lagrange and Samer Lahoud).
 - The objective of the work is to consider the available access technologies (3G, 4G, Wi-Fi) and to propose access network selection methods that can work on large networks with an acceptable computation time in order to optimize both the quality of service and minimize the cost

- CIFRE thesis (2016-2019) on the new protocol stack of the Internet for content delivery (Gwendal Simon)
 - Some novel proposals have been studied, implemented and deployed in the Internet although the understanding of their impact on the network performance are still largely unknown. It is especially the case of HTTP/2 and also QUIC. We want to analyze the impact of these protocols on the content delivery with respect to the other competing traffic flows.
- CIFRE thesis (2016-2019) on the measurement of the quality of Web navigation (Sandrine Vaton)
 - Some new protocols such as HTTP/2, Quic or TLS1.3 have an impact on the quality of experience that users of the web will receive, and also on the metrics that monitoring tools can rely on. We want to analyze new methods and metrics for assessing the quality of web navigation taking into account these new protocols.

7.2 SYSTUF

Participants: Xavier Lagrange,.

- Title: SYSTèmes télécoms pour les Transports Urbains du Futur
- Framework: Fonds national pour la Société Numérique - Usages, services et contenus numériques innovants, Consultation AAP Systèmes de Transport Intelligents
- Duration: 2012-2015 (extended to March 2016)
- Partners : IFSTTAR (formerly INRETS), Eurecom, MERCE (Mitsubishi Electric), Alcatel-Lucent, RATP, ALSTOM
- Abstract: the objective of SYSTUF is to define and implement a new broadband multiservice wireless communication system for public transportation systems (bus, tram, metro). The technology is based on (LTE, Long Term Evolution) and more specifically on LTE mobile relays. On major constraint is to use the same system for critical communications (Communication Based Transport Control), Video transmission (CCTV), passenger information and infotainment. Reop is involved in the performance analysis of the gain provided by mobile relays and the protocols to develop to optimize mobility management.
- See also : <http://systuf.ifsttar.fr/>

7.3 FP7 COMBO

Participants: Annie Gravey, Xavier Lagrange, Souheir Eido, Moufida Feknous, Younes Khadraoui.

- Title: CONvergence of fixed and Mobile BrOadband access/aggregation networks (COMBO)
- Framework: EU FP7
- Duration: January 2013 – September 2016
- Partners : In addition to Telecom Bretagne², the other partners are: JCP-connect, Deutsche Telekom AG, Orange, Telefonica, FON Wireless Ltd, Argela, Ericsson, Alcatel Lucent, ADVA Optical Networking Ltd, Telnet, Aitia, Centre Tecnologic de Telecomunicacions de Catalunya, Politecnico di Milano, Lund University.
- Abstract: COMBO will propose and investigate new integrated approaches for Fixed / Mobile Converged (FMC) broadband access / aggregation networks for different scenarios (dense urban, urban, rural).
- See also : <http://www.ict-combo.eu/>

7.4 CELTIC SooGreen

Participants: Loutfi Nuaymi.

- Title: Service Oriented Optimization of Green Mobile Networks
- Framework: CELTIC project
- Duration: July 2015- June 2018 (3 years)
- Partners : Alcatel-Lucent, Nokia, Orange Labs, Arelis Broadcast, KTH, Intitut Mines-Telecom (Telecom Bretagne, partner and coordinator for IMT, Télécom Sud Paris and Télécom Ecole de Management), Lemasson, ATAWAY, Université de Caen Basse Normandie, Elisa, Polaran, Tele2, Energiforsk, Flexenclosure, BioSyncTechnology, INESC TEC, Eurico Ferreira.
- Abstract: Mobile networks are witnessing an exponential growth of traffic volumes, associated with the emergence of new services. In particular, video services constitute a major part of the traffic and their share is expected to increase. In the same time, Internet of Things (IoT) related traffic will gain in importance with the explosion of the number of connected objects. This situation pushes towards an evolution of network architectures (e.g. LTE-A features on centralized/virtual RAN) and of content delivery solutions (e.g. in network caching). SooGREEN is built around the need of reducing the energy consumption of services in light of the traffic evolutions and exploiting the new network architectures, while keeping in mind the development of smart grids. This includes: Modeling the energy consumption of services in different mobile network architectures and taking into account the end-to-end path, A joint dynamic optimization

²In the above list of participants, only Adopnet participants are cited

of the mobile access network and the content delivery solutions, Proposal of solutions for enabling the bi-directional interaction of the mobile network and the smart grid by exploiting the flexibility of some services and the energy storage capabilities in the network.

7.5 ANR N-GREEN

Participants: Annie Gravey, Ahmed Triki.

- Title: New-Generation of Routers for Energy Efficient Networks
- Framework: ANR 2015
- Duration: October 2015- September 2018 (3 years)
- Partners : Nokia Bell Labs, Intitut Mines-Telecom (Telecom Bretagne, , Télécom Sud Paris and Télécom ParisTech), UVSQ, III/V Lab.
- Abstract: The objective of the N-GREEN project is to propose systems and protocols, and network concepts that can support the predicted traffic increases while significantly reducing energy consumption. The main focus of this project is on identifying building blocks and operational rules for network elements that allow reducing both CAPEX and OPEX. First of all, N-GREEN aims at proving the concept of a new core switch/router architecture offering a higher capacity and reduced power consumption by adopting new optical technologies for the interconnection backplane and optical bypasses. Furthermore N-GREEN will investigate the impact of the introduction of such switch/routers on network architectures, taking into account, on the one hand, the opportunities offered by the WDM packet structure and optical bypass and, on the other hand, major trends on new service architectures and traffic patterns. Energy consumption metrics will be used for the network design. Finally, new routing protocols will be proposed as well as new controllers matching SDN requirements, in order to efficiently manage the N-GREEN network and enable future virtualisation through NFV.

7.6 Live Network Anomaly

Participants: Alberto Blanc, Maha Mdini, Gwendal Simon.

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

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

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

Participants: Gwendal Simon.

- Title: Dynamic Distribution of On-demand and Live Videos in Mobile Network
- Framework: National Natural Science Foudation of China
- Duration: 01/10/2016 to 31/09/2019 (36 months)
- Partners: Xidian University
- Abstract: The objective of the project is to provide the theoretical fondations for content delivery of novel interactive applications baesd on live video streaming.

7.8 Live Watermarking in CDN

Participants: Kun He, Gwendal Simon.

- Title: Enhancing Watermarking Solutions for Live Video Streaming
- Framework: SME and Region Bretagne funding
- Duration: September 2016- February 2018 (18 months)
- Partners: Broadpeak, Kupelseki Group
- Abstract: The objective of this project is to improve the performance of watermarking solutions for live streaming, in particular to reduce the impact of the solution on the overall traffic of the CDN.

7.9 Control distribution in an SDN architecture

Participants: Géraldine Texier.

- Title: Control distribution in an SDN architecture
- Framework: CIFRE Thesis
- Duration: December 2016- December 2019 (36 months)

- Partners: TDF
- Abstract: The SDN architecture specifies a "logically" distributed control but most of the solution are currently defined for a centralized control. We want to propose an architecture and algorithms for the distribution of the control with a focus on the management of Quality of Service in the SDN architecture.

8 Other Grants and Activities

8.1 International Collaborations

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

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, Antonine 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 Adopnet members are the collaboration leaders :

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

Gwendal Simon is one of the 18 scientists who have developed a new program for the promotion of reproducibility in academic research, led by ACM Digital Library (DL). The task force has released a new approach to incentivize researchers to share datasets and more generally artifacts of their study. This approach is based on the concept of badges that are attached to papers. The task force has been invited in various conferences to disseminate the badging system, which has received much attention from leading conferences and journals.

Gwendal Simon is one of the core members of the Multimedia Cloud Computing Interest Group (MCCIG) of the IEEE Technical Committee on Multimedia Communications (MMTC). This interest group promotes research and development in emerging area of cloud computing for multimedia communications, applications, and services. It aims to provide a platform for researchers and practitioners from academia and industry to discuss relevant topics and exchange views on the (potential) issues of utilizing cloud and its resources to further the quality, efficiency, effectiveness, and scope of multimedia communications. MCCIG will assist the IEEE MMTC by organizing and supporting academia events, such as conferences, workshops, and tutorials, special issues of relevant journals, and other efforts to promote this line of research.

Sandrine Vaton and Isabel Amigo are part of the PROVE Stic Amsud project (2016-2017), lead by LAAS-CNRS and in collaboration with Universidad de la República, Uruguay and Universidad de la Concepción, Chile.

Visiting researchers

- Souleymane OUMTANAGA from Institut Polytechnique Houphouet Boigny, Yamoussoukro, Ivory Coast.
- Sie OUATTARA from Institut Polytechnique Houphouet Boigny, Yamoussoukro, Ivory Coast.
- Pablo BELZARENA from Universidad de la República, Uruguay.

Sabbatical.

Géraldine Texier is visiting for 12 months INRIA@Silicon Valley in UC Berkeley, a joint program with INRIA, Californian universities and the CITRIS (Center for Information Technology Research in the Interest of Society).

8.2 National Collaborations

- Members of Adopnet team (Bernard Cousin, Cédric Guéguen, Gwendal Simon) have been detached (for a part of their time) to B◊Com, which is a national research and technology institute dedicated digital technologies. B◊Com provides unique technologies in the field of ultra-high-speed networks in order to accelerate the release of products designed to meet tomorrow's needs.
- Adopnet team members through their research projects collaborate with the worldwide research and innovation cluster, Images & Réseaux. With its network of partners specialized in ICT, Images & Réseaux brings innovators, industrialists and financiers together to support technology, usage and markets collectively.

9 Dissemination

9.1 Organization of conferences

9.2 Program committees

Bernard Cousin is member of the Editorial Board for:

- Wireless Communication & Mobile Computing journal
- International Journal of Networks and Communications
- International Journal of Computer Network and Information Security (IJCNIS).

He is member of IEEE Communications Society (ComSoc) Technical Committee on Information Infrastructure and Networking (TCIIN).

He served, in 2016, in the Program Committee of the following conferences:

- DRCN 2016, 12th International Conference on the Design of Reliable Communication Networks
- FNC 2016, 11th International Conference on Future Networks and Communications
- HPSR 2016, 17th IEEE International Conference on High Performance Switching and Routing
- IC4S 2016, International Conference on Computer, Communication and Computational Sciences.
- ICCCA 2016, IEEE International Conference on Computing, Communication & Automation
- ICCVE 2016, IEEE International Conference on Connected Vehicles & Expo
- NOTERE 2016, a national conference on "Nouvelles Technologies de la Répartition"
- OPTICS 2016, International Conference on Optical Communication Systems
- SETIT 2016, 7th International Conference Sciences of Electronics, Technologies of Information and Telecommunications

Annie Gravey is editor for the Journal of Communications and Networks, an international English-language journal published by the Korea Information and Communications Society. In 2016, she served in the Program Committee of the following conferences:

- APWiMob 2016, Asia Pacific Conference on Wireless and Mobile 2015
- Globecom 2016, IEEE Global Communications Conference, GC' 16 - SAC - E-Health
- ICACCI 2016, IEEE Second International Conference on Advances in Computing, Communications and Informatics
- ICC'16 CQRM (2016 IEEE International Conference on Communications)
- Internet 2016, The Eighth International Conference on Evolving Internet
- Networks 2016 - 18th International Telecommunications Network Strategy and Planning Symposium
- PIMRC 2016, 27th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications
- WCNC 2016, IEEE Wireless Communications and Networking Conference

- Wimob 2016, 10th International Conference on Wireless and Mobile Computing, Networking and Communications

Xavier Lagrange is member of the scientific committee of Annals of Telecommunications published by Springer.

He also serves in the Program Committee of the following conference:

- IFIP Networking 2016
- WD'16 (Wireless Days 2016) - Wireless Networks track
- VTC 2016 Spring, Vehicular Technology Conference,
- VTC 2016 Fall, Vehicular Technology Conference,

Loutfi Nuaymi is regular reviewer for Wiley Editions books proposals. He also served or serves in the Program Committee of the following conferences:

- IEEE Online GreenComm'16 (2016 IEEE Online Conference on Green Communications),
- VTC 2016 Fall, Vehicular Technology Conference Fall 2016

Gwendal Simon is in the editorial board of the IEEE MMTC R-letters related to Multimedia ACM SIG chapter. He was the publicity chair of the ACM MMSys conference. He was an area leader of IEEE ICME 2016 for the program committee of this conference. He also serves in the Program Committee of the following conferences:

- ACM Multimedia 2016, ACM flagship conference on Multimedia
- IEEE ICC 2016, IEEE International Conference on Communications
- IEEE Globecom 2016, IEEE Global Communications Conference
- IEEE ICME 2016, IEEE International Conference on Multimedia and Expo
- Packet Video 2016, 23th IEEE International Packet Video Workshop
- ACM Netgames 2016, 14th ACM Workshop on Network and Systems Support for Games
- ACM Nossdav 2016, 26th ACM workshop on Network and Operating System Support for Digital Audio and Video
- ACM MMSys 2016, the ACM Multimedia System Conference, which is the premier event for multimedia system and networking
- IEEE/IFIP CNSM 2016, IEEE International Conference on Network and Service Management, which is the flagship conference for the network management community

Sandrine Vaton was TPC chair of TRAC 2016, the 8th International Workshop on Traffic Analysis and Characterization. She is associate editor of Transactions on Emerging Telecommunications Technologies. She serves in the Program Committees of the following conferences:

- DCNET 2016, 7th International Conference on Data Communication Networking
- Networking 2016, 15th IFIP International Conference on Networking

Isabel Amigo has served in the Program Committee of TRAC 2016, 7th International Workshop on TRaffic Analysis and Characterization.

10 Bibliography

Major publications by the team in recent years

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