UMR IRISA

Activity report 2013

Dpt 2: Réseaux, Télécommunication et Services

Team AtNET

Advanced Technology in Networking

Rennes

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2 Overall Objectives

2.1 Overview

AtNet team aims at elaborating advanced technology (i.e. network architectures, network protocols and distributed algorithms) for the next generation of the Internet. The design of Next Generation Networks is a big challenge.

Next Generation Networks will offer high value transport services and should provide High Capacity, High Survivability, High Flexibility, Low energy consumption and High Efficiency for the new generation of multimedia distributed applications. Next Generation Networks will have High Capacity: the network should support very high throughput (for instance Tbit/s optical links are expected to be deployed in the next years), and a huge number of network flows with a world-wide coverage. Next Generation Networks will have High Survivability: network service reliability and protection should be assured, and data loss should be avoided by efficient flow control. Next Generation Networks will have High Flexibility: protocols and algorithms should be adaptive to application requirements (for instance wireless mobile multimedia applications), network load, or network policy. Next Generation Networks will have High Energy efficiency: network energy consumption must be reduced in order to

decrease world greenhouse gas emission and increase battery lifetime. This should be provided with High Efficiency since network resources are expensive and could be rare.

AtNet team focuses on *Scheduling*, *Routing* and *Management* issues of Next Generation Networks.

- Scheduling is the process of selecting the best resources for each network user in order to maximize global network throughput while ensuring the best Quality of Service (QoS), fairness and energy efficiency.
- Routing is the process of selecting paths in a network along which to send network traffic. Most usual routing algorithms use only one network path at a time. Our team studies advanced routing protocols (and route computation heuristics) for QoS traffic requirements, load balancing or network protection purposes. For instance, some advance routing techniques enable the use of multiple alternative paths.
- Network management refers to the activities, methods, procedures, and tools that pertain to the operation, administration, maintenance, and provisioning of networked systems. Network operation deals with keeping the network (and the services that the network provides) up and running smoothly. It includes monitoring the network to spot problems as soon as possible, ideally before users are affected. Network provisioning is concerned with configuring resources in the network to support a given service. For example, this might include setting up the network so that a new customer can receive real-time video service. In this network management domain, we focus on network monitoring and network design.

2.2 Key Issues

The key issues of the AtNet research are: Network Resource Allocation, QoS Routing, Energy efficiency and Optical Networks.

1. *Network Resource Allocation*

   Network resource allocation in next generation broadband networks is a challenging issue. For instance, in new wireless networks (4G systems), a solution shall guarantee mobile multimedia transmission services with an adequate QoS. These new multimedia services with tight QoS constraints require to avoid one major issue of computer networks : increase of system capacity while providing high fairness. The past decades have witnessed intense research efforts on this problem. However, network resource allocation considering several metrics is NP-difficult. For example, wireless transmissions are subject to many channel impairments such as path loss, shadowing and multipath fading which cannot be neglected. Similarly in all-optical networks, lightpaths are subject to wavelength impairment, bandwidth granularity and regenerator placement. These phenomena severely affect the transmission capabilities (and/or network cost) and in turn the QoS experienced by applications, in terms of supplementary delays or packet losses which appear when the effective bit rate at the physical layer is too low.

2. *QoS Routing*

   Nowadays, diverse advanced applications are provided over IP-based networks (e.g. IPTV, video-on-demand, telemedicine, e-health, ...). Guaranteeing the Quality of Service (QoS) to such applications remains a challenging problem. Routing is one of the primary mechanisms for providing QoS. It consists of the computation of an end-to-end path which ensures the delivery of the service while meeting the QoS constraints. QoS routing taking into account several metrics is NP-difficult. It is even more complex when multi-domain networks (with confidentiality constraints) or multicast communications or optical constraints have to be taken into account. Indeed, Multicast Routing has been one of the most studied routing issue of the AtNet team. The team members have produced numerous solutions adapted to routing problems on these aforementioned issue. They have been published in high quality scientific publications (see for instance [2, 3, 4, 7, 8, 16, 17, 24, 26]).

   The research of efficient but low cost heuristics to find feasible paths from a source to a destination has been studied by the team. For instance, in [BML09] a heuristic was proposed and deeply analyzed. It provides the first shortest paths in increasing order to find a first feasible one. The results show that this polynomial time computation often provides good paths. A review of the proposed inter-domain and intra-domain QoS routing algorithms was presented. An exact distributed method of intra-domain QoS route computation was proposed in [4]. MPLS-TE mechanisms can help the establishment of QoS inter-domain routes. Some very good results in this domain were presented in [3].

3. *Energy Efficiency*

   In the last decade, many research efforts have been done in order to increase the spectral efficiency of communication networks. Then, some solutions have emerged as good way to guarantee high system throughput and high Quality of Service (QoS). None of them take into account the energy cost of the solution. However, today, it is not sufficient anymore. Many climate problems have been underlined by the majority of world scientists and decreasing world greenhouse gas emission has become a necessity for the world's environment preservation. This requires to also reduce energy consumption in as much sectors as possible including communication networks. Current solutions are not well adapted to this new performance criterion and need active research in diverse domains like home networks or urban MIMO cell networks.

4. *Optical Networks*

   Due to the physical constraints and characteristics in all-optical WDM networks, their management and routing routing are a challenging work [Muk00]. First, in the absence of any wavelength conversion device in optical nodes, the same wavelength should be employed over a light-path which may pass through several nodes (this is referred as

[BML09] A. Bellabas, M. Molnar, S. Lahoud, "Heuristics for Multicriteria Routing Problem", *in: International Conference on Communications Computers and Applications*, Amman, Jordan, 2009.

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

the wavelength continuity constraint). Second, any large network (like most of optical networks) requires sophisticated control and management tools for network reconfiguration, and fault recovery. Third, optimized multicast routing touches well-known but NP-difficult problems. Thus routing or management of optical networks are challenging works. For instance, the reduction of power in an optical fiber should be compensated by internal active amplifiers like erbium-doped fiber amplifier, which, however, introduce many problems such as gain dispersion, gain saturation and noise. Consequently, the complex architectures along with the high-cost of optical nodes make wavelength routing and optical network management a domain which are worth the research effort. Currently we explore smart management for flexible optical networks and transparent reconfiguration of light-trees in WDM networks.

Our research is intended to be *vertical* in the sense that all aspects of network scheduling, network routing and network management are of interest: design, evaluation and implementation. Similarly our research is intended to tackle simultaneously several of the above issues. For instance "energy-efficient resource allocation", "multi-criteria routing in optical network", etc.

3 Scientific Foundations

3.1 Introduction

Keywords: graph theory, linear programming, network routing, network resource scheduling, distributed algorithm, heuristic, branch and bound, integer linear programming.

Research activities in the AtNet research team deals with architectures, protocols and algorithms for the Next Generation Networks. Next Generation Networks will be larger, will offer higher bandwidth, and should be more flexible to cope with new data transmission technologies proposes, for instance, by wireless networks or all-optical networks. Thus network architectures, protocols and algorithms have to be re-explored. We are concerned about the areas of recent challenges: Network Routing (QoS routing, multi-domain routing, multicast routing and routing for multimedia applications) and Network Management (resource allocation, network monitoring, network configuration, energy optimization). Our research is mainly articulated by architectural, protocol and algorithmic works. In this latter, we use the scientific foundations of graph theory and combinatorial optimization. Moreover protocols and algorithms are often tested by simulations because they is no easy access to large scale test networks. In the following, we provide a presentation of the scientific foundations associated with our works.

3.2 Multi-domain routing

Keywords: large scale network, inter-domain routing, multi-domain routing, QoS, autonomous systems, network operator cooperation, cloud infrestructure.

The objective of multi-domain routing is the computation of routes (unicast paths or multicast routing structures) knowing that the routes should cross several interconnected network

domains, whereas the operators of the different routing domains want to preserve the confidentiality of their topology and routing information. From one point of view, the organization of the network in domains fits to the usual way social organizations are organized, and is a good way to keep the scalability problem tractable. From a second point of view, the routing problem has to be solved with only partially available information, thus there is a trade-off between the quality of the routing and the amount of information which can be uncovered.

From the point of view of the network architecture, our activities are related to the distributed PCE-based route-computation architecture which is extensively discussed in international forums such as IETF. The most relevant works on the inter-domain routing can be represented with the references [DdOV07], [FVA06]. From the point of view of the algorithms, the computation of QoS aware inter-domain routes in a given network architecture needs a distributed algorithm that enables to solve a basic NP-difficult optimization problem: the multi-constrained routing. We propose the adaptation of exact multi-constrained route computations as it is in [KM02]to our network context, and also some approximated heuristic solutions.

3.3 Resource allocation in wireless networks

Keywords: network resource allocation, opportunistic scheduling, multipath fading, cross layer design, QoS, QoE, multi-objective optimization.

In contrast with wired communications, wireless transmissions are subject to many channel impairments such as path loss, shadowing and multipath fading [Pro95] and [Gol05]. These phenomena severely affect the transmission capabilities and in turn the system transmission capacity and the QoS. The past decades have witnessed intense research efforts on wireless digital communications in order to provide optimal resource allocation algorithms or heuristics able to bring together high system throughput, high mobile user satisfaction and, when possible, low energy consumption. Several scheduling schemes are proposed and evaluated in the literature. The references [KH95] and [WC99] can be acknowledged as the most relevant works.

Contrary to conventional access methods like Round Robin (RR) and Random Access (RA), primarily designed for the wired local area network context, opportunistic scheduling techniques that take advantage of multi-user diversity are well adapted to the wireless envi-

[DdOV07] S. Dasgupta, J. de Oliveira, J.-P. Vasseur, "Path-Computation-Element-Based Architecture for Interdomain MPLS/GMPLS Traffic Engineering: Overview and Performance", *IEEE Network 21*, 4, Jul.-Aug. 2007, p. 38 – 45.

[FVA06] A. Farrel, J.-P. Vasseur, J. Ash, "A Path Computation Element (PCE)-Based Architecture, Request for Comments: RFC4655", August 2006, RFC 4655.

[KM02] F. A. Kuipers, P. V. Mieghem, "MAMCRA: a constrained-based multicast routing algorithm", *Computer Communications 25*, 8, 2002, p. 802 – 811.

[Pro95] J. G. Proakis, *Digital Communications*, 3rd ed. New York: McGraw-Hill, 1995.

[Gol05] A. Goldsmith, *Wireless Communications*, Cambridge University Press, 2005.

[KH95] R. Knopp, P. Humblet, "Information capacity and power control in single-cell multiuser communications", *in : 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 in Communications 17*, 10, 1999.

ronment and provide high throughput. Indeed, resources are preferably allocated to active mobile(s) with the most favourable channel conditions at a given time (often to the mobile with the greatest SNR). Dynamically adapting the channel modulation and coding allows then to make an efficient use of the radio resource and come closer to the Shannon limit. This maximizes the system capacity from an information theory point of view. However these works fail to reach the multiple-objective goal and often propose a trade-off. In addition, they generally take questionable assumptions such as the hypothesis that the user with the most favourable transmission conditions has always data packets to transmit at a considered time instant. Moreover, they do not take into account the variability of the traffic and the queuing aspects.

Based on previous works, our research deals with these issues [13]. 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 requirement. Frequency diversity, added to time and multi-user diversity are also exploited in a cross layer design and allow to significantly improve opportunistic scheduling approach.

3.4 Resource allocation in optical networks

Keywords: routing and wavelength assignment problem, wavelength allocation, traffic aggregation, all-optical networks, optical constraints.

In order to support traffic growth, optical networks have already evolved towards wavelength routed networks. It is well known that an efficient allocation of networks resource (i.e. wavelength) is determined by the resource granularity. However, in a wavelength routed network, the minimum granularity of an optical connection is the capacity of a wavelength. With capacity growing up to 100 Gbit/s per wavelength, this granularity is becoming larger than common traffic flows generated by users. Thus the requirement for traffic aggregation into the wavelength channels is expected to grow. Today, this aggregation is done at the end points thanks to electrical switching. But with traffic increase, the use of electrical switching generates an important growth in power consumption and network cost. Thus, network operators aim to find solutions that offer such functionality with reduced impact on power consumption and cost. These solutions should switch in the optical layer which may indeed provide cost and power reductions thanks to the corresponding savings in optical-electrical conversions.

In this context, optical multi-band OFDM (orthogonal frequency division multiplexing) technology is a very interesting candidate for future optical networks [Shi11]. Optical multi-band OFDM can handle ultra high bitrates (100 Gbit/s and more). Multi-band OFDM could benefit from an access to finer granularity than the aggregated 100 Gbit/s data rate while remaining in the optical domain. Indeed, using adequate add and drop sub-band functions in optical nodes, optical multi-band OFDM offers all optical switching and aggregation flexibility at granularities finer than the original 100 Gbit/s data stream. OFDM technology appears to be a particularly well adapted technology to sub-band generation thanks to a low modulation rate per sub-carrier leading to very square sub-band spectrum. We have introduced this concept in [**?**]. Moreover

[Shi11] W. Shieh, "OFDM for Flexible High-Speed Optical Networks", *Journal of Lightwave Technology 29*, 10, 2011, p. 1560 – 1577.

one specificity of OFDM modulation is its adaptability to the physical transmission condition. Let us recall that the sub-band optical reach depends on the bit rate carried by this sub-band. A service with a given data rate having to be delivered at a certain distance exceeding the maximum reach of the sub-bands, can be split between two or more sub-bands with reduced bit-rate. This is an alternative solution to regeneration. Reversely, service to be delivered at a very short reach can benefit from the highest bit rate of the sub-band. Reversely, service to be delivered at a very short reach can benefit from the highest bit rate of the sub-band. For instance, we study the performance of this multi-band OFDM concept in terms of used resources and blocking probability compared to legacy scenario based on mono-band opaque or mono-band transparent techniques.

3.5 Energy Optimization

Keywords: energy efficiency, transmit power, home networks, wireless networks, resource allocation.

Taking into account the energy efficiency when optimizing network design is a challenging task. Particularly, legacy network algorithms need to be tuned in order to attain a trade-off between the inevitable user requirement for quality of service and the network operator requirement for network resource minimization (specifically in total energy consumption). Taking for example the radio resource allocation in a wireless network, new algorithms should adapt the user association to the base station and the transmit power of the base stations in order to achieve energy efficiency. The same goes for home networks, where the scheduled downtime of each device should be astutely configured in order to minimize the energy consumption, while keeping satisfying service availability. In both study cases, the optimization comes from a first step that consists of devising realistic energy consumption models for the network devices. For instance, the Earth project introduced an energy consumption model for base stations that linearly scales with their transmit power. The second step consists in formulating and solving a multi-objective problem that balances the total energy consumption in the network devices with the quality of service metrics, such as the user throughput, delay, or the service availability.

4 Application Domains

4.1 New Generation Internet

The application domains of our scientific contributions are mainly related to communication networks. These networks use various types of infrastructure:

- Wireless network infrastructure: our studies focus on wireless cellular communications but also cover ad-hoc and sensor networks. For instance we study WiFi, LTE, and 5G green wireless mobile network.
- Wired network infrastructure: our studies focus on optical networks with automatic control planes (based for instance on G/MPLS).

ATNET team provides adapted solutions that inherit from the particularities of each infrastructure. Solutions for wireless networks take into account the scarcity of the radio resource, the transmission interference, and the access mechanisms (such as OFDMA). Solutions for wired networks take into account the survivability constraints and the optical impairments.

The direct beneficiaries of our work are the telecommunication companies because most of our algorithms or protocols fit into network equipments, and ease the network management. For instance:

- Internet service providers,
- Added value service providers,
- Network operators,
- Network equipment manufacturers.

4.2 Services on Communications Networks

When applicable, our contributions consist of proposing novel architectures for communications networks including protocols and algorithms. This eases the deployment of added value services at lower cost, for instance:

- Home Networking,
- IPTV with IMS,
- Digital TV broadcasting,
- Video streaming,
- Cloud Networks,
- Software-Defined Networking,
- Automatic VPN interconnection.

5 Software

5.1 Network Softwares

Participants: Bernard Cousin [contact point].

The main objective of the AtNet team is to develop network algorithms and protocols which fit as driver software into network equipments. To produce performance evaluation results, these algorithms and protocols are generally implemented into a network simulator (e.g. NS-2, Opnet, etc). They are discrete event network simulators. They support popular network protocols, offering simulation results for wired and wireless networks alike. NS is popular in networking research given its open source model and online documentation.

Websites have been built to provide an online access to our network Softwares:

- On Internet DNSSEC (cf. http://www.idsa.prd.fr/index.php?lang=en)
  - KROd is a program that performs automatic DNSSEC key rollover and automatic conversion from DNS to DNSSEC.
  - A patch of BIND which modifies the behavior of the DS field. Generalized DS allows to have build a DNSSEC chain of trust over a succession of secure and insecure domains (a domain that has insecure parents).
  - libsresolv is a library built with the BIND toolkit. It comes as a patch over the BIND 9.3 sources. It contains a DNSSEC resolver and validator. The goal is to show anything that can be proved from a DNSSEC answer. The validator proves positive and negative answers (it can prove that a domain doesn't exist), it can also prove that some domain are empty non-terminal ones. libsresolv performs bottom-up validation, it is signature oriented.
- On Explicit Multicasting:
  - Into the NS simulator, we have included the Xcast protocol according to the Explicit Multicast (Xcast) concepts. (http://boudania.free.fr/research/xcast/index.htm)
  - Simple Explicit Multicast (SEM) uses an efficient method to construct multicast trees and deliver multicast packets. SEM is original because it adopts the source-specific channel address allocation, reduces forwarding states in non branching node routers and implements data distribution using unicast trees. (http://boudania.free.fr/research/sem/index.htm)
  - Generalized Explicit Multicast (GXcast) is a generalized version of the Xcast protocol. It permits Xcast packet fragmentation and support an increasing number of members in a multicast group. (http://boudania.free.fr/research/xcast/gxcast/index.htm)
- On Multicasting in MPLS Networks:
  - The MPLS Multicast Tree (MMT and it's extension MMT2) is a new approach to construct multicast trees in MPLS networks. This approach utilizes MPLS LSPs between multicast tree branching node routers in order to reduce forwarding states and enhance scalability. In our approach only routers that are acting as multicast tree branching node for a group need to keep forwarding state for that group. All other non-branching node routers simply forward data packets over traffic engineered unicast routes using MPLS LSPs. (http://boudania.free.fr/research/mmt/index.htm)
- On Optical Networks:
  - In our study OMNeT++ is used to design and simulate multi-band optical networks. OMNeT++ is an object-oriented modular discrete event network simulation framework. It has a generic architecture, so it can be (and has been) used in various problem domains: modeling of wired and wireless communication networks, protocol modeling, modeling of queuing networks, modeling of multiprocessors and

other distributed hardware systems validating of hardware architectures. In general, modeling and simulation of any system where the discrete event approach is suitable, and can be conveniently mapped into entities communicating by exchanging messages.

- We developed a simulator for node and link protection using p-cycles for dynamic multicast traffic in optical DWDM networks. This simulator is implemented in MATLAB.

- On Network Monitoring:

  - This simulator is written in C++ under Linux. it uses the ILP solver CPLEX for solving integer linear programs, and the topology generator BRITE for generating random test topologies. It ensures the following features: (i) Given an input network topology, it computes an optimal set of monitor locations and an optimal set of detection paths that can detect all potential link-level anomalies, while minimizing the inherent costs jointly. (ii) Given an input network topology, it computes an optimal set of monitor locations and an optimal set of localization paths that can pinpoint unambiguously the localization of all potential link-level anomalies, while minimizing the inherent costs jointly. (iii) Given an input network topology, it assesses the cost and the speed of continuous anomaly localization (detection and localization procedures are ran simultaneously), and the cost and the speed of reactive anomaly localization (the localization procedure is run only upon detecting an anomaly). On the light of this comparative assessment of the two localization approaches, it suggests a localization configuration (localization approach and monitoring frequency) that offers a good balance between cost and speed for the input topology.

    Note that the simulator computes optimal solutions, when the exact solutions (ILP based solutions) are used. However, exact solutions are not scalable. Thus, heuristic solutions are used for large topologies.

- On Resource Allocation in Wireless Networks:

  - The object-oriented programming capabilities of the Matlab language enable us to develop our discrete event simulator for network selection in heterogeneous environments:. The goal is to elaborate an optimized simulation environment where session arrivals, network selection algorithms, traffic generation, and session departures are implemented. Our simulator is used to evaluate the performance of the different network selection methods, and to compare them to our proposed solution.
  - The OPNET simulation platform has been used in order to design and evaluate the performances of our proposals relating to new opportunistic schedulers. They allow maximizing global system throughput while ensuring fairness without any trade-off. In these works, we have had implemented realistic channel model and traffic sources.

- On Home Power Efficiency for a Green Network:

– This Home Network demonstrator aims at reducing power consumption at both the device and network level. At the device level, the system can turn the devices off when they are not in operation and quickly turn them on when they are predicted to be needed. At the network level, the solution is based on a new convergence layer denoted inter-MAC, which provides a common infrastructure to the different home network paths. HOme Power Efficiency (HOPE) experimental platform reproduces a home wireless network. During its process, energy control messages are sent on a low-power consumption network like ZigBee or by using a low-power consumption protocol like UPnP Low Power. The demonstration shows that the platform can drastically reduce the consumption of home networks. Users can benefit from enriched home multimedia services and efficiently manage their power consumption. This demonstrator has been exhibited at Infocom ([23]).

6 New Results

6.1 Multiconstrained QoS Routing

Participants: Ahmed Frikha, Bernard Cousin, Samer Lahoud.

Keywords: Networking, Routing, Multicast Routing, QoS Routing, Multi-constrained Routing.

Quality of Service (QoS) routing known as multiconstrained routing is of crucial importance for the emerging network applications and has been attracting many research works. In our previous works, we have studied the multicast QoS routing problem for providing multicast routes to enable the communications between a source node and multiple destination nodes. In our new results, we continue to explore a facet of the QoS Routing problem.We study unicast routing that is an NP-hard problem and our goal is to compute paths that satisfy the QoS requirements based on multiple constraints such as the delay, the bandwidth or the jitter. The computation problem becomes more challenging and necessitates special attention when the network is made of several network operator domains where autonomy and confidentiality of network operators should be preserved.

Multiconstrained QoS Routing in Multi-domain Networks Inter-domain quality of service (QoS) routing is a challenging problem for today's Internet. This problem requires the computation of paths that cross multiple domains and meet different QoS constraints. In addition, the used computation methods must meet the constraints of confidentiality and autonomy imposed by the domains of different operators. Path computation element (PCE)-based architecture offers a promising solution for inter-domain QoS routing. It ensures the computation of end-to-end QoS paths while preserving the confidentiality and the autonomy of the domains. In our work ([3]), we propose a novel hybrid end-to-end QoS path computation algorithm, named HID-MCP, for PCE-based networks. HID-MCP is a hybrid algorithm that combines the advantages of pre-computation and on-demand computation to obtain end-to-end QoS paths. Moreover, it integrates a crankback mechanism for improving path computation

results in a single domain or in multiple domains based on the PCE architecture. Detailed analyses are provided to assess the performance of our algorithm in terms of success rate and computational complexity. The simulation results show that our algorithm has an acceptance rate of the requests very close to the optimal solution; precisely, the difference is lower than 1 % in a realistic network. Moreover, HID-MCP has a low computational complexity. Besides, our solution relies on the PCE architecture to overcome the limitations related to inter-domain routing such as domain autonomy and confidentiality.

6.2 Wireless Coverage Extension

Participants: Cédric Guéguen.

Keywords: Wireless Network, Coverage Extension, Incentive Scheduling, Cooperation, Quality of Service, Multipath Fading.

The basic purpose of the extension of coverage area in wireless networks is to increase the network connectivity without increasing the infrastructure. This is one of the main applications of cooperative communications in wireless networks. The coverage extension issue requires the cooperation of border mobile nodes to relay the packets of neighbouring nodes that are located outside the base station area. For instance, the nodes located at two hops from the Access Point (AP) can access the services offered by the AP through a gateway node which could give access to the Internet. Many researchers worked on strategies to find the optimal placement for the gateway nodes in order to guarantee a high Quality of Services (QoS) [SHRL10]. Other works dealt with the optimal number of hops between relay nodes in wireless networks [FY05][SLH+06]. However, they assume that the relay nodes by definition are fixed and cooperative, which is not true in the case of a dynamic wireless network where the nodes freely move and may be selfish.

Incentive Scheduler Algorithm for Cooperation and Coverage Extension in Wireless Networks In the paper [4], we focused on the wireless coverage extension and node cooperation. We proposed a new protocol based on an incentive approach and a scheduling algorithm in order to reward cooperative nodes. Indeed, the cost of cooperation can be prohibitively expensive in terms of QoS and energy consumption which does not motivate some nodes to cooperate. Therefore, we introduce a percentage of cooperation and QoS parameters in the scheduling algorithm, called CEI, in order to incite potential mobile relaying nodes to cooperate and in turn extend the wireless areas. We use the cross-layer approach in order to

[SHRL10] A. K. Sadek, Z. Han, K. Ray Liu, "Distributed Relay-Assignment Protocols for Coverage Expansion in Cooperative Wireless Networks", *IEEE Transactions on Mobile Computing 9*, 4, 2010, p. 505 – 515.

[FY05] A. Florea, H. Yanikomeroglu, "The Optimal number of hops in infrastructure-based fixed relay networks", *in : IEEE Globecom*, p. 3242 – 3247, St. Louis, MO, November 2005.

[SLH+06] M. Sikora, J. N. Laneman, M. Haenggi, D. Costello, T. Fuja, "Bandwidth and Power-efficient routing in linear wireless networks", *IEEE Transactions Inf. Theory 52*, 6, 2006, p. 624 – 2633.

optimize the QoS parameters. The proposed solution does not only incite the nodes to cooperate but also enhance the QoS by increasing the average throughput and decreasing the delay. The results show that the proposed solution does not only enhance the global performances of famous scheduling algorithms like MaxSNR and WFO but also allows the cooperative mobile nodes to increase their own throughput by around 114%. The total amount of data transmitted out of the cell in order to extend the coverage can be increased by around 59% compared to the scheduling algorithm MaxSNR. In our work, we proposed a new cooperative protocol based on an incentive approach that takes into account the QoS for mobile relaying nodes in order to extend the coverage area. This approach consists of increasing the priorities of the relaying nodes according to their cooperation rate. The idea is to reward the relaying nodes for their cooperation instead of penalizing the node which do not cooperate. Consequently, the nodes have no interest in selecting and acting selfishly, by using their throughput only to transmit their own packets. Moreover, our protocol guarantees that the nodes are free to cooperate, because they choose their percentage of cooperation. The proposed solution combines the QoS parameters and cooperation rate using a cross-layer approach with a scheduling algorithm. This solution is called *Coverage Extension based on Incentive scheduling (CEI)*. Moreover, the physical layer information is used in order to take advantage of the time, frequency and multiuser diversity and to optimize the system capacity until it is close to the Shannon limit. Unlike some existing models, our solution can be widely implemented.

6.3 Radio Access Selection in Heterogenous Wireless Networks

Participants: Melhem El Helou, Samer Lahoud, Mohamad Yassin.

Keywords: Wireless Network, Energy Saving, Green Networking, Radio Resource Management, Radio Access Selection, Game Theory.

In wireless heterogeneous networks, one of the most challenging problems is Radio Access Technology (RAT) selection that must be designed to avoid resource wastage.

Radio Access Technology Selection with Joined User-centric and Network-centric Policy Along with the rapid growth of mobile broadband traffic, multiple RATs are being integrated and jointly managed. To optimize heterogeneous network performance, efficient Common Radio Resource Management (CRRM) mechanisms need to be defined. In [6], we tackle the access technology selection, a key CRRM functionality, and propose a hybrid approach that combines benefits from both network-centric and user-centric methods. Network information, that is periodically broadcasted, assists mobile users in their decisions. By broadcasting appropriate decisional information, the network tries to globally control users decision in a way to meet operator objectives. In [7], we investigate different tuning policies, namely the staircase and the slope tuning policies, to dynamically modulate this information. Moreover, mobiles should also integrate their needs and preferences to select their access technology so as to maximize their own utility. In [9], we present a satisfaction-based multi-criteria decision-making method. In comparison with other RAT selection techniques, including network-centric, hybrid and user-centric methods, simulation results prove the efficiency of our hybrid approach in enhancing resource utilization and maximizing user satisfaction.

Dynamic Behavior of Radio Access Technology Selection The dynamic behavior of the RAT selection problem is investigated in [14]. In the latter work, we propose a new hybrid approach that combines a distributed approach with periodic centralized interventions. In the hybrid approach, user inbound sessions perform a distributed network selection while the system regularly intervenes to change client associations and/or to modulate the distributed algorithm in order to guarantee an acceptable level of performance. The results show that the hybrid approach performance is close to that of the optimal solution, and is better than that of the distributed approach in specific scenarios. Moreover, the hybrid approach reduces the overall signaling load for the system by decreasing the number of required handovers.

User Association to Radio Access Points Based on Game Theory Taking the special case of Wireless LANs, we present in [10] a decentralized algorithm, based on non-cooperative game theory, that associates users with access points. We prove that the model at hand is an ordinal potential game, known to have at least one Pure Nash Equilibrium (PNE). Furthermore, we prove that an algorithm based on replicator dynamics converges to the PNEs of our game. Finally, to quantify the efficiency loss of the distributed game approach, known as the price of anarchy, we compare its performance against a centralized approach where resource allocation is made in a way that satisfies all mobile users. It turns out that even though the distributed game results are sub-optimal, the acceptable discrepancy between the two sets of results and the inherent adaptability of the decentralized approach makes it really promising.

6.4 Power Consumption in Wireless LANs

Participants: Farah Moety, Samer Lahoud, Bernard Cousin, Cédric Guéguen.

Keywords: Wireless Local Area Network, Energy Saving, Green Networking.

In the last decade, many research efforts have been done in order to increase the spectral efficiency of wireless communications. In this domain, we propose, first, a study the trade-off between throughput and energy in Wireless Local Area Networks, second, an opportunistic scheduler for wireless networks which is energy-aware.

Energy and Delay Trade-off in Wireless Networks The growing energy demands, the increasing depletion of traditional energy resources, together coupled with the recent explosion of mobile internet traffic call for green solutions to address the challenges in energy efficient wireless access networks. We consider possible power saving through reducing the number of active Base Stations (BS) and adjusting the transmit power of those that remain active while maintaining a satisfying service for all users in the network. Thus, we introduce in [11] an optimization problem that jointly minimizes the power consumption of the network and the sum of the transmission delays of the users in the network. Our formulation allows investigating the trade-off between power and delay by tuning the weighting factors associated to each one. Moreover, to reduce the computational complexity of the optimal solution of our non-linear optimization problem, we convert it in [12] into a Mixed Integer Linear Programming (MILP). We provide extensive simulations for various decision preferences such as power minimization,

delay minimization and joint minimization of power and delay. Presented results show that we obtain power savings up to 20% compared to legacy network models.

Opportunistic Energy Aware Scheduler for Wireless Networks In the last decade, many research efforts have been done in order to increase the spectral efficiency of wireless communications. From now on, opportunistic resource allocations have emerged as the best way to reach this objective. They take into consideration the radio conditions in the allocation process. This allows to guarantee high system throughput and high Quality of Service. However, today, it is not sufficient anymore. Many climate problems have been underlined by the majority of world scientists and decreasing world greenhouse gas emission has become a necessity for the world environment preservation. This requires to also reduce energy consumption in as much sectors as possible including wireless communication networks. The paper [8] proposes to extend the opportunistic approach with the proposition of a new scheduling solution enables to significantly decrease the system energy consumption. It proposes to radically change the classical opportunistic radio resource mapping. Built in an extended cross layer approach, its main principle is to minimize energy consumption exploiting active-sleep mode and channel condition together. At each scheduling event, the OEA solution determines the best transmission opportunities and finds the most profitable resource mapping in terms of number of transmitted bits per Watt. Maximizing the sleeping-time duration while taking into account the channel conditions in the allocation process, OEA allows to make a better usage of radio resources than previous scheme, reaching high spectral efficiency and greatly reducing energy consumption. Performance evaluations show that the global energy consumption can be divided by 2 compared to existing schedulers without jeopardizing system efficiency.

6.5 Energy Management in Home Networks

Participants: Yan Han, Cédric Guéguen, Bernard Cousin.

Keywords: Energy Saving, Green Networking, Home Network, Overlay Control Network, ZigBee.

Today, reducing global greenhouse gas emissions has become a crucial issue for protecting the earth environment. This requires the reduction of energy consumption in as many sectors as possible, including home networks. Home network represents an increasingly large portion of a household's electrical consumption due to the increasing number of digital home devices and the increasing complexity of the underlying communication infrastructure. Limiting a home network's power consumption is a priority for institutions and consumers. We proposed solutions that aims at reducing power consumption at both the device and network level. At the device level, control system can turn the devices off or on according to their usage. At the network level, the solution is based on a inter-MAC layer to choose a greener path. In [5], we proposed an Overlay Energy Control Network (OECN) which can efficiently control devices.

HOPE: HOme Power Efficiency System for a Green Network A home network represents an increasingly large portion of a household electrical consumption due to the increasing

number of digital home devices and the increasing complexity of the underlying communication infrastructure. Limiting power consumption of a home networks is a priority as witnessed by evolving regulation, and a priority for individual consumers wishing to reduce their electric bills. In the paper [13], we proposed a solution that aims at reducing power consumption at both the device and network level. At the device level, our system can turn the devices off when they are not in operation and quickly turn them on when they are needed. At the network level, the solution is based on a new convergence layer denoted inter-MAC, which provides a common overlay infrastructure for the control of the different home network devices. In particular, the inter-MAC can be used to choose a greener path. Our solution on both levels is compatible and complementary to home network energy saving.

6.6 Assessment of Achievements

The results achieved by Atnet team must be compared with the key issues presented in the objective part. Not all key issues have deserved complete attention yet. However, in the past years, most of them have been sufficiently well explored to start and draw relevant conclusions.

We have gained experience in network resource allocation, energy saving in WLANs and home networks, management in optical networks. Nevertheless, there is plenty of left points to be studied. Most of our future researches will deal with the combination of several of the issues cited in the overall objectives section: advanced network management, optimization of network resource scheduling, routing, etc.

In 2013, Atnet team counted three permanent members (one professor and two associate professors), and eight PhD students. During 2013 year, Atnet team members have published 12 scientific papers (2 in international journals, 9 in international conferences with a selection committee and 1 book chapter), and 3 patents. Two Atnet members (E. Salhi, S. Blouza) have successfully defended their doctoral thesis PhD in 2013.

7 Contracts and Grants with Industry

7.1 Grants with Industry

In 2013, some of our team members are supported by the following grants :

- Cifre Grant on green management of home networks using low power wireless network. Our first studies have been patented ([15], [16], [17]). With Orange Labs.
- Cifre Grant on smart management of flexible optical networks. With B-Com.
- Cifre Grant on optimization of Internet transport protocols for real time data content broadcasting systems. With Orange Labs.

8 Other Grants and Activities

8.1 International Collaborations

We are collaborating with standardization bodies and collaborative forums on the ICT domain, for instance IETF for Internet (DNSSEC WG, MPLS WG, XCAST WG, etc.) or with IEEE on wireless network protocols. In 2013, we have participated in IEEE P1903 Next-Generation Service Overlay Network (NGSON) working group. We are member of the Traffic Management (TM) forum.

The IEEE NGSON working group scopes are as follows: To specify protocols among NGSON functional entities (FEs) to support advanced content delivery capability in next generation service overlay networks. The content delivery capability aims to support content discovery, content cache and storage management, content delivery control, and transport Quality of Service (QoS) control including context-aware and dynamically adaptive content delivery operations. To specifiy protocols among NGSON functional entities to support service composition capabilities in next generation service overlay network. The capabilities of service composition aim to support service chaining and instantiation, specification interpretation, service brokering and execution, and context-aware and dynamically adaptive service composition. To specify protocols between NGSON FEs to enable self-organizing management capability. This capability includes activation and deactivation of an NGSON node and addition, deletion, movement and copy of an NGSON function entity from or to NGSON node. This standard also specifies protocols among Service Routing FEs to enable re-organization of overlay structure among multiple SR FEs for recovery from a failed or overloaded SR FE or for performance improvement of service routing.

TM Forum is a global trade association trusted by the world's largest enterprises, service providers and suppliers to help them continuously transform to succeed in the digital economy. It bring together professionals from member companies to share experiences, collaborate and rapidly solve critical business challenges including IT transformation, business process optimization, big data analytics, cloud management, customer experience management and cyber security.

We have very good and long-lasting ties with some international universities, namely Tunisia (Sfax or Manouba University), Lebanon (Lebanese University, Saint Joseph University, Antonine University), Ivory Coast (Cocody University and INPHB) and Algeria (Mascara university).

Two of these international cooperations are supported by formal agreements where AtNet members are the collaboration leaders :

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

Numerous personnel exchanges have been generated by these international collaborations. Through them we have enhanced the scientific expertise of team members and produced several scientific papers these last years. The main activities developed in our collaborative projects concerned routing and management of networks: uncertainty of routing in dynamic

networks, energy conservation in wireless network, multicast routing with QoS, multipath in adhoc networks and multicast connection reconfiguration. In 2013, several mobility grants from University of Rennes 1, Rennes Metropole, french MENRT, Agence universitaire de la Francophonie (AUF), Tunisian department of education, Algerian department of education, Lebanese CNRS, and St Joseph university have supported our research collaborations.

- Melhem El Helou (Ph.D. grant from Saint Joseph University) received a mobility grant from AUF (bureau du Moyen-orient) to travel to Rennes and work with Atnet for two months starting from September 2013. Mr. El Helou works on a Hybrid Approach for Radio Access Technology Selection in Heterogeneous Wireless Networks.
- Maaloul Rihad got a tunisian mobility grant to visit and work with us at Irisa (June - July 2013) on control protocols for energy saving in metro-Ethernet networks.
- Amal Boumedjou, mobility grant from Oran (Algeria), has worked with us at Irisa (March 2013). She is working on routing optimization in Manet networks using a cross layer approach.
- Hela Mliki has got a tunisian mobility grant to visit and work with us at Irisa (September 2013), on Ethernet congestion control for multicast traffic in data centers.
- Several professors (Assohoun Adje, Vincent Monsan, Toussaint Sohou) benefited of a mobility grant from University Houphouet-Boigny (ex Cocody University) from Ivoiry Coast have visited us in December 2013 to developed academic cooperation.
- Omar Smail has got a mobility grant from Mascara University (Algeria) where he is currently assistant professor. He has been invited at Rennes in April 2013. It has worked with us on multipath routing in ad hoc wireless networks with the goals to reduce energy consumption (and thus to enhance network lifetime) and to improve network QoS.
- Mohamad Yassin (University Saint Joseph) was accepted on September 2012 for a Ph.D. grant from CNRS Lebanon and started working on a Ph.D. thesis with AtNet. He has received a modility grant from Rennes Metropole for a 6 months stay in France since December 2013.

8.2 National Collaborations

We have leaded or participated to several national projects with academic and industrial partners, within the different ANR (French National Science Foundation) collaborative programs. We have also a long term partnership with industrial partners such as Orange R&D, and Alcatel-Lucent/Bell Labs. Moreover, we very actively collaborate with major research institutions into the Brittany region:

- B-com is a new Technological Research Institute dedicated to boost development and marketing of tools, products and services that improve everyday's life, thanks to research and innovation in digital technologies. In concrete terms, B-com innovates at the highest level in the areas of hypermedia (ultra high definition images, 3D, intelligent content,

virtual and augmented reality, etc.), smarter and faster networks and e-health. Since 2013, several members of Atnet team are involved in B-com activities in the network area. AtNet is supported by B-com.

- Brittany is the main region in France in the field of networking. Our research team has established collaboration with various research institutions including Telecom Bretagne in Brest and Rennes.

- Most of our research projects have been labeled by the Images et Network cluster. It gathers key players in the information, telecommunications and multimedia fields. It is mainly located in Brittany and Pays de la Loire regions. Together, we are working on the future uses of the internet, television, and mobility.

9 Dissemination

9.1 Involvement in the Scientific Community

In 2013, Bernard Cousin has served as chair in the Technical Program Committee of:

- 17th International Conference on Optical Networking Design and Modeling (ONDM 2013). It held at Brest, in France, on April 15-18, 2013.

In 2013, Bernard Cousin has served as member in the Technical Program Committees of the following conferences:

- 4th International Conference on Ambient Systems, Networks and Technologies (ANT-2013) held on June 25-28, 2013, at Halifax, Nova Scotia, in Canada.

- 14th IEEE International Conference on High Performance Switching and Routing (HPSR 2013) held on July 8-11, 2013 in Taipei, Taiwan.

- International Conference on Connected Vehicles and Expo (ICCVE 2013) held on 2-6 December, 2013, in Las Vegas in USA.

- International Conference on Information and Intelligent System (ICIIS' 2013) held on March 24-26, 2013, at Sousse, in Tunisia.

- 4th International Conference on Photonics (ICP2013) held on 28-30 Oct, 2013 at Melaka, in Malaysia.

- International Conference on Networking and Grid Cloud Computing (ICNGCC'2013) held within World Congress on Computer and Information Technology (WCCIT) on June 22-24, 2013, at Sousse, in Tunisia.

- International Conference on Information Systems Applications (ICISA'2013) held within World Congress on Multimedia and Computer Science (WCMCS'2013) on 4-6 October, 2013 at Hammamet, in Tunisia.

- 2013 World Conference on Information Systems and Technologies (WorldCIST'13) held on 27-30 March, 2013, in Algarve, Portugal.
- 8ème conférence sur la Sécurité des Applications et des Réseaux et Sécurité des Systèmes d'Informations (SAR-SSI) held on Septembre 2013 at Mont de Marsan in France.

In 2013, Cédric Guéguen has served as session chair in:

- 77th International Conference on Vehicular Technology Conference (VTC), session "QoS and Fairness". It held at Dresden, in Germany, on June 2-5, 2013.

In 2013, Bernard Cousin was member of the Editorial Boards of:

- International Journal of Computing and Digital Systems (IJCDS).
- International Journal of Communication Networks and Information Security (IJCNIS)
- International Journal of Networks and Communications (IJNC)

In 2013 Bernard Cousin participated in Reviewing Committee of:

- Nature and Technology journal

In 2013, Samer Lahoud has served as a member of the PhD committee of Emna Salhi. The thesis title is "Detection and localization of link-level network anomalies using end-to-end path monitoring".

In 2013, Bernard Cousin has been director of the PhD and member in the following PhD committees :

- Emna Salhi, "Detection and localization of link-level network anomalies using end-to-end path monitoring" [2], PhD from University of Rennes 1, 13 February 2013.
- Sofiene Blouza, "Etude des potentialités offertes par les technologies de transmission optiques flexibles pour les rséaux métro ou coeur" [1], PhD from University of Rennes 1, 16 May 2013.

In 2013, Bernard Cousin has been reviewer in the following PhD committees:

- Ahmed Amamou, "Isolation réseau dans un datacenter virtualisé", PhD from Paris 6 University, 26 September 2013.
- Juliette Dromar, "Vers une solution de contrôle d'admission sécurisée dans les réseaux mesh sans fil", PhD from Technology University of Troyes, 6 December 2013.

In 2013, Bernard Cousin has been member in the following PhD committee:

- Lida Sadeghioon, "Contribution to the design of optical packet based metropolitan area networks", PhD from University of Bretagne-Sud, 23 October 2013.

Bernard Cousin, in 2013, serves as expert:

- in 2013 ANR Cifre program.

9.2 Teaching

Permanent members of AtNet teams are Professors or Associate Professors at University of Rennes 1. They have important administrative responsibilities and teaching activities in University of Rennes 1.

- Bernard Cousin teaches high speed networking, network security, network survivability, and multicasting at the Master level in the Computer Science department of University of Rennes 1. He gives an introduction to networking at the Licence level in the Computer Science department. He also teaches computer networks at the Engineering department of University of Rennes 1.
- Samer Lahoud teaches courses on IP networks, MPLS networks, and network administration at IUT of Saint-Malo. He is an invited expert at Telecom ParisTech for training sessions for professionals on new technologies in IP networks, with emphasis IP quality of service.
- Cédric Guéguen teaches on queuing theory and sensor network at the Superior Engineering Department of Rennes (ESIR). He also teaches about networks at Licence level and Master level of the University of Rennes 1.
- Cédric Guéguen is in charge of the Master of Network Engineering since September 2012.
- In 2013, Bernard Cousin is an elected member of the administrative board ("Conseil d'administration") of the Engineering department (ESIR) at University of Rennes 1.
- In 2013, Bernard Cousin is an elected member of the scientific board ("Conseil scientifique") of the Engineering department (ESIR) at University of Rennes 1.
- In 2013, Bernard Cousin is in charge of the International Affairs of the Engineering department (ESIR) at University of Rennes 1.

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