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Giorgio Quer, Ramesh R. Rao

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7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
University of California - San Diego
9500 Gilman Drive
Mailcode 0934
La Jolla, CA 92093 -0934

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14. ABSTRACT
In the ARO "Cognitive Protocol Stack Design" project we proposed cognitive networking solutions published in international journals and peer-reviewed conferences. We started by focusing on the three main objectives of the proposal, and we extended our work also to other areas related to cognitive networking, opening also new lines of research that was not possible to forecast at the beginning of the project.
In a nutshell, we proposed both theoretical and practical solutions to the problems of: optimal inter-network

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Report Title

Final Report: Cognitive Protocol Stack Design

ABSTRACT

In the ARO “Cognitive Protocol Stack Design" project we proposed cognitive networking solutions published in international journals and peer-reviewed conferences. We started by focusing on the three main objectives of the proposal, and we extended our work also to other areas related to cognitive networking, opening also new lines of research that was not possible to forecast at the beginning of the project. In a nutshell, we proposed both theoretical and practical solutions to the problems of: optimal inter-network cooperation, cooperative opportunistic routing, spectrum sharing in multi-operator networks, sensing and characterizing the traffic in a multi-channel wireless network, interference management in retransmission-based wireless networks, physical-cyber world interactions during unexpected events, random access protocols for multi channel cognitive wireless networks, Call Admission Control scheme for VoIP over IEEE 802.11 and other networks, network-aware retransmission strategy selection, the exploitation of the Android operating system for the design of a wireless mesh network testbed, the design transmission strategies in a cognitive radio system with primary automatic repeat request, and a machine learning based approach to ensure quality of experience.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
08/31/2012	1.00	Marco Levorato, Urbashi Mitra, Michele Zorzi. Cognitive Interference Management inRetransmission-Based Wireless Networks, IEEE Transactions on Information Theory, (05 2012): 3023. doi:
08/31/2012	6.00	Luca Anchora, Marco Mezzavilla, Leonardo Badia, Michele Zorzi. A performance evaluation tool for spectrum sharing in multi-operator LTE networks, Elsevier Computer Communication, (08 2012): 0. doi:
08/31/2012	2.00	Bheemarjuna Reddy Tamma, B.S. Manoj, Ramesh R. Rao. Traffic sensing and characterization in multi-channel wireless networks for cognitive networking, Elsevier Computer Networks, (05 2012): 1968. doi:
08/31/2013	14.00	Nicolo' Michelusi, Petar Popovski, Osvaldo Simeone, Marco Levorato, Michele Zorzi. Cognitive Access Policies under a Primary ARQ Process via Forward-Backward Interference Cancellation, Journal of Selected Areas in Communications (JSAC), (11 2013): 0. doi:
08/31/2013	15.00	Giorgio Quer, Federico Librino, Luca Canzian, Leonardo Badia, Michele Zorzi. Inter-Network Cooperation Exploiting Game Theory and Bayesian Networks, IEEE Transactions on Communications, (11 2013): 0. doi:
09/26/2014	21.00	Jalil Seifali Harsini, Michele Zorzi. Transmission Strategy Design in Cognitive Radio Systems With Primary ARQ Control and QoS Provisioning, IEEE Transactions on Communications, (06 2014): 0. doi: 10.1109/TCOMM.2014.2317186
09/26/2014	22.00	Matteo Danieletto, Giorgio Quer, Ramesh Rao, Michele Zorzi. CARMEN: a cognitive networking testbed on android OS devices, IEEE Communications Magazine, (09 2014): 0. doi: 10.1109/MCOM.2014.6894459

TOTAL: 7

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

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Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
08/30/2013	11.00	Biljana Bojovic, Giorgio Quer, Nicola Baldo, Ramesh R. Rao. Bayesian and Neural Network Schemes for Call Admission Control in LTE Systems, IEEE GLOBECOM 2013. 09-DEC-13, . : ,
08/30/2013	12.00	Federico Librino, Giorgio Quer, Michele Zorzi. Network-Aware Retransmission Strategy Selection in Ad Hoc Wireless Networks, 5th IEEE CoCoNet Workshop at IEEE ICC 2013. 08-JUN-13, . : ,
08/30/2013	13.00	Matteo Danieletto, Giorgio Quer, Ramesh R. Rao, Michele Zorzi. On the Exploitation of the Android OS for the Design of a Wireless Mesh Network Testbed, MILCOM 2013. 17-NOV-13, . : ,
08/31/2012	3.00	B.S. Manoj,Bheemarjuna Reddy Tamma, Ramesh R. Rao. On the Impact of Physical-Cyber world Interactions during Unexpected Events, ACM International Conference on Wireless Technologies for Humantiarian Relief (ACWR). 21-DEC-11, . : ,
08/31/2012	10.00	Anders Nilsson Plymoth, Per Johansson, Rene L. Cruz, Octav Chipara, William G. Griswold. GRAPEVINE: Hybrid Cooperative Opportunistic Routing for Challenged Wireless Networks Using Fountain Coding, ACM PINGEN. 26-AUG-12, . : ,
08/31/2012	9.00	Giorgio Quer, Federico Librino, Luca Canzian, Leonardo Badia, Michele Zorzi. Using Game Theory and Bayesian Networks to Optimize Cooperation in Ad Hoc Wireless Networks, IEEE ICC. 13-JUN-12, . : ,
08/31/2012	8.00	Alfred Asterjadhi, Federico Librino, Michele Zorzi. Analysis of Random Access Protocols for Multi Channel Wireless Networks, IEEE GLOBECOM. 06-DEC-11, . : ,
08/31/2012	7.00	Giorgio Quer, Nicola Baldo, Michele Zorzi. Cognitive Call Admission Control for VoIP over IEEE 802.11 using Bayesian Networks, IEEE GLOBECOM . 06-AUG-12, . : ,
09/26/2014	16.00	Matteo Danieletto, Giorgio Quer, Ramesh R. Rao, Michele Zorzi. On the Exploitation of the Android OS for the Design of a Wireless Mesh Network Testbed, MILCOM 2013 - 2013 IEEE Military Communications Conference. 17-NOV-13, San Diego, CA, USA. : ,
09/26/2014	17.00	Biljana Bojovic, Giorgio Quer, Nicola Baldo, Ramesh R. Rao. Bayesian and neural network schemes for call admission control in LTE systems, GLOBECOM 2013 - 2013 IEEE Global Communications Conference. 08-DEC-13, Atlanta, GA, USA. : ,
09/26/2014	18.00	Roghayeh Joda, Michele Zorzi. Centralized access policy design for two cognitive secondary users under a primary ARQ process, 2014 ICC - 2014 IEEE International Conference on Communication Workshop (ICC). 09-JUN-14, Australia. : ,

09/26/2014 19.00 Alberto Testolin, Marco Zanforlin, Michele De Filippo De Grazia, Daniele Munaretto, Andrea Zanella, Marco Zorzi, Michele Zorzi. A machine learning approach to QoE-based video admission control and resource allocation in wireless systems,
2014 13th Annual Mediterranean Ad Hoc Networking Workshop (MED-HOC-NET). 01-JUN-14, Slovenia. : ,

09/26/2014 20.00 Giorgio Quer, Michele Zorzi, Marco Mezzavilla. On the effects of cognitive mobility prediction in wireless multi-hop ad hoc networks,
ICC 2014 - 2014 IEEE International Conference on Communications. 09-JUN-14, Sydney, Australia. : ,

TOTAL: **13**

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Fatemeh Arbabjolfaei	0.05	
Nafi Rashid	0.06	
FTE Equivalent:	**0.11**	
Total Number:	**2**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Giorgio Quer	0.26
Anders Nilsson Plymoth	0.07
FTE Equivalent:	**0.33**
Total Number:	**2**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Ramesh Rao	0.03	Yes
FTE Equivalent:	**0.03**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Desmond Vehar	0.01	
FTE Equivalent:	**0.01**	
Total Number:	**1**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
Michele Zorzi	0.06
FTE Equivalent:	**0.06**
Total Number:	**1**

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

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** Introduction of the project and main objectives
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The project “Cognitive Protocol Stack Design," funded by ARO, had three main research areas:
(A1) Cognitive networking and control for tactical environments with limited/imprecise information. The objective of this research was the creation of a probabilistic graphical model for a cognitive networking system that is able to give us precious information on the present and future status of the network parameters, based on their historical data. The challenging aspect was the creation of such model using imprecise and non continuous samples of the network environmental data, as this is the case in a realistic tactical environment, where network information may be limited and corrupted.
(A2) Toward a system view of cognitive opportunistic networks. The challenging problem addressed in this research was how to put together all the pieces related to the design and deployment of an opportunistic cognitive network into a coherent and fully functional system. During the project, we overviewed many techniques for cognitive tactical networks, each of them optimized to solve a specific problem, like e.g., neighbor discovery, resource allocation and optimization, or medium access control and network protocols. These techniques were not designed to work coherently in a complete system. With our research, we partially bridged this gap.
(A3) Tactical protocols/applications design for cognitive networks. This research area was strongly related to the two research efforts of above. The plan was to develop optimal techniques to separately optimize the MAC layer, i.e., inferring and optimal MAC contention window as a function of the values of other parameters; the network layer, i.e., defining an optimized ad hoc routing protocol; the transport layer, i.e., predicting congestion events, in order to avoid them and guarantee a constant communication quality lower bound in time; and the application layer, i.e., designing ad hoc techniques for applications relevant to the tactical network like e.g., call admission control for VoIP in a tactical environment. The optimization of each layer was performed in several papers by adopting the BN paradigm, and the approach was cross-layer, in the sense that while we aimed at optimizing each layer separately, we also exploited the information coming from different layers of the protocol stack.

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** Short summary of the achieved goals
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In the ARO “Cognitive Protocol Stack Design" project we proposed cognitive networking solutions published in international journals and peer-reviewed conferences. We started by focusing on the three main objectives of the proposal, (A1), (A2), and (A3), and we extended our work also to other areas related to cognitive networking, opening also new lines of research that was not possible to forecast at the beginning of the project.
In brief, the main research contributions of this project can be summarized in the following points:
(i) We proposed a novel technique that simultaneously uses Game Theory and Bayesian Networks in order to optimize cooperation, in terms of relay sharing, between two ad-hoc wireless networks
(ii) We developed a hybrid cooperative opportunistic routing technique using Fountain coding, designed for wireless networks in challenged environments, such as an emergency response network.
(iii) We explored the capabilities of our cognitive networks also in a different scenario, studying a performance evaluation tool for spectrum sharing in multi-operator networks.
(iv) We have finalized our work, started in a previous ARO project, on sensing and characterizing the traffic in a multi-channel wireless network using cognitive networking.
(v) We have finalized a more theoretical analysis on cognitive interference management in retransmission-based wireless networks.
(vi) We have performed a practical study on the impact of physical-cyber world interactions during unexpected events.
(vii) We presented an analysis of random access protocols for multi channel cognitive wireless networks, where users can dynamically access portions of the available bandwidth at a given time and location.
(viii) We studied a novel Cognitive Call Admission Control scheme for VoIP over IEEE 802.11 using Bayesian Networks, a probabilistic model integrated into our cognitive network framework.
(ix) We proposed a novel network-aware retransmission strategy selection for ad hoc wireless networks that exploits Bayesian network to select the most suitable network parameters.
(x) We pursued the line of research started in (i) by analyzing more theoretically the game-theoretic strategy selection for cooperation between two networks.
(xi) We started a new effort on the exploitation of the Android operating system for the design of a wireless mesh network testbed, opening new research opportunities in the immediate future.
(xii) We compared two cognitive networking approaches, the Bayesian and Neural networks schemes, to optimize a Call Admission Control for wireless systems.
(xiii) With a more theoretical approach, we also introduced a novel technique for access to spectrum with an incumbent Primary User (PU) by a cognitive Secondary User (SU) using best-effort transmission.
(xiv) We studied the effects of mobility and we proposed a cognitive mobility prediction model to mitigate the problems related to mobility and topology changes in a wireless multi-hop ad hoc network.
(xv) We used a cross-layer formulation to design transmission strategies in a cognitive radio system with primary automatic repeat request (ARQ) control and quality of service (QoS) provisioning;
(xvi) we implemented and released the architecture of the cognitive networking testbed, which can integrate Android and other

Linux based devices.
(xvii) We designed a centralized access policy for two secondary users in a cognitive network during a primary user's ARQ process.
(xviii) We broadened our research scope investigating a machine learning based approach to ensure quality of experience (QoE) thanks to a video admission control and optimized resource allocation in a wireless system.

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** Detailed description of the achieved goals
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In our work presented in a workshop and published in the proceedings of Mobicom 2012, we presented Grapevine, a wireless networking protocol designed to be used in challenged environments such an emergency response network. These environments typically experience a lot of noise, interference, disconnections and high mobility resulting in high packet loss rates. As often critical data needs to be disseminated to other nodes it is important to have a protocol that efficiently delivers data under these conditions, but which is also efficient under good conditions. Grapevine uses fountain coding opportunistically and cooperatively to efficiently deliver data in high throughput wireless multi hop networks, as well as in lossy and delay tolerant networks. Results show that our flooding based protocol is more efficient than traditional protocols in lossy networks in terms of both lower delay and lower overhead.

Continuing on the effort of managing and optimizing cooperation among different users, we considered the concept of resource sharing as one promising way to enhance the performance of radio communications. Since the wireless spectrum is a scarce resource, and its usage is often found to be inefficient, we considered solutions where multiple operators join their efforts, so that wireless access of their terminals takes place on shared, rather than proprietary to a single operator, frequency bands. In spite of the conceptual simplicity of this idea, the resulting mathematical analysis may be extremely complex, since it involves analytical representation of multiple wireless channels. Simulation studies may be very useful to obtain a correct performance characterization of wireless networks with shared resources. In this spirit, we have introduced and evaluated an original extension of the well known ns-3 network simulator, which focuses on multiple operators of the most up-to-date cellular scenarios, i.e., the Long Term Evolution of UMTS employing OFDMA multiplexing. Spectrum sharing is represented through a proper software architecture, where several sharing policies can be framed. A detailed simulation campaign has been run to assess the computational performance of the proposed architecture, and to show its effectiveness in analyzing realistic scenarios. This work was published in Elsevier's Computer Communications.

In a different scenario, sharing frequency bands may still be promising, but is not the only way of exploiting the information collected by the cognitive network. Indeed, in our work on the cooperation between two ad hoc networks sharing the same spectrum resources, we considered relay sharing as a way of cooperation. Relay sharing has been recently investigated as a viable solution to increase the performance of coexisting wireless multi–hop networks. In a paper published at IEEE ICC 2012, we analyze a scenario where two wireless ad hoc networks are willing to share some of their nodes, acting as relays, in order to gain benefits in terms of lower packet delivery delay and reduced loss probability. Bayesian Network analysis is exploited to compute the correlation between local parameters and overall performance, whereas the selection of the nodes to share is made by means of a game theoretic approach. Our results are then validated through the use of a system level simulator, which shows that an accurate selection of the shared nodes can significantly increase the performance gain with respect to a random selection scheme.

In our work published by Elsevier Computer Networks, we considered traffic sensing and characterization as an important building block of cognitive networking systems. However, we note that it is very challenging to perform traffic characterization in multi-channel multi-radio wireless networks. Due to the presence of network traffic in multiple channels, the existing count-based packet sampling methods demand continuous capture on each channel to be effective; this requires a dedicated wireless interface per channel, and hence the existing sampling methods require a very expensive infrastructure and have poor scalability. Time-based sampling methods, on the other hand, offer a cost-effective and scalable solution by reducing the amount and cost of the resources necessary to monitor and characterize the wireless spectrum. The contributions of this paper include the following: 1) a discussion of packet sampling techniques for traffic sensing in multi-channel wireless networks, 2) a comparison of various time-based sampling strategies using the Kullback–Leibler divergence (KLD) measure, 3) a study on the effect of the sampling parameters on the accuracy of the sampling strategies, 4)development of sampling accuracy graphs for easing the process of best sampling scheme selection in multi-channel wireless networks, 5) the proposal of a new metric (traffic intensity) which estimates the busyness of channels by taking into consideration not only the successfully received packets but also corrupt or broken packets, 6) implementation of time-based sampling in a prototype traffic sensor device for multi-channel traffic sensing in IEEE 802.11 b/g networks, and 7) characterization of a campus IEEE 802.11 network environment in a spatio-temporal–spectral fashion using sampled traffic traces collected by traffic sensors.

In another more theoretical work, published in the IEEE Transactions on Information Theory, we considered cognitive radio methodologies that have the potential to dramatically increase the throughput of wireless systems. Herein, control strategies, which enable the superposition in time and frequency of primary and secondary user transmissions are explored in contrast to more traditional sensing approaches which only allow the secondary user to transmit when the primary user is idle. In this paper, the optimal transmission policy for the secondary user when the primary user adopts a retransmission-based error control scheme is investigated. The policy aims to maximize the secondary users' throughput, with a constraint on the throughput loss and failure probability of the primary user. Due to the constraint, the optimal policy is randomized, and determines how often the secondary user transmits according to the retransmission state of the packet being served by the primary user. The resulting optimal strategy of the secondary user is proven to have a unique structure. In particular, the optimal throughput is achieved by the secondary user by concentrating its transmission, and thus its interference to the primary user, in the first transmissions of a primary user packet. The rather simple framework we considered highlights two fundamental aspects of cognitive networks that have not been covered so far: 1) the networking mechanisms implemented by the primary users (error control by means of retransmissions in the considered model) react to secondary users' activity; 2) if networking mechanisms are considered, then their state must be taken into account when optimizing secondary users' strategy, i.e., a strategy based on a binary active/idle perception of the primary users' state is suboptimal.

A more practical application of cognitive networking has been presented at the ACM International Conference on Wireless Technologies for Humantiarian Relief (ACWR). In this paper, we present three physical world events where we conducted passive network traffic measurements to study the interaction between physical and cyber worlds. We consider the following types of events: an active shooter drill, a science festival scenario, and an emergency response drill involving a simulated dirty bomb attack. The network behavior during these events is contrasted with the regular network behavior. In some events, we observed a substantial drop in network traffic, whereas in some others we noticed high traffic surge. Therefore, the deviation observed in the cyber world activity may be exploited to automate the detection of physical world events. The drills also involved setting up a wireless mesh network infrastructure to assist first responders in their rescue operations and provide Internet connectivity to attendees of the science festival. Our passive network measurements provided valuable insights to configure wireless mesh network testbeds more efficiently, thereby providing efficient coordination of the response activity and saving human lives and properties.

In a work presented at IEEE GLOBECOM 2011, we studied random access protocols for multi channel wireless networks. Random access techniques have traditionally been used for the design of efficient medium access control protocols for wireless networks where the entire bandwidth is provided to the users as a single channel to be accessed for communication. In this work, we analyze the broadcast performance of several random access techniques in a multi channel system, where users can dynamically access portions of the available bandwidth at a given time and location. In order to compare these protocols we focus on metrics of interest such as the receiving probability, the system throughput and the network blocking probability. Our results show that these protocols can offer significant improvements in terms of increased system throughput provided that their operational parameters are carefully tuned to achieve near-optimal behavior in a multi channel setting.

In another work presented at IEEE GLOBECOM 2011, we address the problem of provisioning Quality of Service (QoS) to Voice over IP applications in a Wireless LAN scenario based on the IEEE 802.11 standard. We propose the use of a Cognitive Network approach to design a Call Admission Control (CAC) scheme, according to which each user stores relevant information on its past network experience and then uses such information to build a Bayesian Network (BN), a probabilistic graphical model to describe the statistical relationships among network parameters. The BN is exploited to predict the voice call quality, as a function of the Link Layer conditions in the particular scenario considered. Such prediction on the present and future values of the QoS provided is directly exploited to design the cognitive CAC scheme, which is shown to significantly outperform state of the art CAC techniques in a realistic scenario.

In our work presented in the 5th IEEE Workshop on Cooperative and Cognitive Mobile Networks and published in the proceedings of the IEEE ICC 2013 conference, we proposed a novel, network-aware retransmission strategy selection for ad-hoc wireless networks. This technique exploits a Bayesian network to select the most suitable network parameters, measured in a realistic scenario and thus affected by many real causes and carrying only limited/imprecise information (A1). Retransmission strategies have been widely investigated in wireless networks, since they are able to grant considerable benefits in dynamic environments. Distributed schemes, based on cooperative techniques, can also add the benefits of spatial diversity, particularly if combined with Multi-User Detection decoding schemes. However, the impact of each scheme on the rest of the network cannot be neglected, since it also affects the overall network performance. A mathematical approach to evaluate this impact can be very involved, given the potentially very large number of parameters to take into account. In this paper, we proposed a probabilistic approach to determine the expected impact, in terms of interference, of different schemes on the rest of the network. Indeed, to determine the impact of a given strategy on the rest of the network is not an easy task, since it depends on the transmission parameters, the implemented protocol and the network topology. The solution adopted involves a heuristic metric to measure how the usage of a given retransmission strategy can affect the rest of the network. The probabilistic relationships between this metric and some local topological parameters are obtained through a Bayesian network approach. A Bayesian network is used to learn the probabilistic relationships among a set of variables, as a function of a finite dataset of outcomes of the same variables. In this work, the Bayesian network approach is exploited to design a protocol, which can employ different retransmission schemes, with the aim of successfully delivering the data packet with limited impact on the rest of the network. With our framework, it is possible to select adaptively the best scheme to use, as a function of the observation of topological parameters. We also designed a distributed protocol to implement a variety of retransmission schemes, and the performance results confirm the effectiveness of our model over a static choice of the retransmission strategy and also over a selfish retransmission scheme that always selects the strategy that maximizes the probability of success of the retransmission.

In our work in the IEEE Transactions on Communications, we worked on a more theoretical analysis of the game-theoretic strategy selection for cooperation between two networks, which is part of our effort toward a system view of cognitive opportunistic networks (A2).
In this paper, we considered two wireless, multi–hop networks deployed in the same region but operated by different entities. Each node sends packets to every other node in the same network. In the case of no cooperation, the two coexisting networks perform their operations separately: each network only uses its own resources to deliver the data packets generated by its nodes. Since they are assumed to share the same spectrum resources, they compete to access the channel, and inter–network interference may limit the overall performance.
In our approach, each network can also share with the other network a limited number of nodes to increase jointly the performance of both networks. During a learning phase, we observed a set of local parameters: some of them are directly observable (i.e., we can assume that each network knows their values), and they depend only on the topology of the network (topological parameters), like the number of neighbors at a given node. Some other parameters depend on the local characteristics of the traffic load (local performance parameters).
We used the observed data to build the probabilistic relationships among all the parameters, summarized in a Bayesian network. Then we considered the scenario of interest, observing the topological parameters in such a scenario, and we used the Bayesian network to infer the local performance parameters that would be used to calculate a cost metric. We could finally use this information to model the interaction between the two networks through game theory, and to select the best nodes to be shared in order to minimize the chosen cost metric. We measured through simulation the performance improvement due to cooperation. As a result, we found that even when only a small fraction of the nodes is shared, a significant gain can be obtained. In particular, for both lightly and heavily loaded scenarios, the selection scheme based on game theory can achieve almost the same performance as a full cooperation scheme, for the different cost metrics considered.

In our work published in the MILCOM 2013 proceedings and listed in the IEEE Xplore digital library, we present the design of a novel wireless mesh network testbed that exploits the Android operating system. This work starts with the observation that wireless devices running the Android operating system offer a novel opportunity to study network behavior and to observe and modify key networking parameters in real time. This opens up an unprecedented opportunity to study, test and evaluate the performance of a huge number of techniques operating at different layers of the protocol stack and adopting the cognitive networking paradigm. In this paper, we describe our novel IEEE 802.11 mesh network testbed that integrates Android-based devices. The aim is to build a flexible testbed to observe in-stack and out-stack parameters of interest.
In our testbed we wanted to allow the testing of cognitive networking techniques, but at the same time we wanted to create a testbed that would be flexible enough to be used in different tactical, hostile, as well as civilian scenarios, easy to manage, based on relatively inexpensive hardware, and that can be easily recreated by other researchers around the world. To meet these goals, we chose to use tablets and smartphones running the Android operating system, since these devices are commercially available, relatively inexpensive, mobile, and highly customizable. With these devices, we put together the Android wireless mesh network testbed, based on the IEEE 802.11 standard. We provided all the implementation details to create an ad hoc network among these inexpensive commercial devices, and we specified how to observe and modify the networking parameters at different layers of the protocol stack. Our plan was also to share the entire source code, in order to allow other researchers to reproduce the testbed with the same types of devices. In other words, our testbed had both the advantages of a discrete event network simulator, since it was relatively inexpensive and easy to reproduce, and those of a standard network testbed, since it could be directly used in a real networking scenario.
Through some examples, we show the stability of the network and discuss the time evolution of some parameters of interest.

In our work published in the IEEE GLOBECOM 2013 proceedings, we compared two cognitive networking approaches, the Bayesian and Neural networks schemes, to optimize a Call Admission Control (CAC) scheme for a long term evolution (LTE) system. From the literature, as well as from our previous work, we have verified that cognitive networking paradigms may help meet the challenges of operating complex wireless communications networks. In this paper, we contrast the neural network (NN) and the Bayesian network (BN) models to extract information from real-time observations and optimize network performance. These two approaches have been used in our previous research as a valuable cognitive-networking solution, but always separately. Instead, in this paper we compare their performance in a specific scenario to verify if one of them is significantly superior to the other one. In particular, we apply these two models to the problem of CAC for LTE systems, for which several CAC schemes have already been proposed. A state-of-the-art scheme models the call arrival process with queueing theory and it applies the concept of resource reservation. In the presence of an incoming call, extra resources are reserved to avoid quality of service (QoS) degradation. The amount of these extra resources is determined a priori based on the knowledge of user mobility patterns. The major problem is that LTE is expected to be used with a mixture of heterogeneous cells of different sizes (macro/micro/pico/femto cells), deployed in a loosely coordinated fashion, with minimum to no planning. In such conditions, the statistics of the mobility pattern of the users are expected to vary significantly among different cells, and cannot be known in advance. Furthermore, overcoming these variations by a conservative estimation of the extra resources to be reserved would lead to poor resource utilization.
Other CAC schemes for LTE follow a ring-based modeling approach. This modeling approach assumes that users belonging to a cell can be grouped into rings according to their distance from the base station, and that the users located in the same ring

consume the same amount of radio resources. Even though these schemes show significant performance improvements compared to the previous CAC models for LTE, they still rely on a priori modeling of the radio environment, which is not realistic. In particular, in the presence of frequency selective fading, as well as path loss variations due to obstacles such as walls and buildings, the prediction of the needed amount of resources based solely on the distance between users and the base station may be highly inaccurate.
In other words, the vast majority of previously proposed CAC algorithms for LTE are based on some a priori known analytical models to predict the variations in the resource utilization. Thus, they may fail when these models do not match the actual deployment conditions, which is expected to happen in the vast majority of LTE deployment scenarios. For this reason, an LTE CAC scheme relying on a learning-based approach, which can react to the actual conditions faced by each cell, looks more promising. In previous work, we considered such a scheme based on NNs. In this paper, we simulate a realistic LTE scenario with mobility in ns-3 and we select the most relevant features that can be observed by the base station. Then, we design two new CAC schemes that autonomously learn network behavior from the observation of selected features, i.e., NN and BN models for CAC in an LTE system. We studied how best to select the most relevant features that can be observed by the base station. The NN and the BN models learn the network behavior by observing selected features during a training set. Their performance, in terms of CAC accuracy, is compared to a state-of-the-art CAC scheme for LTE. Both our schemes can outperform the state-of-the-art scheme. Moreover, the BN scheme can also meet different system requirements by opportunistically tuning its parameters. In future work, we plan to exploit further the flexibility of these cognitive networking techniques in other, realistic networking applications (A3).

We published a work related to the (A3) research area of this project in the Journal on Selected Areas in Communications. In this work, we introduced a novel technique for access by a cognitive Secondary User (SU) using best-effort transmission to a spectrum with an incumbent Primary User (PU), which uses Type-I Hybrid ARQ. The technique leverages the primary ARQ protocol to perform Interference Cancellation (IC) at the SU receiver (SUrx). Two IC mechanisms that work in concert are introduced: Forward IC, where SUrx, after decoding the PU message, cancels its interference in the (possible) following PU retransmissions of the same message, to improve the SU throughput; Backward IC, where SUrx performs IC on previous SU transmissions, whose decoding failed due to severe PU interference. Secondary access policies are designed that determine the secondary access probability in each state of the network so as to maximize the average long-term SU throughput by opportunistically leveraging IC, while causing bounded average, long-term PU throughput degradation and SU power expenditure. We proved that the optimal policy prescribes that the SU prioritizes its access in the states where SUrx knows the PU message, thus enabling IC. An algorithm is provided to allocate additional secondary access opportunities optimally in states where the PU message is unknown. Numerical results were shown to assess the throughput gain provided by the proposed techniques.

In our work presented at the IEEE International Conference on Communications (ICC 2014), Cognitive radio and network symposium, we address an important problem in mobile ad hoc networks, namely, the intrinsic inefficiency of the standard transmission control protocol (TCP), which has not been designed to work in these types of networks. The general workflow behind our contribution is structured as follows.
1) We observe the overall TCP throughput degradation by means of simulations performed with ns3, an open-source discrete-event network simulator for Internet systems. We consider both a static scenario and a mobile scenario, and we vary the channel characteristics to simulate different realistic scenarios. We identify a set of critical network states, and in this phase we also collect the values of some network parameters as a function of time, which are stored in a training dataset.
2) We exploit the training dataset to learn the probabilistic relationships among the communication parameters, and we organize this probabilistic information in a Bayesian network (BN). The BN is designed in order to provide real-time information on the mobility status of the network.
3) We define a set of actions to be adaptively taken in order to address the problem of each critical network state, once the network state has been inferred by means of the BN.
4) Finally, we design a cross-layer framework that allows to dynamically take actions at the TCP and IP levels, i.e., to apply the corresponding strategy defined in 3).
We also perform a simulation campaign to show the performance improvements in terms of increased average throughput and decreased length of the outage intervals, i.e., the time intervals in which the communication is frozen due to topology or network problems.

The work published in the IEEE Transactions on Communications (June 2014) deals with transmission strategy design in a cognitive radio system. In this work, we consider an underlay cognitive radio paradigm with a primary packet system, which implements ARQ-based error control. We propose cognitive transmission strategies, which provision for minimum primary QoS requirements. The proposed strategies take advantage of opportunities that arise during ARQ retransmissions of the primary system at the link layer, and adapt channel fading variations by employing adaptive modulation and coding (AMC) and power control at the physical layer. In this cross-layer formulation, the cognitive throughput is optimized subject to 1) a packet-loss-rate (PLR) constraint on the cognitive link, and 2) a minimum required throughput and a PLR constraint on the primary link. We first derive analytical expressions for the link-layer throughput of the cognitive link defined in terms of the data rate successfully received at the receiver side. Next, we present optimized AMC and power control schemes for the cognitive transmitter.
The main contributions of this work are the following:

1) First, we define the link layer throughput performance as the data rate successfully received at the receiver side, which includes the effect of both packet retransmissions (ARQ protocol) and the employed physical layer architecture. We then derive analytical expressions for the throughput performance of the primary and secondary links when the cognitive transmitter employs a constant- power AMC (CP-AMC), or an AMC scheme with dynamic power control at the physical layer.
2) Next, a cross-layer approach for transmission policy de- sign at the secondary system is adopted. We illustrate that the optimization of the secondary throughput performance under QoS constraints can be formulated as an optimization problem, which can be addressed efficiently in two distinct stages. In particular, we present optimized AMC and power control schemes for the cognitive transmitter which guarantee a PLR constraint for the cognitive link, and a minimum required throughput and a PLR constraint for the primary link.
Numerical results show significant improvement in terms of the cognitive throughput and PLR performance. Namely, when the cognitive transmitter employs both power and rate control the throughput-maximizing strategy is determined based on a tradeoff between the primary PLR and delay (in terms of the number of retransmission rounds) QoS metrics.

Starting from our work published at MILCOM 2013, we continued our investigation on this research line and we published the journal version on the IEEE Communications magazine, September 2014. At the basis of this work is our expertise on wireless devices running the Android operating system, which offer a novel opportunity to study network behaviors, and to observe and modify, in real time, key networking parameters. This opens up an unprecedented opportunity to study, test, and evaluate the performance of techniques operating at different layers of the protocol stack and adopting the cognitive networking paradigm. In this work, we describe our novel IEEE 802.11 mesh network testbed that integrates Android-based devices (Cognitive Android Mesh Network testbed, CARMEN).
The aim was to build a flexible testbed to observe in-stack and out-of-stack parameters of interest that, with some modifications, can be used to test networking techniques in both civilian and emergency scenarios. We provide the implementation details to create an ad hoc network among these inexpensive commercial devices, and specify how to observe and modify the networking parameters at different layers of the protocol stack. We also run some standard protocols on the network, and we obtain some repeatable results, which are similar to other results from the literature and confirm our testbed as a valid tool for ad hoc network performance evaluation.
CARMEN can be used to test cognitive networking techniques, since each node can observe and modify its in-stack parameters, that is, those parameters that can be directly observed and acted on at different layers of the protocol stack. Furthermore, the devices are equipped with other sensors to observe out-of-stack parameters (i.e., those parameters that are not directly related to the protocol stack, e.g., environmental or positioning data) that can be exploited to design and test novel cognitive networking protocols. We can envision its use, with minor modifications, in both standard civilian and emergency scenarios.
In a nutshell, our approach is based on the following principles:
1) The nodes in our testbed are commercial devices (smartphones and tablets), which are relatively inexpensive if compared with the ad hoc hardware commonly used to build a wireless mesh network testbed;
2) The testbed allows the collection and the modification of several parameters at different layers of the protocol stack, thus many cognitive networking techniques can be tested within such framework;
3) The testbed can be reproduced with a limited effort, as detailed in this article.
The implementation of the CARMEN testbed is divided into the following phases:
1) Enable ad hoc communication among the nodes.
2) Organize nodes in a multihop network.
3) Observe/modify some networking parameters as required by cognitive networking techniques.
4) Allow nodes' mobility.
The entire source code, with patches and Android ROM binary code, can be downloaded from https://github.
com/CognetTestbed, reused, and modified.
In future work, the flexibility of this testbed will be exploited to test our newly developed cognitive networking techniques. In the future, we expect other groups to adopt this paradigm, giving rise to a network of developers that can further enrich the functionalities of this platform.

In our work published in the IEEE International Conference on Communications (ICC 2014), workshop on Cooperative and Cognitive Mobile Networks, an underlay cognitive radio network that consists of two secondary users (SU) and one primary user (PU) is considered, in which the PU employs Type-I Hybrid ARQ.
In this work, an optimum access policy for two SUs is designed, which exploits the redundancy introduced by the Hybrid-ARQ protocol in transmitting copies of the same PU message and interference cancelation at the SU receivers. The aim is to maximize the average long term sum throughput of SUs under a constraint on the average long term PU through- put degradation. We assume that the number of retransmissions is limited and both SUs have a new packet to transmit in each time slot. Noting the PU message knowledge state at each of the SU receivers and also the ARQ retransmission time, the PU-SU1-SU2 network is modeled using a Markov Decision Process (MDP). Due to the constraint on the average long term PU throughput, we then have a constrained MDP (CMDP). The access policy in one state shows the probability of accessing or/and not accessing the channel by the two SUs.
The simulation results demonstrate that due to the use of interference cancellation (IC), a cognitive radio network composed of two symmetric SUs converges to the upper bound faster than a cognitive radio network with one SU for large enough SNR of

the channels from the PU transmitter to SU receivers. To obtain the optimal solution, a linear program (LP) corresponding to the CMDP is applied. Numerical results demonstrate the benefits of the proposed optimal policies.

We also started an investigation on a machine learning based approach to ensure quality of experience (QoE) thanks to a video admission control and optimized resource allocation in a wireless system. In our work at the Annual Mediterranean Ad Hoc Networking workshop (MED-HOC-NET) proceedings and listed in the IEEE Xplore digital library, we discuss the rapid growth of video traffic in cellular net- works, which is a crucial issue to be addressed by mobile operators. An emerging and promising trend in this regard is the development of solutions that aim at maximizing the QoE of the end users. However, predicting the QoE perceived by the users in different conditions remains a major challenge. In this paper, we propose a machine learning approach to support QoE-based Video Admission Control (VAC) and Resource Management (RM) algorithms. More specifically, we develop a learning system that can automatically extract the quality-rate characteristics of unknown video sequences from the size of H.264-encoded video frames. Our approach combines unsupervised feature learning with supervised classification techniques, thereby providing an efficient and scalable way to estimate the QoE parameters that characterize each video. This QoE characterization is then used to manage simultaneous video transmissions through a shared channel in order to guarantee a minimum quality level to the final users. Simulation results show that the proposed learning-based QoE classification of video sequences outperforms commonly deployed off-line video analysis techniques and that the QoE-based VAC and RM algorithms outperform standard content-agnostic strategies.
More specifically, we consider a large set of H.264-AVC video clips coded at different source rates, which correspond to different perceived quality levels. We then assess the quality level of each video in terms of the average Structural SIMilarity (SSIM) index. After a suitable normalization and re- scaling of the encoded source rate, we are able to analytically approximate the empirical SSIM-to-bitrate characteristics of each video by means of a polynomial expression, which is then used by QoE-aware VAC and RM algorithms. Unfortunately, this method requires to calculate the SSIM rates for each video and to fit the corresponding polynomial function, which is computationally prohibitive in realistic scenarios. However, we show that the polynomial coefficients can be reliably estimated using a machine learning approach. Crucially, the proposed method does not require to process the original content of the video frames, but only uses network information available after the encoding process, namely the video frame size. The rationale is that the SSIM-to-bitrate function of a video is closely related to the dynamics of its content, and this information is reflected in the structure of the corresponding sequence of frame sizes after the encoding. Indeed, the content of a video influences the structure of its compressed version (e.g., highly-dynamic videos, containing complex spatial and temporal structure, will likely result in larger frame sizes). Thus, we build a training dataset containing the frame sizes of the different Group-of-Pictures (GOPs) of the test videos, and upon this dataset we train a Restricted Boltzmann Machine (RBM) in an unsupervised fashion. The RBM captures the latent features such as input data, thus providing a high-level representation that can be exploited by supervised learning algorithms to estimate the polynomial coefficients that estimate the SSIM-to-bitrate characteristics of unknown videos, which is then used by the aforementioned QoE-aware VAC and RM algorithms.
As a proof of concept, we apply our approach to a simple transmission scenario with a congested link shared by multiple video flows, e.g., a wireless downlink video streaming scenario. We show that, after an off-line learning phase, our approach can run online, performing VAC of unknown videos with basically negligible computational complexity.

Finally, we have started as part of the current project the design of a context-aware Device-to-Device communication technique with a punishment mechanism. This work is motivated by the amount of traffic which is increasing dramatically: social media has driven the spread of file sharing (photos, music, and video), while many widespread mobile applications require frequent data exchanges with a remote server. Handling this amount of communications with a given quality of service (QoS) is challenging. Currently, 5G technologies are being developed to answer the need for further increasing network capacity, and among them, device-to-device (D2D) communications are attracting some attention. The main idea in D2D is to let the mobile terminals communicate directly in a semi-autonomous way, with minimal control by the base station (BS). The network is thus divided into two tiers: the cellular tier, which includes all the terminals communicating to a BS, and the D2D tier, including all the mobiles performing peer-to-peer communications without relying on any infrastructure. Conceptually, this scenario is similar to a cognitive radio network, where unlicensed (secondary) users try to communicate over reserved frequency bands without hampering the transmissions of the licensed (primary) users. There are two ways to share the spectrum in this scenario: 1) the available spectrum is orthogonally shared between D2D and cellular tiers, with the risk of spectrum underutilization, and 2) the two tiers coexist in the same frequency bands, causing mutual interference.
The focus of this paper is on non-orthogonal D2D transmissions, where uplink resources are exploited for D2D communications. The involved mobiles use the same uplink resources as the terminals of the cellular tier. In addition, idle mobile terminals can serve as relays for the D2D communications by forwarding some packets, creating a multi-hop D2D scheme. These helper terminals employ a decode and forward scheme by transmitting on the uplink channels, acting as half-duplex relays.
A strategy to organize D2D communications is to let the BS schedule all the transmissions. This approach is indeed not feasible in a dense network scenario, where the number of idle mobiles involved in D2D communications is very high. Another strategy consists in letting the D2D sources freely access the channels, without any control by the BS. The additional interference may indeed be detrimental for the cellular tier.
In our work, we propose a channel access mechanism for a D2D source with two possibly conflicting goals: to maximize the end-to-end throughput (selfish goal, SG), and to reduce the interference to the other ongoing communications (network goal,

NG). The NG is not easy to define. More than one cellular communication might be disturbed by one D2D communication, and the impact on each of them in turns depends on the channel condition, on the current interference level and on the topology of the network.

In our approach, we gather context awareness by: 1) collecting key information about the surrounding channels and topology, and 2) applying a probabilistic approach, based on belief networks (BNs), to predict the impact of the D2D on the surrounding BSs, measured in terms of relative capacity loss. This context-aware scheme is inherently adaptive to a time varying environment: it increases the throughput when possible, with little harm to the cellular tier, and it reduces or suspends data transmissions, when they become excessively harmful for a BS.

In order to counteract the problem of interference at the BS, we add a punishment mechanism to limit the activity of disturbing terminals. The punishment is triggered whenever a given D2D source causes an excessive capacity loss at the BS. Possible punishments, enforced by a BS, consist in temporary imposing: 1) a limitation on the allowed transmission power of the mobile, or 2) a forced silent period. This punishment strategy aligns the SG and the NG for a given D2D transmission, since causing an excessive interference can trigger the punishment, which in turns has a severe effect on the D2D throughput. In other words, the punishment mechanism is a strong incentive for a selfish D2D source to proactively limit its network impact.

Technology Transfer