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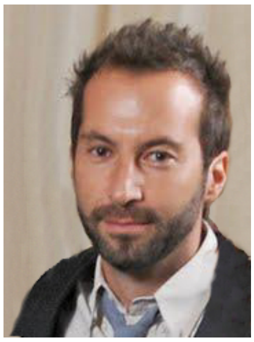

Education

2000-2006 **PhD, University of Southern California, Los Angeles, US**
Thesis title: Efficient Media Access and Routing in Wireless and Delay Tolerant Networks. Advisors: Prof. C. Raghavendra & Prof. K. Psounis

1994-2000 **Diploma, National Technical University of Athens, Greece**
Department of Electrical and Computer Engineering

Employment

2010 – present **Assistant Professor, Mobile Comm. Dept., EURECOM, France**
Wireless Technologies, Protocols and Systems Group

2007-2010 **Senior Researcher, Swiss Federal Institute of Technology (ETH), Switzerland -** Communication Systems Group (CSG)

2006-2007 **Research Associate, INRIA, Sophia-Antipolis, France**
Project-team Planete, Topic: Delay-Tolerant Networks and Mobility Modeling

2000-2006 **Research Assistant, University of Southern California, US**
Department of Electrical Engineering, Topic: Ad-hoc and Sensor Networks

Research Projects

2015 - present **EU Horizon 2020, COHERENT** – Coordinated Control and Spectrum Management for 5G Heterogeneous Radio access Networks

2014 - present **LABEX UCN@SOPHIA** – Vehicles as a Mobile Cloud: Leveraging present Mobility for Content Storage and Dissemination

2013 - present **Intel Mobile, Network Optimizations in Small Cell Networks** – joint radio access and backhaul optimization for energy consumption and load-balancing

2013-2015 **Intel Mobile, Flow-based Wireless Data Offloading** - Analysis, optimization, and prototyping of data offloading algorithms for multi-NIC user terminals

2012 - present **EU ICT FP7 COLOMBO** – Cooperative self-organizing system for low carbon mobility at low penetration rates

2010-2013 **ANR Project LICORNE** – Performance analysis and protocols for the coexistence of multiple cognitive multihop networks.

2010-2013 **EU FP7 Fire SCAMPI** - Social aware mobile and pervasive computing

2009-2010 **NOKIA Research Grant** – Project AwareNet

2009-2012 **ETH Internal Research Grant** – Using Social Networks for Routing in Wireless Self-Organizing Networks

Teaching Experience

2011-present	**Network Modelling**, EURECOM, France, graduate level (42h)
2014-2015	**Winter school on Complex Networks**, lecture and lab session (5h)
2007-2010	**Advanced Topics in Communication Networks**, ETH Zurich, Switzerland, graduate level (12h)
2007	**Challenged Networks**, INRIA, Sophia-Antipolis, France, MSc in Networks and Distributed Systems, graduate level (18h)

Distinctions

Best Paper Awards	IEEE SECON 2008, IEEE WoWMoM 2012
Best Paper Runner Up	ACM MobiHoc 2011, IEEE WoWMoM 2015
Other Awards	Technical Chamber of Greece (TEE) Award, for academic distinction (1999-2000)
Citations (H-index)	6605 citations (H-index: 28), as of June 2015

Professional Service

Keynote	IEEE workshop on on Autonomic and Opportunistic Communication (AOC), “Opportunistic Offloading on the Edge”, Boston, June 2015
TPC chair	IEEE NetSciCom 2014: co-located with IEEE INFOCOM, May 2014 ACM CHANTS 2014: co-located with MOBICOM 2013, September 2013. IFIP IWSOS: Zurich, 2009.
Panels	IEEE AOC 2011, IEEE NetSciCom 2013
TPC member	IEEE Infocom, ACM Sigmetrics, ACM Mobihoc, IEEE Secon, and others.

PhD Students / Postdocs

2014-present	**L. Vigneri** (EURECOM, co-supervised) - Vehicles as a Mobile Cloud: Leveraging Mobility for Content Storage and Dissemination
2013-present	**N. Sapountzis** (EURECOM, co-supervised) – Network Level Optimizations for Small Cell Networks
2013-2015	**D. Ciullo** (EURECOM, Post Doc) – Smart Data Flow Offloading over WiFi
2011-2015	**P. Sermpezis** (EURECOM) - Performance Analysis of Mobile Social Networks with Realistic Mobility and Traffic Patterns
2011-2015	**F. Mehmeti** (EURECOM) - Performance Analysis and Optimization of Wireless Access in Cognitive and Heterogeneous Networks
2008-2014	**A. Picu** (ETH Zurich) - Using Social Networks for Data Dissemination in Wireless Self-Organized Networks
2008-2012	**T. Hossmann** (ETH Zurich, co-supervised) - Efficient Dynamic Graph Models for Representing Opportunistic Node Communications
2008-2013	**D. Schatzmann** (ETH Zurich, co-supervised) - Monitoring Spam and BotNet Behavior using Network Flow Data
2008-2011	**A. Krifa** (INRIA Sophia-Antipolis, co-supervised) - Optimal Buffer Management Policies for Delay Tolerant Networks

Post-PhD Publications

Books & Book Chapters

2013 Thrasyvoulos Spyropoulos, Andreea Picu, “Chapter: Opportunistic Routing,” Mobile Ad Hoc Networking: Cutting Edge Directions”, Second Edition, 419-452.

2011 Athanasios Vasilakos, Yan Zhang, T. Spyropoulos, “Book: Delay Tolerant Networks: Protocols and Applications,” CRC Press, 2011.

2009 George Parissidis, Merkourios Karaliopoulos, Rainer Baumann, Thrasyvoulos Spyropoulos, and Bernhard Plattner, “Chapter: Routing metrics for wireless mesh networks,” Guide to Wireless Mesh Networks, 199-230

Journal Papers

2015 Pavlos Sermpezis, Thrasyvoulos Spyropoulos, "Modelling and analysis of communication traffic heterogeneity in opportunistic networks", to appear in **IEEE Transactions on Mobile Computing.**

2015 Andreea Picu, Thrasyvoulos Spyropoulos, “DTN-Meteo: Forecasting the Performance of DTN Protocols Under Heterogeneous Mobility,” **IEEE/ACM Transactions on Networking**, 23(2): 587-602 (2015)

2014 Pavlos Sermpezis, Thrasyvoulos Spyropoulos, “Understanding the effects of social selfishness on the performance of heterogeneous opportunistic networks,” **Elsevier Computer Communications**, Special Issue on Opportunistic Communications, 48: 71-83 (2014)

2013 Kaijie Zhou, Navid Nikaein, Thrasyvoulos Spyropoulos, “LTE/LTE-A Discontinuous Reception Modeling for Machine Type Communications,” **IEEE Wireless Communication Letters** 2(1): 102-105 (2013)

2012 Theus Hossmann, George Nomikos, Thrasyvoulos Spyropoulos, Franck Legendre: “Collection and analysis of multi-dimensional network data for opportunistic networking research”. **Elsevier Computer Communications** 35(13): 1613-1625 (2012)

2012 Mikko Pitkänen, Teemu Kärkkäinen, Jörg Ott, Marco Conti, Andrea Passarella, Silvia Giordano, Daniele Puccinelli, Franck Legendre, Sacha Trifunovic, Karin Anna Hummel, Martin May, Nidhi Hegde, Thrasyvoulos Spyropoulos, “SCAMPI: service platform for social aware mobile and pervasive computing,”. **ACM Computer Communication Review (CCR)** 42(4): 503-508 (2012)

2012 Amir Krifa, Chadi Barakat, Thrasyvoulos Spyropoulos, “Message Drop and Scheduling in DTNs: Theory and Practice”, **IEEE Transactions on Mobile Computing**, Vol. 11, No. 9, Pages 1470-1483, 2012.

2011 G.Parissidis, M. Karaliopoulos, T. Spyropoulos, B. Plattner, “Interference-aware Routing in Wireless Multihop Networks, **IEEE Transactions on Mobile Computing**. Vol. 10, No. 5, Pages 716-733, 2011

2010 Thrasyvoulos Spyropoulos, Naveed Bin Rais, Thierry Turletti, Katia Obraczka, and Thanos Vasilakos, “Routing for Disruption Tolerant Networks: Taxonomy and Design,” in **ACM/Kluwer Wireless Networks (WINET)**, Vol. 16. No. 8, 2010.

2009 T. Spyropoulos, T. Turletti, and K. Obraczka, “Routing in Delay Tolerant Networks Comprising Heterogeneous Populations of Nodes,” in **IEEE Transactions on Mobile Computing**, vol.8, no.8, 2009.

2009 W. J. Hsu, T. Spyropoulos, K. Psounis, and A. Helmy, “A Realistic Mobility Model for Time-Variant User Mobility in Wireless Networks,” in **ACM/IEEE Transactions on Networking**, vol.15, no.8, 2009.

2009 D. Schatzmann, M. Burkhart, T. Spyropoulos: “Inferring Spammers in the Network Core,” Springer-Verlang **Lecture Notes in Computer Science (LNCS)**,(from PAM’09), 2009

Selected Conference Publications

2015 P. Matzakos, T. Spyropoulos, and C. Bonnet, “Buffer Management Policies for DTN Applications with Different QoS Requirements,” to appear in **IEEE GLOBECOM 2015,** San Diego, CA, Dec. 2015.

2015 N. Sapountzis, T. Spyropoulos, N. Nikaein, and U. Salim, “An Analytical Framework for Optimal Downlink-Uplink User Association in HetNets with Traffic Differentiation,” to appear in **IEEE GLOBECOM 2015**, San Diego, CA, Dec. 2015.

2015 Esa Hyytiä, Thrasyvoulos Spyropoulos, and Joerg Ott, “Offload (Only) the Right Jobs: Robust Offloading Using the Markov Decision Processes,” in Proc. of **IEEE WoWMoM 2015**, Boston, Massachusetts, June 2015.

2014 Nikolaos Sapountzis, Stylianos Sarantidis, Thrasyvoulos Spyropoulos, Navid Nikaein, Umer Salim, “Reducing the energy consumption of small cell networks subject to QoE constraints,” in Proc. of **IEEE GLOBECOM 2014**, Austin, Texas, December 2014

2014 Fidan Mehmeti, Thrasyvoulos Spyropoulos, “Is it worth to be patient? Analysis and optimization of delayed mobile data offloading,” in Proc. of **IEEE INFOCOM 2014**, Toronto, Canada, May 2014

2014 Pavlos Sermpezis, Thrasyvoulos Spyropoulos, “Not all content is created equal: effect of popularity and availability for content-centric opportunistic networking,” in Proc. of **ACM MobiHoc 2014**, Philadelphia, Pennsylvania, August 2014.

2013 Hicham Khalife, Vania Conan, Jeremie Leguay, Thrasyvoulos Spyropoulos, “Point to multipoint transport in multichannel wireless environments,” in Proc. of **IEEE WCNC 2013**.

2013 Fidan Mehmeti, and Thrasyvoulos Spyropoulos, “Who Interrupted Me? Analyzing the Effect of PU Activity on Cognitive User Performance,” in Proceedings of **IEEE ICC 2013**.

2013 Fidan Mehmeti, and Thrasyvoulos Spyropoulos, “To Scan or Not To Scan: The Effect of Channel Heterogeneity on Optimal Scanning Policies,” in Proc. of **IEEE SECON 2013**.

2013 Fidan Mehmeti, and Thrasyvoulos Spyropoulos, “Performance Analysis of "On-the-spot" Mobile Data Offloading,” in Proceedings of **IEEE GLOBECOM 2013**.

2013 Pavlos Sermpezis, and Thrasyvoulos Spyropoulos, “Information Diffusion in Heterogeneous Networks: The Configuration Model Approach,” in Proceedings of **IEEE INFOCOM Workshop on Network Science in Communication (NetSciCom)**, Torino, Italy, April 2013.

2013 Francisco Santos, Benjamin Ertl, Chadi Barakat, Thrasyvoulos Spyropoulos, Thierry Turletti, “CEDO: Content-Centric Dissemination Algorithm for Delay-Tolerant Networks,” in Proceedings of **ACM MSWIM 2013**.

2012 Andreea Picu, Thrasyvoulos Spyropoulos and Theus Hossmann "An Analysis of the Information Spreading Delay in Heterogeneous Mobility DTNs" Proceedings of **IEEE WoWMoM 2012**, IEEE, San Francisco, CA, USA, pages 1-9, June 2012

2012 Andreea Picu and Thrasyvoulos Spyropoulos "Forecasting DTN Performance under Heterogeneous Mobility: The Case of Limited Replication" Proceedings of **IEEE SECON 2012**, IEEE, Seoul, South Korea, pages 1-9, June 2012.

2011 Andreea Picu and Thrasyvoulos Spyropoulos, "Performance of Distributed Algorithms in DTNs: Towards an Analytical Framework for Heterogeneous Mobility", Proceedings of **IEEE GLOBECOM 2011**, IEEE, Houston, TX, USA, pages 1-6, December 2011.

2011 Amir Krifa, Chadi Barakat, Thrasyvoulos Spyropoulos, "MobiTrade: Trading Content in Disruption Tolerant Networks", in proceedings of **ACM MOBICOM Workshop on Challenged Networks (CHANTS)**, Las Vegas, September 2011

2011 Theus Hossmann, Thrasyvoulos Spyropoulos, and Franck Legendre, "Putting Contacts into Context: Mobility Modeling beyond Inter-Contact Times," in **ACM MobiHoc 2011**, Paris, May 2011.

2011 Theus Hossmann, Thrasyvoulos Spyropoulos and Franck Legendre, "A Complex Network Analysis of Human Mobility," **IEEE INFOCOM Workshop on Network Science in Communication (NetSciCom)**, Shanghai, China, April 2011.

2010 Dominik Schatzmann, Wolfgang Mühlbauer, Thrasyvoulos Spyropoulos and Xenofontas Dimitropoulos, "Digging into HTTPS: Flow-Based Classification of Webmail Traffic," in **ACM Internet Measurement Conference (IMC 2010)**, Melbourne, Australia, Nov. 2010.

2010 Andreea Picu and Thrasyvoulos Spyropoulos, "Distributed Stochastic Optimization in Opportunistic Networks: The Case of Optimal Relay Selection", in **ACM MOBICOM Workshop on Challenged Networks (CHANTS) 2010**, Chicago, IL, Sep. 2010.

2010 Theus Hossmann, Thrasyvoulos Spyropoulos, and Franck Legendre, "Know Thy Neighbor: Towards Optimal Mapping of Contacts to Social Graphs for DTN Routing," **in IEEE INFOCOM 2010**, San Diego, CA, March 2009.

2009 Theus Hossmann, Franck Legendre, Thrasyvoulos Spyropoulos, "From Contacts to Graphs: Pitfalls in Using Complex Network Analysis for DTN Routing," in Proceedings of **IEEE INFOCOM Workshop on Network Science in Communication (NetSciCom)**, Rio de Janeiro, Brazil, April, 2009

2009 Simon Heimlicher, Hanoch Levy, Merkouris Karaliopoulos, and Thrasyvoulos Spyropoulos, "Leveraging Partial Paths in Partially-connected Networks," in **IEEE INFOCOM 2009**.

2009 Dominik Schatzmann, Martin Burkhart, Thrasyvoulos Spyropoulos: "Inferring Spammers in the Network Core," in **Passive and Active Measurement (PAM**) Conference, Apr. 2009.

2008 Amir Krifa, Chadi Barakat, Thrasyvoulos Spyropoulos, "Optimal Buffer Management Policies for Delay Tolerant Networks," **IEEE SECON 2008**, June 2008.

2008 G.Parissidis, M. Karaliopoulos, M. May, T. Spyropoulos, B. Plattner, "Interference in Wireless Multihop Networks: A Model and its Experimental Evaluation**," IEEE WoWMoM**, June 2008.

2007 W. J. Hsu, T. Spyropoulos, K. Psounis, and A. Helmy, "Modeling Time-variant User Mobility in Wireless Mobile Networks," in Proceedings of **IEEE INFOCOM**, May 2007.

PhD Research - Efficient Media Access and Routing in Wireless and Delay Tolerant Networks

The goal of this thesis was to devise media access and routing algorithms for Mobile Ad Hoc Networks (MANETs). Two main classes of MANETs have been considered, (i) dense and connected, and (ii) sparse and intermittently connected. The thesis consists of two main parts, corresponding to each class.

In Part I, we consider "traditional" MANETs, where the node density is high enough so that connected end-to-end paths exist between the majority of participating nodes. In this context, multi-hop routing algorithms, namely modifications of standard routing schemes, can be used. However, mobile nodes (e.g., phones or sensors) have limited battery power, making energy efficiency an important new metric to consider in this context. What is more, some key scalability results appeared, namely the seminal work by Kumar and Gupta [1], suggesting that multi-hop routing over MANETs leads to zero end-to-end throughput, in the limit of large networks. To this end, some researchers, including us, have suggested the use of directional antennas to improve both energy- and throughput-related performance of MANETs.

Our key contributions in this domain have been the following: (i) We proposed a joint scheduling and routing algorithm for a network of nodes with directional antennas, that chooses routing paths, based on end-to-end traffic demand, and schedules directional link transmissions optimally, based on matching algorithms [2]; (ii) We revisited the asymptotic capacity results of [1], when nodes use directional antennas, and showed that although there is a constant factor improvement, the asymptotic behaviour remains the same [3] ; (iii) Assuming that nodes use "smart" antennas, we proposed modifications to the collision avoidance and virtual NAV mechanisms of the 802.11 media access control (MAC) protocol. This allows an improved performance through directional transmissions, and appropriately placing nulls towards hidden and exposed terminals, demonstrating significant performance gains in finite size networks [4].

In Part II, we turn our attention to ad hoc networks that are sparse, and/or have high mobility, so that end-to-end paths either don't exist most of the time, or are hard to maintain. The key differences in such networks are the following: (i) a message might need to be stored and carried on a relay, possibly for long time intervals (compared to transmission and propagation times), until a good next hop is encountered; due to these potential delays, such networks are often referred to as Delay Tolerant Networks (DTN); (ii) since no end-to-end paths might exist, routing consists of a sequence of forwarding decisions based on probabilistic and predictive models of future connectivity opportunities, without any guarantees of eventual delivery; this is often referred to as "opportunistic routing".

In this context, our key contributions can be summarized as follows: (i) We performed an analytical study of a large number of "single-copy" routing algorithms, and proved closed form expressions for their performance as a function of key mobility parameters [5]. (ii) We studied multi-copy routing algorithms, that distributed redundant copies of the same message to different relays, in order to increase the probability of one of them being delivered on time; we then proposed a simple, and efficient scheme, called Spray & Wait, that can achieve performance only a constant factor away from the optimal with orders of magnitude reduction of network overhead compared to state-of-the-art schemes, at the time. This scheme can be also tuned online, with limited network knowledge to achieve desirable performance tradeoffs, and was proven to have increasingly better performance as the network size scales up. This work has been widely cited (1800 for the workshop and 800 for the journal version) and has been a standard reference for future DTN protocols. [6][7] (iii) We derived analytically the expected meeting time for two random-walk based and a more realistic, community-based model, a key property for predicting DTN routing performance, and showed how these can be used to derive closed form performance results [8].

References

[1] P. Gupta, and P. R. Kumar, "The capacity of wireless networks," IEEE Transactions on Information Theory, 46(2), 388-404.

[2] A. Spyropoulos, and C.S. Raghavendra, “Energy efficient communications in ad hoc networks using directional antennas,” In Proc. of IEEE INFOCOM 2002.

[3] A. Spyropoulos, and C.S. Raghavendra, “Asympotic capacity bounds for ad-hoc networks revisited: the directional and smart antenna cases,” In Proc. of IEEE GLOBECOM 2003

[4] T. Spyropoulos, and C.S. Raghavendra, “Adapt: a media access control protocol for mobile ad hoc networks using adaptive array antennas,” In Proc. of IEEE PIMRC 2004.

[5] T. Spyropoulos, K. Psounis, and C.S. Raghavendra, “Efficient routing in intermittently connected mobile networks: The single-copy case,” IEEE/ACM Transactions on Networking (TON), 16(1), 63-76.

[6] T. Spyropoulos, K. Psounis, and C. S. Raghavendra. "Spray and wait: an efficient routing scheme for intermittently connected mobile networks." In Proc. of ACM SIGCOMM workshop on Delay-tolerant networking (WDTN), 2005.

[7] T. Spyropoulos, K. Psounis, and C.S. Raghavendra, “Efficient routing in intermittently connected mobile networks: the multiple-copy case,” IEEE/ACM Transactions on Networking, 16(1), 77-90.

[8] T. Spyropoulos, K. Psounis, and C.S. Raghavendra, “Performance analysis of mobility-assisted routing,” In Proc. ACM MobiHoc 2006.

Post-PhD Research

Summary and Approach: My research work after the PhD has explored a number of different areas related, for the most part, to wireless networking problems. Due to the emergence of a number of networking environments with "challenging" conditions for traditional networking (e.g., vehicular networks, underwater networks, mobile sensor networks), as well as the rapidly growing demand for mobile data and new applications, DTNs received a lot of attention as an alternative networking paradigm in both "extreme" as well as "regular', urban settings. For this reason, I have continued working on this topic, building up on the foundations set during my PhD, along the three main directions. In addition, I have also started exploring a number of new areas related to future cellular networks. The approach followed is in most cases analytical, at first, applying different tools like stochastic process theory, queueing theory, spectral graph theory, optimization theory, etc. to model the problem. Given an analytical model, the work is then often complemented with the design of an efficient algorithm for the problem, and extensive validation through realistic simulations (using real data any time these are available). In the following, I briefly describe some of these areas and related contributions. Some additional areas I've worked on, such as Cognitive Networks, Internet Traffic Classification, and Distributed Storage, are not mentioned here for brevity.

Performance Modelling and Prediction in DTNs: Analytically predicting the performance of DTN algorithms is important both for understanding the feasibility of different applications in this context, but also to tune key protocol parameters towards achieving desired performance tradeoffs. The majority of analytical models for DTNs up to that point have used simplifying assumptions: *homogeneous mobility*, namely that all pairs of nodes encounter ("contact") each other as a Poisson process with equal rate, and *homogeneous traffic*, namely that any node may have a message for any other node with equal probability. While this facilitates analytical models based on Markov chains, common sense, as well as an abundance of real mobility traces suggested this to be unrealistic. To this end, I have worked on introducing heterogeneity for mobility and traffic parameters, as well as correlations between them, into existing analyses, proving closed form expressions for a number of generalized scenarios:

Heterogeneous mobility [1]: We have assumed that different pairs of nodes might meet with different rates. Specifically, we assume that these rates might correspond to an arbitrary contact matrix that can capture, skewed node degree distributions, community structure, etc., often observed in social networks and mobility traces. We have then proved an upper bound on the delay of epidemic routing, based on the spectral properties of the contact graph. This paper received the best paper award in IEEE WoWMoM 2012.

Heterogeneous and correlated mobility and traffic [2]: We go a step further, assuming that the probability that two nodes want to exchange traffic is not uniform, and might also depend on the mobility properties of the nodes. We then study analytically how this correlation affects performance, and demonstrate that simple replication algorithms might offer considerably smaller performance benefits, compared to what is expected for uniform, non-correlated models.

Heterogeneous and correlated node selfishness [3]: While commonly assumed that all nodes are willing to cooperate and act as relays, in practice some nodes might be willing to act as relays only for a specific set of sources or destination, different for different nodes. Although studies existed where some nodes or some messages might not be forwarded, these all assumed a uniform probability of not cooperating. In practice, this set might depend on social or mobility properties between nodes. To this end, we analysed the performance of networks with heterogeneous mobility, where the probability of forwarding a message between two nodes depends on their meeting rates. Our key results include closed-form expressions for the performance under rather generic cooperation and mobility models, as well as showing that node selfishness is less detrimental than normally considered, when selfishness is negatively correlated with strength of contact ties.

Heterogeneous mobility and complex forwarding algorithms [4]: While the above works were able to analyse performance in heterogeneous DTNs, they did so for relatively simple, "random" forwarding algorithms, belonging to the first generation of schemes proposed in the field. Subsequently, a number of sophisticated "utility-based" algorithms have been proposed that estimate and use mobility properties, social structure, and other relevant information to predict future contact opportunities and chose appropriate relays to forward messages to. Such schemes largely outperform random ones, but introduce correlation and memory into the system, making simple, markov chain based analysis intractable. To this end, we have proposed DTN-Meteo, an analytical framework that combines an arbitrary contact trace (related to heterogeneous mobility) and an arbitrary utility-based forwarding rule into an appropriate absorbing markov chain. This framework not only allows to predict the performance of state-of-the-art routing algorithms in heterogeneous networks, but also to identify (and improve) protocol shortcomings, such as the chance to get stuck in local maxima.

Summarizing, my work in this area after my PhD has helped extend significantly the range of scenarios and protocols for which analytical predictions can be made, and consolidated the knowledge regarding what scenarios are amenable to exact analysis (e.g. [2][3]) and when one needs to resort to bounds or numerical results ([1][4]). The gap between the two still remains, and it would be interesting to derive closed form approximations for even more realistic settings.

Mobility Modelling: The above works have introduced some realism to the rather simple mobility models used initially. Nevertheless, the complexity and realism of models used in analysis remained limited, in order to ensure tractability. Simulation-based evaluations, on the other hand, require mobility models that are as realistic as possible. The emergence of real mobility traces from a number of different networks, suggested the use of such traces directly in simulation studies. Yet, these traces are often small (a few 10s of nodes) and represent a single instance. Extensive sensitivity analysis requires one to be able to scale up the size of the network and manipulate key parameters. To this end, we have proposed a synthetic mobility model, TVCM, that introduces social structure, such as node communities and preferred locations, in the mobility model, and can be tuned to emulate the statistical properties of real mobility traces, such as the distribution of inter-contact times and contact durations [5]. While a number of other synthetic models with similar goals have been proposed in parallel, one advantage of TVCM is that it builds up from simple modules and remains analytical tractable with respect to key metrics of interest.

The emergence of real traces, allowed researchers to study additional properties of human mobility beyond the key feature of skewed inter-contact times. Specifically, a number of researchers at the time suggested that human mobility exhibits social properties, and proposed routing protocols that take advantage of these properties to improve routing decisions. To this end, in [6] we have analysed a number of mobility traces in order to investigate the extent to which social properties such as high clustering coefficient, small world phenomena, and skewed degree distributions indeed can be observed. Furthermore, in [7], we have extended this work and have found that a key property observed in real traces, related to how communities of nodes interact with each other, is not well captured by state-of-the-art mobility models. We have then proposed a generalized extension that can be applied to TVCM or other models (HCMM[8] was used as an example in this paper) to correct this behaviour without affecting other social properties. This was work was runner up for the best paper award in ACM MobiHoc 2011.

Protocol Design based on Social Network Analysis (SNA): The first protocols proposed for DTNs where based on random replication, e.g., forwarding the message to a random subset of relays, and forwarding based on simple predictions of future contacts, e.g., a node that met the destination more recently was deemed to have a better chance to encounter the destination again. However, as explained earlier, studies of real traces have found considerable structure in the mobility properties of nodes in various settings. A number of authors suggested that mobility, which in the context of DTNs affects future contacts between nodes, can be predicted, in a stochastic sense, so that better forwarding decisions can be made.

A key departure from existing protocols at the time, considering only pair-wise meetings, has been to consider the mobile network as a whole, aggregating the observed mobility statistics into a ("social") contact graph. Then, instead of just looking at the mobility relation between the candidate relay and the destination, one could consider the position of the relay in the whole graph (e.g., the "centrality" of the node) or the relative positions of the relay and the destination (e.g., belonging to the same community). In this spirit, in an initial work in this direction [9], we investigated how to modify the Spray and Wait protocol to consider the relative mobility of the node (corresponding essentially to "degree centrality" in a weighted graph), and provided some analytical and simulation based evidence for the performance improvement achievable thus.

A number of research papers have since used different concepts from social network analysis (SNA), in addition to the ones mentioned above, in order to proposed DTN algorithms that were proven to perform considerably better than random or simple utility-based schemes, with SimBet [10] and BubbleRap [11] being the most frequently cited. Nevertheless, these protocols, as well as most such protocols suffered from the same drawback: how to actually create the contact graph on which the necessary SNA metrics (e.g. centrality) are calculated. In principle, one looks at past contacts between a pair of nodes, and if this number exceeds a threshold a link between the pair is included in the graph. This threshold sometimes was taken to be equal to 1, i.e., if at least one contact occurred between the nodes a link is created, or was determined empirically by looking at the achieved performance. Alternatively, one could use a sliding time window of some duration, and look at past contacts only during that window. Nevertheless, in all these cases, unless the threshold or time window is correctly chosen, the contact graph might end up being almost fully meshed (too large window) or very sparse (too small window). In [12], we have studied the effect of such windowed-based aggregation. Our simulation results suggest that in most mobility scenarios, most choices of time window values or thresholds lead to either too dense or too sparse graphs for which the performance of SNA-based protocols collapses. In fact, the range of values for which good performance is achieved is rather narrow. This complicated the problem of practical SNA-based protocol design, because one cannot know in advance what this value is. To this end, we proposed a distributed non-supervised learning algorithm that uses the spectral properties of the observed graph, and iteratively tunes the window duration to maximize the algebraic connectivity of the graph. This latter has been found to be strongly and robustly correlated with the window values that maximize performance of SNA-based schemes both in synthetic and real mobility traces.

In addition to the line of work on Mobility Modeling and Opportunistic Networking, continuing till today, as soon as I joined Eurecom, I started exploring some additional research areas, such as Data Offloading, Small Cell Networks, and Cognitive Networks. I got interested in these areas not only due to the importance they carry in the context of future cellular networks, a key theme of interest in our department, but also because I recognized that the analytical skills that I have developed throughout my PhD and post-PhD years could be applied to a number of interesting problems therein. While this required a learning curve to familiarize myself with the various technologies involved, as well as a large body of literature behind each area, a number of interesting contributions were made already, and summarized below.

Mobile Data Offloading: Operators are having a difficult time keeping up with the exponential increase in data traffic demand. Upgrading to new technologies (e.g. 4G) is expensive, and not profitable due to flat rate plans. For these reasons, operators are investigating ways to offload as much data as possible through alternative means, such as WiFi networks and D2D communication. We have attempted to model both problems analytically, in order to better understand the impact of different network parameters on performance, as well as the feasibility of each approach. We have also used these models to optimize various aspects of offloading:

Flow-based offloading over WiFi: Currently, offloading over WiFi consists of switching *all* traffic to WiFi, when this is available. While this already offloads up to 30-40% of the total traffic, it is not clear how this depends on network characteristics, and also how it affects the performance of the user. In [13], we performed an analytical study of standard WiFi-based offloading based on a 2D Markov queueing model, and provided closed-form expression for both the offloading efficiency and user per-flow delay. In [14], we extended the queueing analytic model of [13], to study scenarios were flows can be delayed, up to a user- or application-defined deadline, until WiFi becomes available. In the case of user-defined deadlines, we have also shown how to optimally tradeoff delay-tolerance for better performance, e.g., in terms of cellular plan usage, energy consumption, etc.

Offloading on the edge: While some data traffic can be offloaded through WiFi, coverage is often sporadic. Furthermore, WiFi access points as well as other small cells (e.g., femto- or pico-cells) are often backhaul limited. To this end, caching near the edge of the network has been proposed as a means to reduce the load on the backhaul and core network, for content requested by multiple nodes (e.g., popular videos). In [15], we consider a scenario were content is cached on user devices. When another device is interested in the same content, it can request it from a neighboring device already storing it, instead of using up valuable radio and backhaul resources. A novelty of this approach is to allow some delay until some device with the content is encountered (if no such device is found, then the content is fetched as usual). This is in stark contrast with some existing works, considering device storage and D2D communication [16], which require that the two devices are within range at the time the content is requested, and thus requiring extremely dense topologies and being feasible only for highly popular contents. We show that this tradeoff allows one to use mobility of nodes to increase the effective coverage of each cache, offloading considerably more data with reasonable additional delays. Finally, in [17], we extend this model to assume a HetNet setup were content can be cached on both small cells and devices, and retrieved locally. We analyse the various costs involved, and formulate and study how to optimally place which contents on what types of nodes.

Small Cell Networks: Another popular way of dealing with excessive data demand in future cellular networks, is increased densification. Overlaying macrocell topologies with many smaller cells, such as pico- or femto-cells, can improve both coverage (if small cells are installed at the edge) and capacity (e.g., at hotspot locations). Nevertheless, dense complex topologies consisting of many heterogeneous cells, give rise to a number of problems that need to be addressed. The energy consumption of dense cellular networks is a growing concern for operators. Yet, turning off a base station (e.g., when traffic is temporarily low) should not lead to excessive performance degradation for users that need to be re-associated. In [17], we made a first step towards an analytical investigation of this tradeoff, assuming both elastic and non-elastic traffic, and analytically related them to key parameters such as user traffic mix, cell load, user density, etc. Unlike existing studies, this analysis is applicable to short time scales as well (up to a few minutes), and initial results demonstrate significant additional power savings without violating QoS constraints. Furthermore, user association in HetNets is a complex tradeoff, between maximizing the performance of the user in question, and improving the network-wide performance through load-balancing. In order to optimally make this decision in future networks, one needs to carefully consider the different types of traffic generated by UEs (best-effort and dedicated) as well as uplink and downlink traffic. In [18], we formulate an optimization problem that considers all these aspects, and derive a fully distributed algorithm that converges to the optimal solution. We further show that this optimal solution is the weighted harmonic mean between the individually optimal solutions derived when considering only a single dimension of the problem (e.g. only downlink best-effort traffic).

References:

[1] A. Picu, T. Spyropoulos. and T. Hossmann "An Analysis of the Information Spreading Delay in Heterogeneous Mobility DTNs" IEEE WoWMoM 2012.

[2] P. Sermpezis, T. Spyropoulos, "Modelling and analysis of communication traffic heterogeneity in opportunistic networks", to appear in IEEE Transactions on Mobile Computing.

[3] P. Sermpezis, T. Spyropoulos, “Understanding the effects of social selfishness on the performance of heterogeneous opportunistic networks,” Computer Communications, 2014.

[4] A. Picu, T. Spyropoulos, “DTN-Meteo: Forecasting the Performance of DTN Protocols Under Heterogeneous Mobility,” IEEE/ACM Transactions on Networking.

[5] W. J. Hsu, T. Spyropoulos, K. Psounis, and A. Helmy, “A Realistic Mobility Model for Time-Variant User Mobility in Wireless Networks,” ACM/IEEE Transactions on Networking 2009.

[6] T. Hossmann, T. Spyropoulos, and F. Legendre, “A Complex Network Analysis of Human Mobility,” IEEE INFOCOM Workshop on Network Science in Communication (NetSciCom) 2011.

[7] T. Hossmann, T. Spyropoulos, and F. Legendre, “Putting Contacts into Context: Mobility Modeling beyond Inter-Contact Times,” ACM MobiHoc 2011.

[8] C. Boldrini, and A. Passarella, “HCMM: Modelling spatial and temporal properties of human mobility driven by users' social relationships,” Computer Communications, 2010.

[9] T. Spyropoulos, T. Turletti, K. Obraczka, “Routing in Delay Tolerant Networks Comprising Heterogeneous Populations of Nodes,” IEEE Transactions on Mobile Computing 2009.

[10] E. Daly, and M. Haahr. "Social network analysis for information flow in disconnected delay-tolerant MANETs." IEEE Transactions on Mobile Computing, 2009.

[11] P .Hui, J. Crowcroft, and E. Yoneki. "BubbleRap: Social-based forwarding in delay-tolerant networks." IEEE Transactions on Mobile Computing, 2011.

[12] T. Hossmann, T. Spyropoulos, and F. Legendre, “Know Thy Neighbor: Towards Optimal Mapping of Contacts to Social Graphs for DTN Routing,” IEEE INFOCOM 2010.

[13] F. Mehmeti, T. Spyropoulos, “Performance analysis of ‘on-the-spot’ mobile data offloading,” IEEE Globecom 2013.

[14] F. Mehmeti, T. Spyropoulos, “Is it worth to be patient? Analysis and optimization of delayed mobile data offloading,” IEEE INFOCOM 2014.

[15] P. Sermpezis, T. Spyropoulos, “Not all content is created equal: effect of popularity and availability for content-centric opportunistic networking,” ACM MobiHoc 2014.

[16] N. Golrezaei, A. Molisch, G. Dimakis, and G. Caire, "Femtocaching and device-to-device collaboration: A new architecture for wireless video distribution." IEEE Communications Magazine 2013.

[17] N. Sapountzis, S. Sarantidis, T. Spyropoulos, N. Nikaein, U. Salim, “Reducing the energy consumption of small cell networks subject to QoE constraints,” IEEE Globecom 2014.

[18] N. Sapountzis, T. Spyropoulos, N. Nikaein, U. Salim, “An Analytical Framework for Optimal Downlink-Uplink User Association in HetNets with Traffic Differentiation,” IEEE Globecom 2015.