A Communications-Theoretic Approach to the Modeling, Analysis and Optimization of Heterogeneous Cellular Networks by Using Stochastic Geometry

Application Context and Reference Scenario: The traditional cellular network fails to keep pace with the mobile data explosion forecasts. We need innovative technologies and cellular topologies that can meet these demands in an energy-efficient and sustainable manner. To address this challenge, and, thereby, to maintain profitability, it is crucial to develop energy-efficient wireless architectures, transmissions schemes, protocols, cooperative relaying and heterogeneous network solutions based on smaller cells. In fact, competing forces, i.e., spectral efficiency and throughput vs. energy efficiency and low-complexity, are rapidly changing the topology of operational cellular networks, which are undergoing a major modification: the migration from voice centric, circuit switched and centrally optimized networks towards data centric, packet switched and high-throughput networks. The cellular network of the future will be: i) heterogeneous and characterized by a small cell infrastructure relying on inexpensive and low-power base stations (e.g., femtocells) in order to achieve high data rates; ii) green, by evolving from a throughput optimized scenario towards throughput and energy optimized networks; iii) interference-aware, by exploiting (instead of tolerating) interference and, thus, realizing the expected benefits of small-cell-based heterogeneous networking; iv) characterized by a high level of cooperation among base stations and user terminals, by achieving improved coverage and reduced energy consumption through relay-aided transmission, as well as an improved reliability and reduced packet transmissions/retransmissions through distributed diversity and Network Coding (NC); and v) relying upon new air-interface techniques and physical-layer standards for increasing the energy efficiency, reducing the implementation and
signal processing complexity, whilst meeting the required spectral efficiency. In this emerging cellular network topology, low-power nodes are overlaid within a macrocell hence creating a wireless heterogeneous network. These low-power nodes may be picocells, femtocells, fixed and mobile relays, cognitive radios, remote radios heads, distributed antenna-elements, etc. From this description of heterogeneous cellular network architecture, it is clear that the heterogeneity expands the coverage, improves the network capacity, reduces the energy consumption and enhances the link reliability through a more dense deployment of low-cost and low-power access points. The reason behind all these potential advantages of the heterogeneous cellular network architecture is simple: the densification of access points inherently reduces the distance between the network elements. Since, based on electromagnetic laws, the received power falls off with the transmission distance and obeys an inverse power-law where the exponent is known as the path loss exponent, this implies that reducing the distance has a beneficial impact on both the capacity and the transmission power. More specifically, the capacity can be increased and the transmission power can be reduced. The mathematical modeling of cellular networks is usually conducted through abstraction models, which rely upon simplified spatial models for the locations of the Base Stations (BSs). Common approaches include the Wyner model, the single-cell interfering model, and the hexagonal grid model. However, these abstraction models are either inaccurate for many operating conditions or they still require extensive numerical computations. As a result, the analysis and design of cellular networks is often conducted by resorting to network simulations for selected scenarios, which represent specific arrangements of BSs. Furthermore, none of these approaches is scalable and flexible enough for application to the emerging heterogeneous cellular network scenarios because of the large number of BSs, of the more complicated interference patterns, as well as of the fact that no low-power BS is dominant with respect to the others. Thus, usual approximations are no longer applicable. To circumvent these problems, a new abstraction model for the mathematical analysis of heterogeneous cellular networks is emerging, which is referred to as Poisson Point Process (PPP) based abstraction. With the aid of this abstraction model, the locations of the BSs are modeled as points of a homogeneous PPP. Recent results have confirmed that the PPP-based abstraction model is capable of accurately reproducing the main structural characteristics of operational cellular networks. The usefulness of the PPP-based abstraction model originates from its analytical tractability and from the possibility of leveraging mathematical tools of applied probability, such as stochastic geometry, for performance analysis. Owing to its mathematical tractability, the PPP-based abstraction model is now routinely used for the analysis and design of wireless networks in general and cellular networks in particular.

Opportunities for Research: This application context is rich of research opportunities. By leveraging the emerging PPP-based approach for modeling, analysis and optimization of heterogeneous cellular networks, we intend to study the fundamental performance of this emerging application scenario by understanding the potential of many important building blocks in terms of error probability, coverage, rate, energy efficiency, etc. Network-coded cooperative wireless networks are an important atomic element of the heterogeneous cellular network of the future. In that regard, it is extremely important to study how the randomness due to the network topology and to the user mobility impacts the diversity order of various types of relaying protocols with and without NC. Furthermore, we are interested in understanding the impact of the channel and spatial state information on the design of the relay protocol and on the decoding complexity at the destination when NC is applied at the relays. The impact of the intra-source and intra-relay channels is also a subject of practical interest, since these channels can be either a source of interference and
an opportunity for improving the decoding performance at the relays. In addition, we intend to provide an answer to these research issues by taking into account the other-cell interference, which may be generated by both users and access points using direct link transmissions as well as other users using relaying and network-coded cooperative communications. The statistical distribution of this aggregate interference for distributed networks is unknown to date. To better understand, consider a simple scenario with a single source, a single relay and a single destination. Even though the transmissions of the relay and the source occur in different time-slots, the spatial positions of the interferers are likely to be almost static during the two time-slots. As a consequence, the interferences perceived at both the relay and destination are partially correlated and the correlation depends on the relative distance of the nodes. The statistical distribution of this interference as a function of the spatial locations is unknown even for the three-node scenario. However, it plays a crucial role both for performance analysis and for interference-aware transceiver design. In addition, future cellular networks will likely exploit multiple-antenna techniques, with a densification of the co-located antennas as well. The analysis of Multiple-Input-Multiple-Output (MIMO)-aided heterogeneous cellular networks is an avenue of research possibilities due to the large variety of single-user, multi-user, distributed and coordinated MIMO solutions that can be used, none of them being the best choice for each application scenario. For example, for many MIMO-aided cellular networks, the statistical distribution of the intra-cell and inter-cell interference is not known in closed-form due to some correlations arising from the application of beamforming vectors and precoding matrices. Finally, it is worth mentioning the single-RF MIMO is considered to be a good candidate as a new energy and spectral efficient physical layer transmission scheme for emerging heterogeneous cellular networks. We will carefully investigate the potential of single-RF MIMO transmission in this application context. The development of tractable mathematical frameworks for the analysis of cellular networks comprising both MIMO and relay-aided transmission is one of the long-term research objectives of this Ph.D. project proposal.

The Principal Investigator is currently involved in important European projects in the area of heterogeneous cellular networks (CROSSSFIRE and NEWCOM#). The Ph.D. students will benefit from this vast experience on the topic.

- **Publications of the laboratory in the field (max 5)**

- **Specific requirements to apply, if any**

Candidates with a strong background on electrical engineering, wireless communications are welcome. A strong mathematical background is an important requirement for this position.

**Biography of the Principal Investigator**

Marco Di Renzo (S'05-AM'07-M'09) was born in L'Aquila, Italy, in 1978. He received the Laurea (cum laude) and the Ph.D. degrees in Electrical and Information Engineering from the Department of Electrical and Information Engineering, University of L'Aquila, L'Aquila, Italy, in April 2003 and in January 2007, respectively. In October 2013, he received the Habilitation à Diriger des Recherches (HDR) degree majoring in Wireless Communications Theory, from the University of Paris-Sud XI, Paris, France.

From August 2002 to January 2008, he was with the Center of Excellence for Research DEWS, University of L'Aquila, L'Aquila, Italy. From February 2008 to April 2009, he was a Permanent Research Associate with the Telecommunications Technological Center of Catalonia (CTTC), Barcelona, Spain. From May 2009 to December 2009, he was an EPSRC Research Fellow with the Institute for Digital Communications, The University of Edinburgh, Edinburgh, United Kingdom.

Since January 2010, he has been a Tenured Academic Researcher (Chargé de Recherche Titulaire) with the French National Center for Scientific Research (CNRS), as well as a faculty member of the Laboratory of Signals and Systems (L2S), a joint research laboratory of the CNRS, the Ecole Supérieure d'Electricité (SUPELEC) and the University of Paris-Sud XI, Paris, France. His main research interests are in the area of wireless communications theory. He is an author of 44 and 117 peer-reviewed journal and conference papers, respectively. He is a Principal Investigator of four European-funded research projects (Marie Curie ITN-GREENET, Marie Curie IAPP-WSN4QoL, Marie Curie ITN-CROSSFIRE and Marie Curie IAPP-SmartNRG).

Dr. Di Renzo is the recipient of the special mention for the outstanding five-year (1997-2003) academic career, University of L’Aquila, Italy; the THALES Communications fellowship for doctoral studies (2003-2006), University of L'Aquila, Italy; the Best Spin-Off Company Award (2004), Abruzzo Region, Italy; the Torres Quevedo award for research on ultra wide band systems and cooperative localization for wireless networks (2008-2009), Ministry of Science and Innovation, Spain; the “Dérogation pour l’Encadrement de Thèse” (2010), University of Paris-Sud XI, France; the 2012 IEEE CAMAD Best Paper Award from the IEEE Communications Society; the 2012 Exemplary Reviewer Appreciation Award from the IEEE WIRELESS COMMUNICATIONS LETTERS of the IEEE Communications Society; the 2013 IEEE VTC-Fall Student Best Paper Award from the IEEE Vehicular Technology Society; the 2013 NoE-NEWCOM# Best Paper Award; and the 2014 IEEE ICNC Single Best Paper Award Nomination of the Wireless Communications Symposium from the IEEE Communications Society. He currently serves as an Editor of the IEEE COMMUNICATIONS LETTERS. He is a Founding Member of the IEEE Green Cellular Networks Special Interest Group sponsored by the Technical Subcommittee on Green Communications and Computing of the IEEE Communications Society.