# Application for a PhD Grant Programme

# at the Laboratory of Excellence UCN@SOPHIA

### September 2015

**Infrastructures: Heterogeneity and Efficiency "To design novel wired/wireless infrastructures, offering high performance and autonomous operation".**

Autonomous systems have the potential to provide the user with new services. These services range from social networking to global sensing (e.g. improving quality of life / providing better medical services). For that purpose, we will develop energy- and spectrum-efficient transmission methods, design autonomous network "clouds" that gravitate at the edges of the core network and study the algorithmic foundations of the general context of autonomous computing and communication systems (role of awareness).

## Title of the PhD Project:

## Ultra-dense cloud-based wireless networks: Design and Analysis

Involved Research Units: EURECOM (hosting research unit) and Inria.

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# Context and State of Art

If the 4G wireless architecture was conceived to satisfy the increasing demand of high data rate, the next 5G wireless systems shall satisfy not only the increasing demand of higher and higher data rates at very competitive prices but it shall also be able to efficiently accommodate for and adapt to a huge dynamic range of services, applications, and types of devices expected in the near future (e.g. see smart cities technologies). In order to achieve these twofold very challenging objective, appealing candidate architectural solutions leverage on the key complementary concepts of ultra-densification and heterogeneity. The concept of ultra-densification exploits the basic idea that bringing a radio transmitter and receiver closer together reduces the necessary transmit power to overcome pathloss and other power-wasting-phenomena (e.g. fading) enhancing power and spectral efficiencies. In 4G, it motivated the introduction of small cells. Appealing ultra-dense scenarios for 5G wireless networks envision ultra-dense distributed antenna systems based on remote distributed antennas (usually referred to as remote radio heads), empowered by the e-cloud for a centralized processing. This architecture, referred in the following as ultra-dense network (UDN) eliminates the downside of inter-cell interference in uncoordinated small cells (e.g. femto-cells) and heavy signaling in coordinated cells (e.g. Cooperative MultiPoints). Heterogeneity is necessary to efficiently cover the above mentioned huge dynamic range of applications and services. From an architectural point of view, it concerns the co-existence of emerging and legacy technologies such as operator-driven UDNs and massive-MIMO enriched macro-cells, and at a second level, user-deployed or "crowd-sourced" access nodes, such as Wi-Fi access points, femto-cells, or even smart-phones acting as local access prosumers. This heterogeneous ultra-dense architecture is referred in the following as heterogeneous-UDN (H-UDN).

We intend to provide insights and fundamental understanding of critical, unknown aspects of this complex heterogeneous scenario and leverage on them to propose practical and efficient criteria and algorithms for practical design and implementation of 5G ultra-dense networks. Thus, this doctoral program is completely aligned with the objectives of the Labex strategic direction **Infrastructures***: Heterogeneity and Efficiency "To design novel wired/wireless infrastructures, offering high performance and autonomous operation".* More specifically, we will focus on the following aspects:

- Analysis of the fundamental limits of the system in terms of spectral and energy efficiency for UDN and H-UDN;
- Design of scalable optimum or nearly optimum resource allocation algorithms for UDN and H-UDN.

The fundamental limits of UDNs are unknown while a deep understanding is determinant in defining research and technological strategies. UDN systems empowered by the e-cloud should merge the benefits of the previously proposed architectures such as uncoordinated small cells and CoMP without having or substantially limiting their downsides. The aim of the proposed doctoral program is to explore the fundamental limits and potential of this architecture and, specifically, taking into account the ***geographical distribution*** of antennas, eventually multiple antennas per site, of users and/or channel properties such as slow/fast fading. Fundamental metrics playing a key role in the system behavior are system parameters, such as the system load, i.e. the ratio between number of users and antennas, their geographical distributions, concentration of antennas at each wireless access port, and physical parameters, such as exponent loss. An additional variable in the performance of these systems is the kind of transmitters and receivers adopted. To analyze this aspect we will consider linear and optimal transmitter/receivers. Large system analysis will provide insights on the impact of these parameters on spectral and energy efficiency and will unveil the interplay between these key parameters.

Beside these strategic insights, the proposed large system analysis will provide practical algorithms and criteria for system design such as indications on the wireless access port deployment, the number of antennas per access port, antenna selection. The promised enhancements in spectral and power efficiency of UDN with centralized processing steam from theoretical capability of this architecture to utilize all received signals as signal of interest instead of interfering signals and jointly process them. These potentials collide with a substantial increase in complexity whose practical limiting impact is further exacerbated by the real time requirements of communication systems. Therefore, it is crucial to develop low complexity adaptive techniques capable to acquire crucial information and use it to reconfigure the system on the fly for optimal resource allocation of both physical resources such as frequency and power and computational resources.

A concrete example of algorithms for complexity reduction by and for resource allocation Is provided by access points clustering. Although ideal models for UDN empowered by the e-cloud consider a completely centralized processing, in practical systems is necessary to find a good compromise between the jointly processed signals and the complexity of the receiver. By jointly processing a very large number of received signals it is possible to optimally combat interference but it has a complexity in general unaffordable for real time systems. Then, it is necessary to cluster antennas properly to process jointly only signals from the antennas in the cluster while minimizing the detrimental effects of interference. An optimal clustering is a problem of unaffordable complexity in real system that requires scalable suboptimal solutions with nearly optimal performance or controlled performance loss.

In this heterogeneous context, the absence of a well-planned access point deployment and frequency allocation implies that the geographical location of transmitters and receivers and the natural signal attenuation introduced by the physical propagation mean play a fundamental role. As we detail in the following, the analysis available in literature is able capture these effects only in the case of scalar signal processing but not in the case of vector processing (joint processing of multiple signals transmitted/received at different location). This doctoral program aim at filling this gap.

UDNs with super-centralized signal processing empowered by the e-cloud merge the concept of distributed antenna systems (DAS), introduced first in [SRR87,K96], with the concept of extended multicell networks with cooperating multiple antenna base stations introduced in [W94]. In the latter context, random matrix theory (RMT) resulted as a very powerful investigation tool. The analysis of these systems dates back to the works of Zaidel et al. [ZSV01] and it is based on a simple one-dimensional linear network referred in literature as Wyner network. The Wyner model is also adopted in most of the subsequent contributions based on RMT. As examples, in [ABEH06] the benefit of cooperation on a multi-cell MIMO network is studied as the number of users and antennas at the base station grow large, in [LZS10] a more refined model is considered with directional antennas and finite number of users and antennas at the cooperating base stations. An extensive review on the fundamental limits of cooperative cellular systems can be found in [SSBH+07]. Key downsides of these analyses based on RMT are due to the fact that the models do not account for the geographical random distribution of transmit and receive wireless nodes. A two-dimensional network model with randomly distributed nodes was proposed in [MB13] and targeted the optimization of the transmit power. The randomness in the system is obtained by locating transmit and receive pairs  randomly in a lattice. Coherent potential approximation, a technique applied in statistical mechanics, is applied.

Recently, significant efforts have been spent in the analysis of cellular DAS in downlink [CA07, HWKS11, ZA08, LY13] assuming that the antennas are deployed at fix locations in a regular grid or as Poisson Point Processes with a certain intensity. This latter assumption opened the way to the application of stochastic geometry (e.g. [BB09]). A detailed overview can be found in [LY13]. Multiuser DAS in uplink were studied in [GXZW07] and [FLZW+10] using random matrix theory (e.g. [CD11]) and considering a given finite area. Due to strong underlying approximations, in both cases, a good match between simulations and theoretical results appears when the system becomes insensitive to the receive antenna layout, as pointed out in [D11]. In [D11] a single cell of given area with receive antennas uniformly distributed within the cell is considered. A lower bound for the multiple access channel capacity is provided under the assumption of constant receive power per user terminal, channel state information (CSI) at the receiver and with or without CSI at the transmitter.

When the network topologies are described by Poisson point processes (PPP), stochastic geometry (SG) provides the analytical tools for network analysis. However,  tractability does not extend to vector channels. First attempts to combine tools from RMT and SG to the study of networks with random topology are proposed in [HMCD12] and [AMWD+12]. Recently, an novel promising approach that embeds the geometric randomness of PPPs directly into a random matrix was introduced by the authors of this proposal [C14] by extending the class of Euclidean random matrices.

Up to the authors' knowledge, the analysis of the fundamental limits of H-UDN systems is limited to the cases scalar signal processing for completely independent heterogeneous networks whose nodes are modeled as independent PPPs by applying SG.

As already mentioned, in real networks, the cloud-empowered UDN architecture requires a dynamic clustering of the access points and of the corresponding signals to be jointly processed. This task was completely absent in previous generation networks and, recently, it is attracting  a wide interest in the scientific community. Static, dynamic, and hybrid approaches are object of intensive research. The interested reader can refer to [PLH15] for an detailed overview of the available results. In [DV14], a dynamic clustering of RRHs along with an opportunistic scheduling of the users is proposed with the objective of maximizing the overall system utility. By avoiding the schedule of user terminals at the edge of an certain RRHs' cluster implies a substantial performance enhancement. This policy is shown to be asymptotical optimum under a dynamic clustering of the RRHs. Complexity and scalability are the typical downsides of the existing approaches and the network heterogeneity is not typically considered. In this doctoral program, we intend to mitigate or completely avoid these limitations applying to this setting approaches borrowed from complex networks.

# Challenges

The key features of UDNs and H-UDNs lie in the geographical distribution of users and network access points (RRHs), such that transmit- and receive-nodes are closer, and in the joint processing of multiple transmit- or receive-signals, referred shortly as vector signal processing. The actual benefits in terms of fundamental limits (e.g. spectral and power efficiency) of UDN and H-UDN requires an analysis able to capture simultaneously the impact of network node geographical locations and the joint processing. As observed in the previous section, this joint analysis is not available since the widely used tools offered by SG model effectively the geographic random distribution of the communication nodes but not vector signal processing. In a complementary way, the available results in RMT enable a large system analysis of the vector signal processing but do not capture the randomness in the geographic location of nodes. Thus, mathematical tools for a systematic and comprehensive analysis of UDN and H-UDN are not available and developed yet. Furthermore, as indicates recent study [Ketal15] a basic PPP stochastic geometry model might not represent sufficiently accurately the real distribution of antennas. Therefore, ideally new tools would be more versatile with respect to modelling of antenna locations. Consequently, the fundamental limits of UDN and H-UDN are unknown to a large extent while their analysis is crucial to steer effective research directions and develop successful technologies. Large system analysis provides fundamental, insightful knowledge on system quantitative properties by a description based on cardinal macroscopic parameters of the system and it is especially suitable to provide general guidelines for scientific and technical developments. Inspired and motivated by the strategic relevance of the topic and supported by our initial results in [C14, C14a], we intend to take up the challenge of developing analytical tools able to capture simultaneously the impact of network node geographical locations and the joint signal processing in order to provide a large system analysis of UDN and H-UDN empowered by the cloud in terms of spectral and power efficiency.

A variety of different aspects such as channel characteristics, e.g. line of sight (LOS), fading with and without LOS, different kinds of heterogeneity, have to be analyzed and they will require most likely, independent analysis.

One more challenge is to strike a delicate balance between centralized and distributed solutions. Most likely we shall need to design an hierarchical approach, in particular, based on hierarchical clustering, for resource allocation schemes which apply centralized or distributed approach based on the required level of decentralization at a given level of hierarchy. Markov Chain Monte Carlo (MCMC) methods and Gibbs Sampling methods are examples of flexible easily distributed approaches for resource allocation [Ketal07,SS12].

It is apparent that there is tradeoff between the fundamental performance parameters like rate and spectral/power efficiency and complexity: more signals are jointly processed higher is the network performance and higher will also be the complexity. Real time constraints, power and hardware costs make unfeasible an ideal global processing and require an analysis of this tradeoff to design a dynamic system able to achieve nearly-optimum performance with low or affordable complexity.

# Methodologies and Expected Results

Random Matrix Theory (RMT) resulted in a very powerful tool to investigate spectral efficiency of single-cell and multi-cell multiuser systems with multiple antenna array at the communications nodes while stochastic geometry (SG) unveiled fundamental properties of geographically distributed nodes. We intend to capitalize on our expertise on RMT (e.g. [CM07],[CMD10],[ACK15]), on recent developments on sparse random matrices and stochastic geometry [AAG14], eventually combined, to get strategic insights on the fundamental limits of UDNs and H-USNs empowered by the e-cloud.

More specifically, we intend to leverage on a recent result of ours [C14, C14a] where we generalized the class of Euclidean random matrices (ERM) to two independent sets of points in order to capture the randomness of geographical locations of distributed transmit and receive antennas in a unique channel matrix.

ERM are a group of random matrices introduced in [MPZ99] and found applications in various fields of physics, from the theoretical description of supercooled liquids to disordered superconductors. Given a random set in an Euclidian space $E$ and a deterministic function $f : E \times E \rightarrow R$, the entries of an ERM realization consists of the values of $f(\cdot, \cdot)$ on all possible pairs of elements of the random set. A detailed overview can be found in [GS11, GS13] and several techniques to approximate the eigenvalue distributions and spectral properties of ERM are proposed. More recently, EMR received attention from the mathematical community with relevant exact results in the case as the dimensions of the Euclidean space grows large with the matrix size [B08, B12]. However, these classes of ERM are not suitable to model communications systems. Up to the authors' knowledge, the results in [C14, C14a] are the first extension of ERM theory to a two independent sets of points as well as the first application of ERM theory to telecommunication systems. We apply an approximated decomposition of ERM widely utilized in physics which enables the application of free probability theory (e.g. [HP00]). The results in [C14, C14a] model communication systems with strongly attenuated channels with only LOS and without fading. Extensions to channels with Rayleigh or Rice fading is far from being simple as well as possible extensions to consider collocated antenna arrays. The analysis of classes of ERM modeling co-existing independent UDNs or H-UDN also requires the development of ad-hoc results.

In the proposed doctoral program, we are interested in exploring the fundamental limits and potentials of both UDN and well defined scenarios of H-UDNs and, eventually, their trade-off by a large system analysis accounting for centralized signal processing and random geographical distribution of the nodes, in presence of fading and eventually multiple collocated antenna arrays at the network nodes. The effect of macroscopic system parameters, such as load, i.e. the ratio between number of UEs and antennas, geographical distribution of EUs and wireless access ports, concentration of antennas at each wireless access port, and physical parameters, such as exponent loss on the network performance will be analyzed. An additional variable in the performance of these systems is the kind of transmitters and receivers adopted. To analyze this aspect we will consider linear and optimal transmitter/receivers.

As already mentioned, large system analysis, based on the ERM tools that will be studied in the doctoral program, will be insightful to understand the impact of global network parameters on the network performance. Additionally, it will provide practical criteria for the system design such as indications on the wireless access point deployment, the number of antennas per access point, antenna selection.

For the analysis of heterogeneous scenarios that cannot be completely captured by classes of ERMs, we will consider the possibility to combine results from RMT, ordered statistics, and SG.

In UDNs empowered by the cloud, (a) scalability, (b) flexibility to adapt to user geographical distribution, and (c) robustness e.g. to limited channel state knowledge, carrier and delay synchronization are fundamental requirements for resource allocation. Dynamic clustering of signals for joint processing limited to signals within each cluster, is an appealing answer to these constraints. However, an optimal clustering is a problem of extreme complexity in itself and the standard solutions are not tailored to deal with a very large number of nodes. In this doctoral program, we resort techniques typically used in complex networks and based on random graphs to propose an innovative approach to this problem. Complex networks are intrinsically characterized by a gigantic number of nodes and algorithms for complex networks are designed to meet the above mentioned requirements of scalability, flexibility and robustness. More specifically, we will redesign and adapt algorithms known as community detection algorithms, to cluster antennas with low complexity.

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