Spatial spectrum reuse in heterogeneous wireless networks: interference management and access control

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Abstract. The scope of this dissertation is to deal with challenges arising from the introduction of femtocells and D2D communications in cellular networks standardized by 3GPP Release 8 and beyond, i.e., Long Term Evolution (LTE) and LTE-Advanced (LTE-A) networks. More specifically, for the case of femtocells, the interference management problem is studied, while for the D2D communications the radio resource management and the spectrum access challenges are addressed. First, different control channel interference management schemes for femtocell-overlaid LTE/LTE-A networks are studied, while an innovative power control scheme for the femtocell downlink transmissions is proposed, utilizing the end user's quality of experience. Considering the much more dynamic environment defined by the D2D communications in a cellular network, two D2D spectrum sharing approaches are proposed, one based on resource allocation, and one based on contention. In both of the cases, the main requirement is the solution of the device discovery problem. To this end, enhancements in the 3GPP standardized access network are proposed, enabling a resource request/allocation procedure for device discovery transmissions, while a spatial spectrum reuse scheme is designed and evaluated, as an effort to reduce the consumption of radio resources for discovery transmissions.

1 Dissertation Summary

1.1 Motivation and scope

Nowadays, wireless communication services and broadband Internet access have converged to deal with the present requirements for ubiquitous and highly reliable communications. International Mobile Telecommunications-Advanced (IMT-Advanced) quantifies these requirements promising an all-Internet Protocol (IP) packet switched network with data rates analogous to those provided by wired communication systems.

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In this direction, a new architecture of cellular networks introduces a major paradigm shift from wide-range cells with high transmit power (macrocells) to low-power small-sized cells. The success of this shift relies on capitalizing on the performance improvements derived by increasing the spatial spectrum utilization and enhancing the indoor coverage. Historically, spatial spectrum reuse has been, by far, the most efficient approach in improving cellular system capacity, compared to approaches such as the adoption of efficient modulation schemes. Also, the enhancement of indoor coverage will be essential in the near future, since the majority of the voice and data traffic will originate from indoor users. To this end, the 3rd Generation Partnership Project (3GPP) standardized a novel type of small-sized cells called femtocells or femtos. Since the licensed spectrum resources are expensive and scarce, femtocells are expected to spatially reuse licensed spectrum under the so-called co-channel deployment. Installed by the consumers in an unplanned manner, they also provide the option to serve only a limited set of subscribed users through the so-called closed subscriber group (CSG) mode, changing in that way the landscape of cellular networks in the following years. However, before operators and consumers reap the benefits provided by femtocells, several challenges must be addressed, including the mitigation of the generated interferences.

In parallel to the femtocell proliferation, one of the prominent topics considered toward achieving IMT-Advanced requirements is the Device-to-Device (D2D) communications, i.e., direct communications in a cellular network, without the intervention of the base station, when the transmitter and the receiver are in close proximity. Differing from conventional approaches, such as Bluetooth and WiFi-direct, D2D communications utilize licensed spectrum, while no manual network detection-selection is needed. Comparing to the very appealing cognitive radio communications, where secondary transmissions are allowed in parallel with primary cellular transmissions, D2D communications are established by standard/primary cellular users, reaping the benefits of being synchronized and controlled by the central (primary) base station. The introduction of D2D communications in cellular networks is expected to be beneficial from a variety of perspectives. The short distance between D2D users results in better channel conditions, leading to higher data rates, lower delays and lower energy consumption. Additionally, D2D users are connected through a direct link and the intermediate transmission to a base station is avoided, saving network resources and processing effort from the network. Also, the coexistence of cellular and D2D links can lead to more efficient spectrum utilization and higher spatial spectrum reuse, while new business models, probably with a new charging policy for users, may be designed. However, D2D communications do not come without a cost. On the one hand, interference-free conditions between D2D and cellular transmissions, as well as among D2D pairs are required, while on the other hand, the device discovery problem should be faced, i.e., the need for a D2D transmitter to know whether the target receiver is in its vicinity and, thus, in valid distance to start a D2D communication.

The 3GPP (3rd Generation Partnership Project) already provides the fundamental specifications for the femtocells in Release 8 and Release 10 for LTE (Long Term Evolution) and LTE-A (LTE-Advanced) networks, respectively, while the first efforts for standardizing D2D communications begun in Release 12, under the term Proximity Services (ProSe).

Taking all the above into account, the scope of this dissertation is to deal with challenges arising from the introduction of femtocells and D2D communications in LTE/LTE-A cellular networks. More specifically, the focus is on the following challenges:

- **Interference management in femtocell-overlaid networks**
  This problem refers to femtocells that reuse the cellular spectrum under the co-channel deployment, raising new types of interference. The problem is more severe when femtocells operate under the closed subscriber group mode, and, thus, deny the access to non-subscribed users. In this case, the interference perceived during the downlink by unsubscribed users in femtocell proximity needs more investigation. Special investigation is needed for the interference in control channels, which carry vital information for the connection maintenance.
- **Spectrum access and management for D2D communications**
  This problem refers to the management of the radio resources used for the direct transmissions in a cellular area. The main issue is how the available radio resources will be shared between cellular and direct communications, and also how the radio resources that are used for direct transmissions will be allocated to the D2D transmitters. The target is to guarantee interference-free conditions to cellular and D2D users.
- **Spectrum access and management for device discovery**
  This problem is quite similar to the previous one. However, it referred to discovery transmissions, i.e., frequent, low range direct transmissions with no QoS requirements that are used by a device in order to discover another device in its vicinity. Device discovery is an important procedure and is required prior the establishment of a D2D communication. The nature of these transmissions calls for designing different spectrum access and management schemes, than that used for the D2D communications.

A comprehensive study of the above mentioned problems is provided, while some innovative solutions and working directions are proposed.

1.2 Dissertation contributions

In this dissertation, the reader can find a comprehensive description of the architectural and physical layer aspects of the LTE/LTE-A networks, as well as, the current standardization efforts for D2D communications and the main specifications for solving the device discovery problem. However, the dominant contributions of this dissertation are summarized below:

- A thorough study of fundamental and emerging interference schemes for femtocell-overlaid LTE-A networks, and a qualitative and quantitative performance comparison from the perspective of control channel protection is provided. The focus is on the downlink control channel interference caused by femtocells to macrocell users located in the total macrocell area or in a target femtocell area, while the impact of the femtocell deployment density on such interference is assessed.

- An examination on whether and in what extent the interferences in a femtocell-overlaid network are reflected as variations in the end-users' satisfaction is provided. Additionally, the relation between the SINR (signal to interference plus noise ratio) and the perceived Quality of Experience (QoE) at an interference-victim is studied and formulated towards designing a QoE-aware power control interference management scheme.
- A graph-coloring secondary resource allocation scheme for D2D communications is proposed. Under this scheme, interference information together with the primary resource allocation (for the cellular uplink transmissions) are represented by an enriched node contention graph (eNCG), which is utilized by graph-coloring algorithms to provide a secondary allocation for D2D communications.
- A contention-based spectrum access scheme for D2D communication in an LTE network is proposed, providing the performance analysis in terms of normalized throughput, access delay and energy consumption. The solution adapts the distributed coordination function (DCF) of the IEEE 802.11 standard to the LTE UL physical layer structure. For the analysis, Euclidian geometry is used to estimate the access and discovery probabilities (i.e., the probability a D2D transmitter to be outside the interfering area of a cellular transmitter and the probability the target D2D receiver to be located in transmitter's range) in an interference isolated cell.
- A set of enhancements is proposed in the conventional resource request/allocation procedure of an LTE-A access network towards allowing the allocation of spectrum resources for discovery transmissions. The proposed enhancements abide by the specification for device discovery provided by 3GPP.
- The spatial spectrum reuse opportunities posed by the FFR technique in the UL period of a multi-cellular LTE network are analytically studied and a D2D coordinator is proposed towards exploiting these opportunities for discovery transmissions. Simulations are used to validate the results of the theoretical study.

2 Results and discussion

2.1 Interference management in femtocell-overlaid networks

The interference problem in femtocell-overlaid networks is very challenging for the following reasons:

  - Femtocell proliferation creates a highly dense network,
  - femtocells are deployed by the end-consumers i.e., in a random/unplanned deployment manner,
  - a heterogeneous network is created (two-tier network) and femtocells are expected to spatially reuse licensed spectrum defining the co-channel deployment, and
  - femtocells can provide the option to serve only a limited set of subscribed users through the closed subscriber group (CSG) mode (no handover option for non-subscribed users)

In a femtocell-overlaid (or femto-overlaid) LTE-A network, where femtocells operate under the co-channel deployment and the closed subscriber group (CSG) mode, multiple types of interference can be found. A possible classification divides them into data and control channel interferences. Our main focus was on control channel IM in LTE-A networks overlaid by CSG femtocells. A categorization of fundamental and emerging IM schemes and a performance comparison from the perspective of control channel protection are provided. Four different categories of IM approaches are considered (frequency-domain, time-domain, power control, and resource allocation), and the advantages and limitations of each approach are presented. The evaluation focuses on the downlink (DL) control channel interference caused by femtocells to macrocell users located in the total macrocell area or in a target femtocell area; also, the impact of the femtocell deployment density on such interference is assessed. Considering the data channel protection in femto-overlaid LTE-A networks, we move beyond the conventional approaches, and design and evaluate a QoE-aware power control interference management scheme, revealing the importance of involving QoE in IM procedures.

Main results

- The interference protection of control channels is a severe problem which poses the design of interference management schemes tailored to these channels. A thorough study on LTE-A standardized tools used for control channel protection is provided, while qualitative and quantitative comparison reveals the special characteristics of each scheme.
  - The carrier aggregation (CA) with cross carrier scheduling and the almost blank subframes (ABS), require hard coordination among femtocells and between femtocells and macrocells. It is shown that due to this requirement the above mentioned interference protection schemes cannot follow the dynamic nature of femtocell deployment posing for fast, reliable, and efficient coordination algorithms.
  - Extensive performance evaluation process shows that in dense femtocell-overlaid networks, the control channel protection through distributed uncoordinated interference protection schemes is preferable.
  - The power control (PC) approach is proved to be one of the most efficient uncoordinated interference protection schemes. The drawback of this scheme is that the interferences at the victim users cannot be reduced further than a bound defined by the required signal strength/quality at the serving users.

  One of the main results is depicted in Fig. 1, where we present the cumulative distribution function (CDF) of SINR values that can be potentially perceived by MUEs in a femtocell-overlaid area served by a specific eNB sector. Fig. 1a shows the performance of CA with cross-carrier scheduling and ABS schemes compared to a baseline scenario with no use of IM and a conventional one where no femtocells are used. Both IM schemes shift the CDF curve to the right, pushing the low SINR values to overcome the control channel decoding threshold (CCDT). However, a tail of very low level SINRs remains in both the CA and ABSs curves, validating that the elimination of interference in interference-hot areas, such as close to HeNBs or in macrocell edges, is very challenging. Comparing the two IM schemes, the use of ABSs seems to have slightly better performance than that of CA with cross-carrier scheduling, especially due to the existence of coordination with the eNB that cancels the interference caused by the coordinated HeNB (typically the stronger interferer). Applying a PC scheme supplementary to these schemes leads to further improvement (Fig. 1b), sufficiently increasing the number of SINR values that exceed the CCDT. As depicted in Fig. 1b, the dynamic nature of PC allows for efficient combination with other IM schemes, especially for low SINR values, shorting the tails of the performance curves.

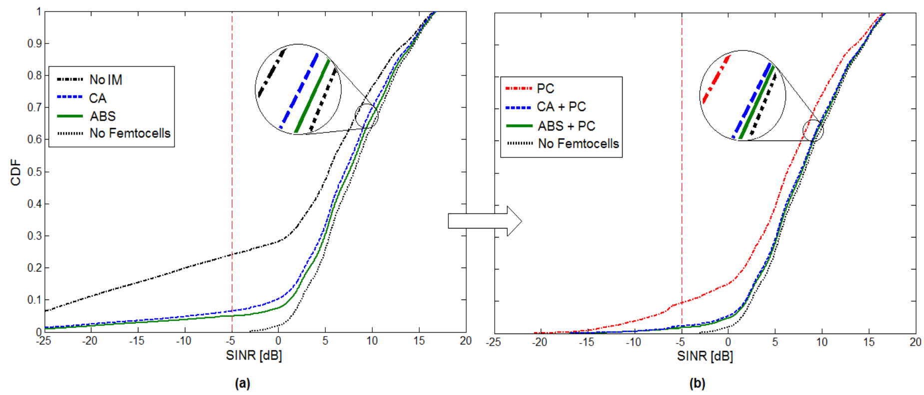

Fig. 1. Control channel interference in total cell area

- The involvement of QoE in network management is also studied, and a QoE-driven power control scheme for interference management is proposed. Simulation results show that the involvement of QoE criteria in interference management procedures is beneficial. More specifically, the proposed QoE-driven power control scheme decreases the transmission power of the femtocell base stations in lower levels that that achieved by QoS-based power control, reducing altruistically the interference at macrocell users and guaranteeing the QoE at serving users (Fig. 2).

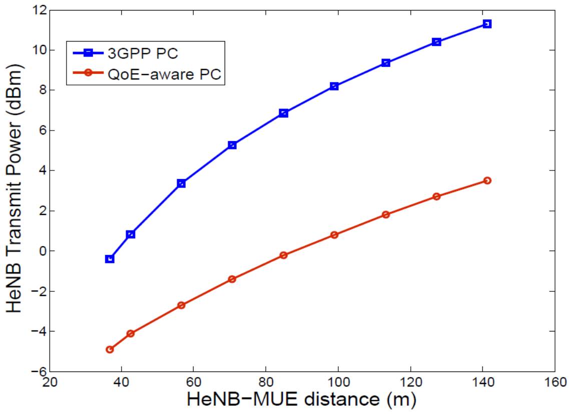

Fig. 2. Comparison of the proposed QoE-aware PC with the 3GPP PC formula

2.2 Spectrum access and management for D2D communications

Focusing on the problem of finding radio resources for D2D communications in an LTE network we propose the spatial reuse of UL cellular spectrum for D2D communications. More specifically, two different approaches are proposed. In the first one, eNBs are responsible for collecting interference information and allocating resources to D2D pairs, while in the second one, eNBs allocate a spectrum portion for D2D communications and the D2D transmitters follow a contention-based approach to access the spectrum.

Main results

- It is shown that, under a full knowledge of the interference map in a network, graph coloring theory can be used for allocating radio resources to D2D communicating pairs, achieving high spatial spectrum reuse factors and sufficiently serve multiple requests for D2D communications (Fig. 3). Simulation results show that gathering and processing interference information at the base station is a very complex problem which also burdens the network with extra signaling. This result raises the investigation for schemes where unreliable interference information or part of the interference information is available.

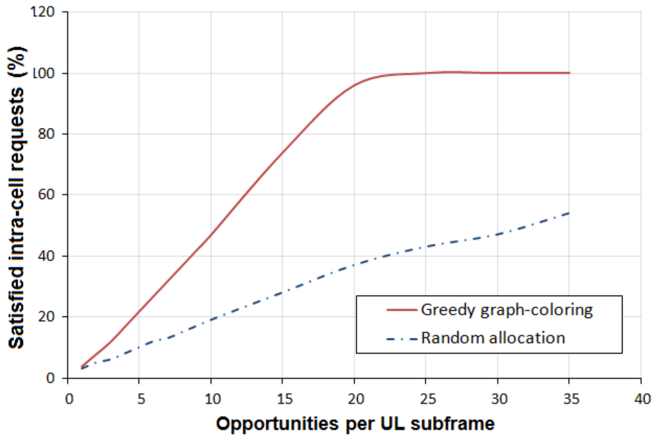

Fig. 3. Comparison of graph-coloring and random resource allocation

- Performance analysis is provided in terms of normalized throughput (see Fig. 4), access delay and energy consumption, of a contention-based scheme for D2D communications, where the D2D pairs compete to access the spectrum with no need for interference information collection and processing in a central node. For the analysis 4 scenarios are defined:
  - Scenario A1: D2D pair knows that there is no interference from the UL cellular transmission and the device discovery procedure has been applied and guarantees that D2D peers are in proximity.
  - Scenario A2: D2D pair knows that there is no interference from the UL cellular transmission. However, device discovery is not considered and a D2D transmitter tries to communicate without knowing whether the target D2D receiver is in its vicinity.
  - Scenario B1: shared spectrum is used by cellular UL and D2D communications and the D2D pair is not aware whether there is interference from the cellular UL transmission. Also, for this scenario a device discovery procedure has been applied and guarantees that D2D peers are in proximity.
  - Scenario B2: shared spectrum is used by cellular UL and D2D communications and the D2D pair is not aware whether there is interference from the cellular UL transmission. Also, the D2D transmitter tries to communicate without knowing whether the D2D receiver is in its vicinity.

  The performance of a contention-based scheme is highly correlated with the number of competing D2D pairs, and also the access and discovery probability (i.e., the probability a D2D transmitter to be outside the interfering area of a cellular transmitter and the probability the target D2D receiver to be located in transmitter's range). Euclidian geometry provides us with upper bounds for those probabilities in an interference isolated cell.

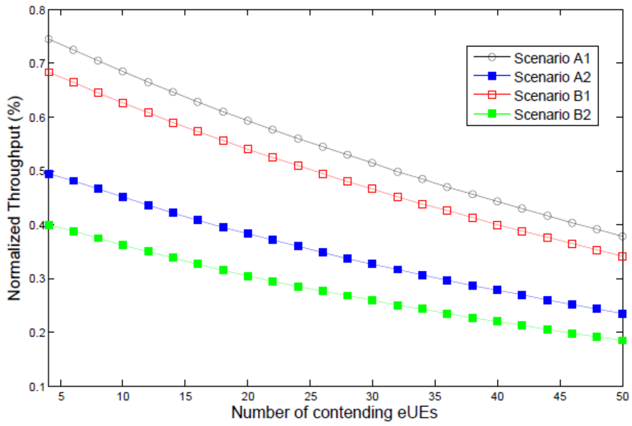

Fig. 4. Achievable normalized throughput of a single D2D pair

2.3 Spectrum access and management for device discovery

One of the main challenges that need to be addressed prior the introduction of D2D communications to cellular networks, is the discovery of devices in close proximity. The solution of this problem requires frequent transmission of discovery signals with which a UE announces its presence on a specific area or requests discovery information from a target UE. In both of the cases consumption of radio resources is needed. Moreover, considering the current efforts for launching D2D communications into the market, the discovery transmitters will rapidly increase, consuming in a more intense and massive way radio resources. Taking this into account, we examine whether the spatial reuse of the uplink (UL) cellular spectrum is a good candidate towards reducing the consumption of radio resources for discovery transmissions.

Main Results

- Thorough study of the LTE/LTE-A standardized access procedures shows that an application layer identity can be used for enabling resource allocation signaling for reactive device discovery transmissions. To this end, empty records allocated for future use in standardized (Radio Resource Control) RRC connection request and (Buffer Status Report) BSR messages, can be utilized to communicate the new identities to the serving base station.
- It is proved that, under certain conditions for the network density and the wireless environment, the fractional frequency reuse (FFR) technique can be exploited both as an inter-cell interference protector and an enabler of additional discovery transmissions.
  - Analytical results show that, for LTE/LTE-A network parameters, interference-unaware spatial spectrum reuse is suitable only for low-range low-demand transmissions, such as the discovery transmissions. Fig. 5 depicts the degradation of cellular transmissions for difference discovery transmission characteristics.

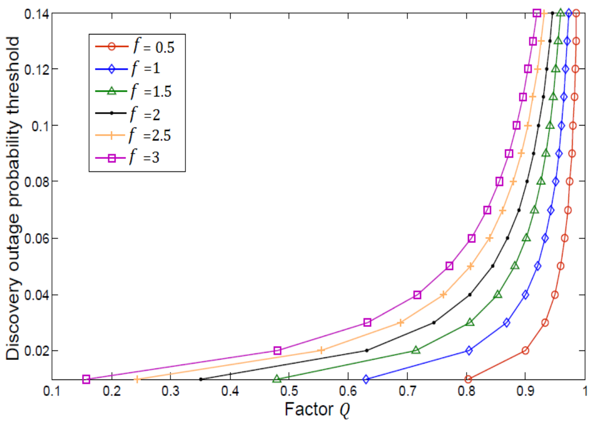

Fig. 5. Quantification of degradation factor Q for different discovery outage probabilities and target spatial spectrum reuse factors (f)

– Simulations validate that the theoretical bounds found through the analysis can be used in a realistic environment. More specifically, monitoring of the cellular transmission performance shows that the measured degradation is below the analytically calculated degradation threshold (Fig. 6).

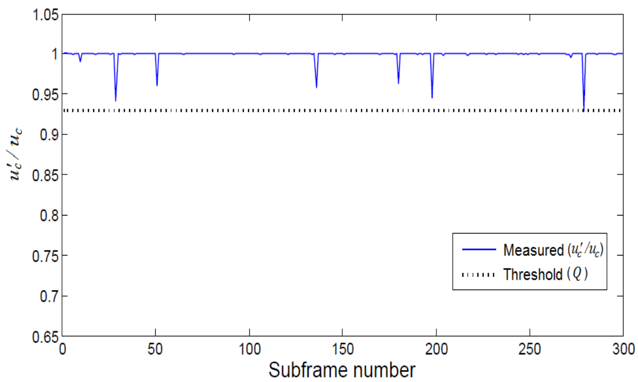

Fig. 6. Measured degradation ($\boldsymbol{u_c'/u_c}$ ratio) and comparison with the degradation threshold $\boldsymbol{Q}$

3 Conclusions

The introduction of femtocells and D2D communications in 3GPP cellular networks (LTE/LTE-A) shifts the conventional spatial spectrum reuse paradigm, to a more dynamic, flexible and distributed one. Femtocells are expected to be the most energy-efficient and cost-effective solution for improving spatial spectrum utilization and indoor coverage, while D2D communication defines an emerging technology which, in 4G networks, is expected to play an important role under the public safety concept, while in 5G networks will totally change the cellular communication landscape. In both of the cases, the design of more efficient radio resource management, interference management and spectrum access schemes is required. This dissertation focused on a subset of those challenges, contributing on the designing of the mobile communications of the future. Some solid and efficient solutions have been proposed, which abide by the most recent specifications defined by 3GPP. The main focus was on mitigating the interference in femtocell-overlaid networks and enabling D2D communications in LTE/LTE-A networks. Three general outcomes highlight the future research directions: first, the use of QoE promises a completely new network management and service provisioning model, second, a sharp change in the current spectrum management is required to accomplish a successful integration of cellular and D2D communications, and third, the solution of device discovery problem will launch a series of new proximity services, providing user devices with an augmented sense of their vicinity.

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