Cognitive Radio Enabling Opportunistic Spectrum Access in LTE-Advanced Femtocells

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Abstract— **The Cognitive Radio (CR) paradigm provides mechanisms and methodologies for an utmost and efficient use of scarce spectrum resources. Among its implementations, Opportunistic Spectrum Access (OSA) enables the use of otherwise-unutilized licensed spectrum provided no interference is caused to the licensee. This paper focuses on the application of this concept for indoor femtocell deployments where, in addition to own licensed spectrum resources, opportunistic spectrum resources can be aggregated. Provided certain interference among femtocells, coordination mechanisms are required. In this framework, this paper studies the use of Media Independent Handover (MIH) signaling to report interference measurements that allow a central controller to make femtocells share white spaces. Moreover, whenever an excessive femto-to-femto interference would require coordination, the proposed opportunistic spectrum access scheme enhances spectrum efficiency and reduces interferences. Results indicate that the proposed opportunistic system significantly improves capacity without requiring additional intelligence in the femtocell.**

Keywords - LTE, IMT-Advanced, 3GPP, 4G, Femtocell, Cognitive Radio, CR, Performance, Carrier Aggregation

I. INTRODUCTION

The current deployment of Long Term Evolution (LTE) is an important step forward towards the fulfillment of a real broadband wireless system. LTE promises to deliver data-rates of up to 300 Mbps (downlink) and 75 Mbps (uplink) assuming 20 MHz bandwidth. Moreover, recent research and standardization efforts have focused on improving the LTE spectral efficiency in order to meet, or even exceed, the International Mobile Telecommunications-Advanced (IMT-A) requirements [1]. Some of these innovations are being considered by the Third Generation Partnership Project (3GPP) as part of the LTE-Advanced (LTE-A) system. Among the considered proposals to be adopted by LTE-A, special attention is paid on the following three key items: (1) Optimized management of heterogeneous cell deployments (macro-/pico-/femtocells). (2) Aggregation of both continuous and discontinuous spectrum (a.k.a. carrier aggregation). (3) Dynamic and efficient use of available spectrum resources enabled by Cognitive Radio (CR) techniques.

Femtocells provide a cost-effective solution in the cellular communications arena by improving indoor coverage, allowing operators to provide high data-rate services wherever the outer macrocell signal is weak. In general, the outer signal strength is severely reduced in indoor environments mainly due to building-penetration losses due to e.g. walls. Generally, this isolation from the outer world, along with reduced transmission powers (typically 10-20 dBm), allows femtocells to reuse the macrocell working frequency band with a consequent capacity increase. However, if the isolation is not good enough to prevent interference with the macrocell activity, femtocells should be re-allocated to use other frequency bands. Alternatively, and bearing in mind the well-known spectrum scarcity and the fact that some bands are lightly-used, the femtocell could seek for unoccupied spectrum bands belonging to other technologies. In this case, CR methodologies and functionalities can be used in order to identify idle frequency bands thus allowing opportunistic and interference-free transmission with the licensed (or primary) system, concept that is known as Opportunistic Spectrum Access (OSA) [2].

This paper focuses on the opportunistic use of the so-called TV White Spaces (TVWS) by LTE-A femtocells. This scenario is justified by the rather inefficient channel allocation scheme present in the Digital TV (DTV) system. Therein, some TV channels are never occupied in a given geographic area so as to reduce the interference to co-channel or adjacent channel stations [3]. In this situation, a low-power transmitter, like a femtocell, operating on locally vacant TV channels would not interfere with the active TV channels. In fact, the regulation bodies from North America and Europe are starting to promote the use of OSA in TVWS. Moreover, it is worth noting that such TVWS can be better exploited if OSA is carried out in an indoor rather than outdoor scenario, since the isolation provided by buildings permits a higher frequency reuse and reduces interferences. Another case of interest to operators is to use CR for femtocell backhauling. This may potentially allow a mobile operator to gain control into the user's home, without depending on neither the DSL coverage nor the operator delivering broadband to the home network.

Interference coordination problem among macro and femtocells or, in general, among cells has been already tackled in the literature, see e.g. [4]-[5]. Pre-processing of cell measurements and exchange of information between entities are necessary in order to adjust the transmission parameters to avoid interference. However, as stated by several market analyses, the success of LTE femtocells depends on the low complexity (and price) of these equipments and hence simple solutions should be designed to devise a practical methodology for OSA. We propose the joint usage of 1) IEEE 802.21 Media Independent Handover (MIH) to allow interference awareness and 2) a central controller in charge of the interference coordination among opportunistic femtocells. The main relevance of this proposal arises from its immediate applicability in LTE-A, since all required signaling is currently available in the network and system modeling follows accurately the specifications. Furthermore, this proposal does not involve any additional computational cost for the femtocells, and therefore resulting appealing for both network vendors and operators.

This paper is structured as follows. First, we introduce the mechanisms which are already considered in the LTE-A specifications and can help to make use of idle portions of unlicensed spectrum in a non-interfering basis in femtocells. Next, we introduce a novel centralized spectrum manager for enabling OSA in LTE femtocell networks overlay, giving the description of the signaling exchange and providing a dynamic femtocell spectrum allocation mechanism. In order to validate our proposed system, we provide some system performance results in terms of throughput obtained from simulations in a synthetic scenario. Finally, we highlight the main conclusions from the work.

II. IMPLEMENTATION ISSUES IN LTE

We adopt the concept of Cognitive Femtocell Base Station (CFBS) defined in [6], which expands the normal capabilities of LTE-A femtocells (Home eNodeB or HeNBs in 3GPP nomenclature). Briefly, a CFBS is a simple low-power LTE access point connected with the core network via wired broadband IP connection (e.g. DSL). In addition, relevant CR functionalities are built in the CFBS, such as spectrum sensing, interference management and efficient resource allocation. In the ambit of this work, CFBSs enhance LTE-A capabilities by aggregating spectrum belonging to TVWS. The implementation of the proposed system brings a series of issues to solve. The following subsections aim at identifying the set of tools available on LTE-A that enables OSA.

A. Cognitive Carrier Aggregation

In order to meet the IMT-A requirement of 100 MHz bandwidth, LTE-A defines a novel technique named carrier aggregation [7]. The specification states that UEs (User Equipments) may simultaneously receive or transmit on one or multiple frequency bands or Component Carriers (CCs) depending on their capabilities [7]. In the context of CR, additional portions of spectrum can be used on an opportunistic and non-interfering basis. OSA relies mainly on this capability, which provides more flexibility in the aggregation of spectrum resources, enhancing both data rate and spectrum efficiency. In this context, the flexibility of OFDM-based systems, such as LTE, enables exploiting spectrum opportunities during primary idle periods by selecting an adequate set of subcarriers for transmission.

B. Interference awareness

As stated before, CFBS must be able to perform spectrum sensing tasks in order to be aware of the channel status and make the co-existence with other licensed or unlicensed systems possible. LTE-A HeNBs have mechanisms to detect surrounding cells during self-configuration and normal operation [8]. Therefore, the spectrum sensing capability comes at no extra cost. However, single sensor measures are uncertain due to the changing behavior of the radio environment in mobile communications. In this sense, UEs must also report the presence of unlisted neighbor cells using the same spectrum. Fortunately, this capability is already included in the LTE specifications. In the following, we describe how UEs can sense alternative frequency bands.

Spectrum sensing is characterized by the sensing time (T_S) and the sensing period (T_P). T_S refers to the time spent to determine the signal strength for a certain frequency band whereas T_P determines how often a particular band is monitored by the cognitive user. According to [9], the sensing time and sensing period can be directly associated with the gap pattern parameters defined in the standard for UE measurement procedures in the `RRC_CONNECTED` state: Measurement Gap Length (MGL) and Measurement Gap Repetition Period (MGRP). These two parameters are represented in Fig. 1.

MGL is fixed while MGRP is configurable in multiples of the frame length –i.e. 10ms– allowing freedom of choice in the trade-off between up-to-date sensing data and system performance. The configuration of MGRP and the set of frequencies to monitor can be done through Radio Resource Control (RRC) signaling, which also guarantees that the eNodeB *–i.e.* base station– knows these inactivity periods in which UEs sense and performs scheduling accordingly.

C. Interference coordination among HeNBs in LTE-A

LTE specifications highlight the importance of signaling for interference control among HeNBs [8]. Therefore, direct femtocell-to-femtocell message exchange via the X2 interface [9] has recently been included in the standard [7], although the information flow and interference mitigation mechanisms are not clarified. However, this direct communication entails knowing the neighbor a priori. This is not a problem, since HeNBs are connected via S1 to a HeNB gateway (HeNB-GW) that could send a list with the IP directions of these neighbors in order to establish a virtual connection through the HeNB-GW.

Once connected, HeNBs can coordinate themselves autonomously using the LOAD INDICATION procedure in the X2 Application Protocol (X2-AP) [10]. This procedure enables HeNBs to inform about their loads and interference conditions to neighbor HeNBs. For the interference state in the downlink, a bitmap known as Relative Narrowband Transmit

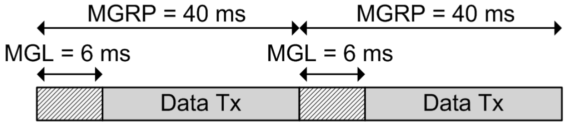

Figure 1. Gap pattern for spectrum sensing in LTE-A

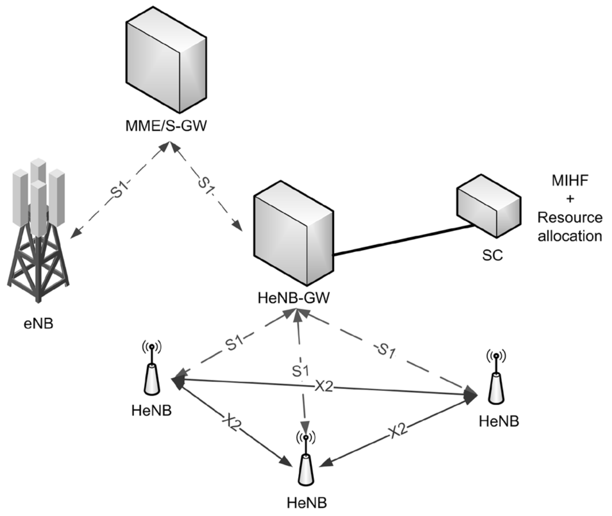

Figure 2. LTE-A system architecture with spectrum coordinator

Power (RNTP) indicator can be exchanged among HeNBs in order to inform the neighbor cells if the HeNB intends to transmit on a certain Resource Block (RB) over a certain power threshold or not (one bit per RB in the frequency domain). The threshold level and the periodicity of report generation are fully configurable. In the uplink, HeNBs can exchange two messages: the Interference Overload Indication (IOI), which indicates the interference level on all RBs, and the High Interference Indication (HII), which informs about the future plans for the uplink transmission. The use of these indicators allows HeNBs to autonomously allocate the most suitable RBs to their served UEs according to the interference level introduced by their neighbors.

The main technical problem of distributed mechanisms for interference coordination based on the X2 interface is that they could consume a significant part of the computational capacity in the femtocell. Moreover, signaling overhead could also collapse the femtocell provided its low cost design. In the next sections it is proposed a new set of procedures for signaling and interference coordination of opportunistic femtocells that keeps complexity of femtocells low, provided that decisions are made in an external entity.

III. PROPOSED OSA MECHANISM FOR LTE-A FEMTOCELLS

An alternative to distributed decision supported by the X2 interface is to centralize the decision making in a new entity called Spectrum Coordinator (SC) associated with the HeNB-GW (see Fig. 2). The purpose of the SC is to notify the resources in the cognitive band that femtocells should use, according to the surrounding femtocells activity. This new centralized element brings up two new challenges, namely, the mechanism to detect all the CFBS surrounding active neighbors and the scheduler that allocates resources to active CFBS in a non interfering basis.

In order to manage the cognitive spectrum, the SC creates a dynamic list containing all the active CFBS and their interfering neighbors. To this end, all CFBSs must report sensing measurements to the SC using specific signaling. Provided that the LTE-A standard does not consider this possibility, we suggest the usage of MIH signaling [11]. Specifically, the proposed solution will take advantage of the MIH Event Service (MIHS), which consists in the notification of predefined events occurred in the PHY layer. This feature is enabled by an entity called MIH Function (MIHF), which also receives and processes the MIH notifications. In our approach, the MIHF is implemented in the SC. Therefore, the SC centralizes all the information needed to perform the resource allocation for inter-femtocell interference avoidance.

Algorithm I – Association and sensing phase

```
New CFBS
(1)  Associate to the SC via S1
(2)  Initialize the list of the cognitive RBs: $RB_i=1, 2\ldots N$
(3)  Initialize the list of the RB state to unoccupied: $RB\_state(RB_i)=0$
(4)  Switch to sensing phase
(5)  while true do
(6)  for each RB do
(7)      Measure the SINR level of the considered RB: $SINR_i=value$
(8)      if $SINR_i$ is greater or equal than the SINR threshold $\gamma_{SINR}$
(9)          if $RB\_state(RB_i)$ is equal to $0$
(10)             Change $RB\_state(RB_i)$ to 1
(11)             Sends a MIH_Link_Detected.indication to the SC
(12)         end if
(13)     else
(14)         if $RB\_state(RB_i)$ is equal to $1$ then
(15)             Change $RB\_state(RB_i)$ to 0
(16)             Sends a MIH_Link_Parameters_Report.indication
(17)         end if
(18)     end if
(19) end for
(20) end while
```

The complete procedure of MIH-based resource allocation for cognitive femtocells comprises four different phases: i) Association phase, ii) sensing phase, iii) resource query phase and iv) operation phase.

i. Association phase (see steps (1)-(3) in Algorithm I)

When the CFBS is installed in a given location and turned on, it connects to the local HeNB-GW via the S1 interface. Once the link is established, the SC subscribes to event notifications from that CFBS, which also implements MIHF. Therefore, the SC sends to the CFBS an `MIH_Event_Subscribe` message with the list of RBs to be monitored and the type of notifications to be generated.

ii. Sensing phase (see steps (4)-(20) in Algorithm I)

The CFBSs monitor the activity in the TVWS, similarly to a UE operating in the listening mode. The femtocell will use its network listening capability to synchronize with the operator's network and decode the broadcast and control channels of the neighboring cells. Moreover, this information can be useful for identifying surrounding cells and the operator they belong to, or even if they are macrocells or femtocells, and to estimate the path loss to them. In case of activity detection in the TVWS (primary or cognitive), the CFBS forwards a `MIH_Link_Detected.indication` message to the SC, which contains information about the active RB, the measured Signal-to-Noise Ratio (SNR) and which system or cell ID is exploiting the resource. The `MIH_Link_Parameters_Report.indication` events also allow the SC to be aware of the discontinuance of interferences. These reports are submitted when the measured power level crosses a predefined threshold established by the

SC with the `MIH_Link_Configure_Thresholds` primitive. This threshold determines the level of interference between CFBSs that make the SC to decide coordinating the CFBSs activity. Results in section V will show the optimum threshold for coordination. It is worth highlighting that the sensing phase remains active while the CFBS is operational. From all the reports collected from all the CFBS, the SC is able to create and update a database containing the active CFBSs, which resources are they using and which is their interference status, i.e. their neighbor cells. In order to overcome the well-known hidden node problem, the femto-UE is required to detect neighbor activity (via RRC signaling) in the cognitive band and notify it through measurement reports.

iii. Resource query state

The CFBS will only turn active and start operating when it detects an active UE in its coverage area. But before allocating resources to this UE, its serving CFBS must query the SC which resources to use. In short, in case two or more near CFBSs are competing for resources in near locations, the SC will distribute RBs among them, always trying to avoid interferences. In this paper we propose the implementation of a simple Hard Frequency Reuse (HFR) scheme [12]. The bandwidth is divided into *n* disjoint sub-bands of 6 resource blocks, since this is the minimum bandwidth that can be allocated to a LTE cell. Sub-bands are assigned to cells taking into account that interfering cells must have different sub-bands.

When the SC receives a notification that involves a change of the interference condition of any of the CFBS, it will start the resource management process. First, the SC will identify the source of the notification and all the neighboring CFBSs that overlap that source or any of its neighbors. We will denote this group of cells as cognitive femtocell cluster. Then, the SC will sort all the CFBSs in the cluster according to the number of neighbors. Following this list in decreasing order, the SC will allocate sub-bands ensuring that there is not overlap with neighbors. If it is impossible to allocate a sub-band for a certain CFBS without co-channel interference, then the SC will assign the band with lowest interference level. In case the SC has gone through the whole list and there are still resources to be allocated, the process will start again, with two sub-bands to each cell and so on. As an illustrative example, Figure 3 shows a possible solution for the HFR resource allocation algorithm in a given cognitive femtocell cluster, where interfering CFBS (circles) are interconnected (lines).

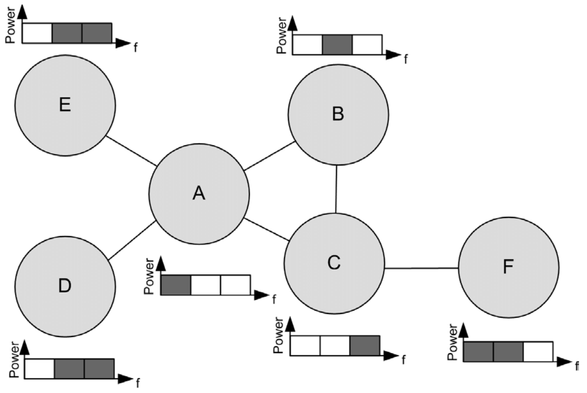

Figure 3. Possible interference-avoidance cognitive spectrum allocation for a femtocell cluster after the resorce query phase.

iv. Operation phase

The resulting spectrum allocation will not remain static during the operation phase. The SC is directly connected to the HeNB-GW and thus it can monitor the volume of traffic of each CFBS and also the modulation scheme used. The SC may dynamically administrate the resources and “steal” some RBs from cognitive femtocells which are not efficiently using all the allocated resources and allocate them to satisfy the demand of highly occupied femtocells. On the other hand, in order to overcome the hidden node problem, the CFBS cross-checks its sensing information with the measurement reports that LTE UEs periodically generate. In case that the UE detects a set of links that is not contemplated in the neighbor list, the CFBS will send a `MIH_Link_Detected.indication` with the detected information to the SC for the re-allocation of resources.

IV. SCENARIO DESCRIPTION AND ASSUMPTIONS

Assessment methodology of this work was based on system level simulations following the guidelines specified by the International Telecommunication Union (ITU) Radiocommunication Sector (ITU-R) for the performance analysis of International Mobile Telecommunications Advanced (IMT-Advanced) technologies [13]. The system simulation platform used in this assessment was specifically created for this work and calibrated in the framework of the Wireless World Initiative New Radio + (WINNER+) project [14] in order to ensure validity of results.

It was simulated a scenario where several CFBSs coexist [15] and made opportunistic use of a TVWS of 5 MHz bandwidth in the UHF band (600 MHz). The CFBSs covered a circular area of 30 m radius and their transmit power was 18 dBm using omnidirectional antennas. For the sake of simplicity, the channel model consisted only of the large scale parameter extracted from [13]. Given that in a real scenario the number and location of the femtocells cannot be controlled by the operator, a fixed number of 8 CFBSs was randomly spread along an urban scenario. To each CFBS, four active users were attached. It was assumed that femto-UEs were indoor. The scheduling algorithm was proportional fair.

V. RESULTS

The evaluation of the selected scenario has been carried out through extensive simulations, using different scenario instances by randomly varying the CFBS positions, and so giving a wide range of interference situations as a result. The performance indicators used in these results have been organized in terms of the interference plus noise level, measure that should be used by the SC to determine in which situations coordination is required. The analysis of the outcome of this study has focused in the high interference part of the available results.

The first performance indicator analyzed is the percentage of CFBS users without service. As it can be observed in Fig. 4, the interference plus noise threshold above which it is worth using the SC, providing an improvement in the service

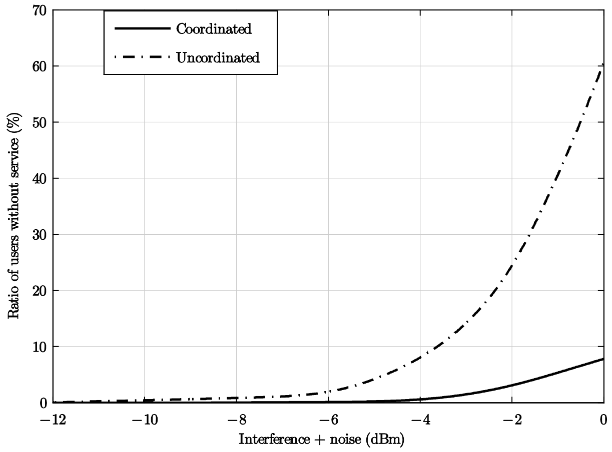

Figure 4. Percentage of users without service

probability, is -12 dBm. This outcome is supported by the fact that cell-edge user throughput when coordination is performed is more than 100% better (in mean) than in the case without coordination, for levels above that threshold.

On the other hand, the analysis of the mean cell throughput results shown in Fig. 5 confirms the need of coordination in high interference scenarios. The cell throughput is more than 100% better with coordination than without it between -12 dBm and -6 dBm. The coordination provides better service probability and higher throughput, improving user experience. As the interference plus noise level increases, the gain obtained by the coordination progressively reduces until both curves virtually overlap from -2 dBm on, where the interference condition is unbearable despite the SC.

VI. CONCLUSIONS

This work has shown that the implementation of an OSA scheme is feasible in LTE systems using the available mechanisms specified by the standard, except for the specific signaling between the CFBS and the SC. However, this issue can be tackled with the proposed MIH approach.

From the provided results, it can be observed that coordination is required when the isolation among femtocells is not high enough. It is of utmost importance to determine the conditions under which coordination should be applied in order to obtain a performance gain. To this end, a threshold in terms of interference plus noise level has been provided in this paper.

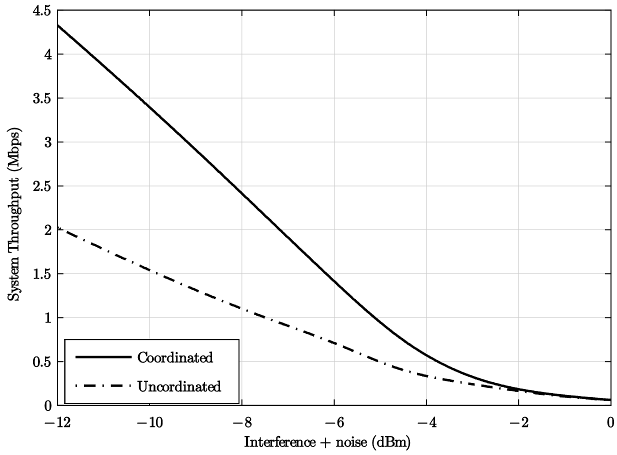

Figure 5. Comparison of mean cell throughput

Moreover, it has been shown that even using a very simple coordination algorithm in the SC, the performance of the system improves significantly under severe interference situations. The coordination provides a better throughput, both mean and cell-edge, and the non-service probability is drastically reduced.

ACKNOWLEDGMENT

The authors would like to thank the funding received from the Spanish government within the Project number TSI-020100-2011-266 and TEC2011-27723-C02-02. The authors would also like to acknowledge the contributions of their colleagues in the COST IC1004 action.

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