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Opportunistic Spectrum Access in LTE-Advance Networks

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Objectives

The main objective of this dissertation work is to suggest a feasible and affordable 3GPP LTE solution which enables opportunistic spectrum access on white spaces. This system operation expansion over unlicensed frequency bands has two immediate advantages: 1) to make a more efficient use of the scarce electromagnetic spectrum and 2) to improve the LTE system performance, increasing the system throughput.

Aiming at our main objective, we want to provide LTE with additional tools that allow a continuous monitoring of the occupancy of unlicensed frequency bands in a given area. Such entity shall compile all the sensing measurement from the LTE users in a given area and make a decision about the channel state considering the latest reports. Therefore, we also aim at providing an efficient and simple cooperative decision making algorithm.

Methodology

The steps followed during the dissertation were: (1) to carry out an exhaustive study of the state of art in cognitive radio mechanisms and their integration into legacy wireless networks. (2) To design a spectrum coordinator and the associated signalling. (3) To assess the new proposal using simulations in synthetic and real scenarios.

Theoretical developments made

This work does not provide any kind of pure theoretical development. However, it can be considered as mathematical developments the definition of the three different cooperative spectrum state decision algorithms.

Prototype development and laboratory work

The whole evaluation of the system performance was carried out in lab work by means of computer simulation. At iTEAM there are two different network simulators available: SPHERE and NS-2. SPHERE simulates L1 and L2 protocol layers, while NS-2 is meant for upper protocol layer simulations. Both simulators are IMT-A compliant, so the results obtained from them are fully reliable. Nevertheless, some small modifications were introduced in SPHERE in order to adapt it to the specific research work objectives. It was also designed and successfully implemented an interface for the communication and message exchange between the two abovementioned simulators.

Results

- It has been proved that cognitive mechanisms actually enhance the overall LTE system performance. Using opportunistic transmissions, the electromagnetic spectrum is more efficiently exploited.
- The cooperative decision-making algorithm proposed in this Master Thesis provides better performance than other hard decision mechanisms found in the literature.
- This study has shown that increasing the number of radio resources by using alternative frequency bands entails an increase in cell and user traffic rate. This performance improvement allows either higher quality in video transmission, which implies higher bit-rate, or accommodating a larger number of users. Furthermore, video delay is greatly reduced, and in some cases real-time experiences are possible, such as medium-quality video transmitted on a 10MHz LTE bandwidth system using TETRA.

- However, indiscriminate use of unlicensed resources is not desirable. Indeed, very aggressive exploitation would cause numerous collisions, degrading user experience and the effective traffic. This is why the parameter setup was carefully studied.

Future work guidelines

We provide the following hints as future work guidelines to follow:

- To develop a more complex and efficient coordinated spectrum access decision-making algorithm. The new algorithm might also consider traffic models and implement self-learning capabilities.
- To improve the user location system accuracy. For instance, the system could take advantage of the GPS positioning system implemented in the new mobile terminals.

Scientific publications

The following list contains all the research publications associated to this Master of Science dissertation work:

- "Análisis de Viabilidad y Rendimiento de un Sistema LTE Cognitivo," Telecom I+D 2011.
- "CORAGE: an OFDMA-based Cognitive Radio System in Emergency Scenarios," CogART 2011.
- "Implementing Opportunistic Spectrum Access in LTE-Advanced," EURASIP Journal on Wireless Communications and Networking 2011 (in revision phase).
- "Cognitive Radio Enabling Opportunistic Spectrum Access in LTE-Advanced Femtocells," IEEE ICC conference, 2011 (in revision phase).

Abstract

Long Term Evolution Advanced (LTE-A) has emerged as a promising mobile broadband access technology to cope with the increasing demand of traffic in wireless networks. However, the higher spectral efficiency of LTE-A is not enough without a better management of the scarce and overcrowded electromagnetic spectrum. Cognitive Radio (CR) has been proposed as a feasible solution to the problem of spectrum scarcity. Among all the mechanisms provided by CR, the Opportunistic Spectrum Access (OSA) aims at making opportunistic use of certain licensed bands whenever the primary system is not affected. This operation requires spectral awareness in order to avoid interferences with licensed systems. In spite of having some spectrum sensing mechanisms, LTE-A technology lacks other tools that are needed in order to improve the knowledge of the radio environment. In this framework, this Master Thesis studies the implementation of a Geo-located Data Base (Geo-DB) that collects the location of free pieces of spectrum available for OSA, based on a cooperative channel-state declaration. Moreover, the potential benefit of this LTE-compliant OSA solution is evaluated using a calibrated simulation tool. The results allow us to optimally configure the system and show that the proposed opportunistic system is able to significantly improve its performance with the available bandwidth.

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I. INTRODUCTION

I.1. *MOTIVATION*

Throughout the last decade, the mobile communications world has experienced a constant and fast evolution due to the continuous increase of data traffic consumption by mobile users. Aiming at a real mobile broadband, the Third Generation Partnership Project (3GPP) has introduced the future generation of mobile communication networks known as Long-Term Evolution (LTE). This technologies promises to deliver data-rates of up to 300 Mbps (downlink) and 75 Mbps (uplink) assuming 20 MHz bandwidth [1]. However, the road towards IMT-Advanced systems, such as LTE-Advanced (LTE-A), poses more ambitious requirements and thus some challenging new techniques are still being discussed in the framework of 3GPP to reach or go beyond these requirements. As one of their key features, all IMT-Advanced technologies foresee the aggregation of continuous or discontinuous spectrum in order to achieve wider bandwidth and consequently increase transmission capability. This concept is known as Carrier Aggregation (CA). Several studies –see [2] as an example– reveal an important increase in average user throughput when CA is performed while cell edge user throughput remains unaffected. The main problem is the reduced amount of spectrum that nowadays is allocated to future mobile technologies.

I.2. *RELATED WORK*

Electromagnetic spectrum is a scarce resource whose use is licensed by governments. Besides, the use of the spectrum is not uniform, that is, some bands are heavily exploited while others are lightly-used. Literature refers to these underutilized portions of spectrum as spectrum holes or white spaces [3]. Cognitive Radio (CR) has been proposed as a feasible solution to this inefficient use of the radio spectrum [4]-[5], providing a set of methodologies and functionalities in order to cope with this burden. Among the functionalities provided by CR, Opportunistic Spectrum Access (OSA) is devised as a dynamic method to increase the overall spectrum efficiency by allowing non-licensed (or secondary) users to utilize unused licensed (or primary) spectrum. For this purpose, a correct channel vacuity declaration is fundamental. That is, we must make sure that a channel targeted for secondary use is actually not being utilized by a licensed user and vacate the channel if such user suddenly appears. Otherwise, OSA might cause a harmful interference with the licensed activity. Being aware of the band status, an opportunistic use can be made whenever the channel is idle. The Digital TV band is an example of inefficient use of spectrum since, depending on the geographical location, only certain channels are occupied. This fact has been noticed by standardization bodies that are working to make possible spectrum sharing without causing harmful interference to the primary (or licensed) system [6]-[8]. In [9], the feasibility of exploiting free TV channels with wireless technologies was studied showing that there is a clear opportunity to enhance IMT-Advanced systems performance by exploiting, for instance, the frequency band freed-up from the analog to digital TV switch-over, which is referred in literature as digital dividend (DD) [10]. Zhao *et al.* investigated the framework of spectrum sharing schemes based on cognitive sensing for the LTE-A and Digital TV coexistence [11]. However, they did not address the practical issues related to the implementation of this framework.

Channel status, the keystone of CR, can be easily acquired using spectrum sensing, which is usually performed by the secondary users that report the measurements to the system. An important issue in spectrum sensing is the reliability of the partial measurements made by a single user. It is well known that mobile radio systems suffer from multipath fading and shadowing, causing severe degradation to the signal, which may lead opportunistic secondary users not to detect the primary activity in a certain moment or location [12]. Moreover, sensors may also suffer from the hidden node problem in which the primary signal strength at the non-licensed user position is weak but opportunistic transmission interferes with the licensed operation. In order to mitigate these drawbacks, longer observation times are suggested to improve performance. Xu *et al.* optimized sensing periods and transmission times in energy-constrained CRs [13]. In this sense, it is worth noting that sensing periods cannot be extended as much as desired since fast opportunity detection is desirable in practical CR networks [14]. Moreover, increasing sensing times reduces transmission times with a subsequent reduction in data throughput. Cabric *et al.* addressed spectrum sensing implementation in detail and provided a wide overview of the problematic [15]. One of the most critical aspects discussed in this study is again the abovementioned uncertainty of primary activity detection based on a single-sensor. As a solution to alleviate this problem, they suggested cooperative spectrum sensing. In the framework of OSA, a system is denoted as cooperative if spectrum access decisions are based not only on the measurements reported by one user but also on information from other cognitive users. In contrast, in a non-cooperative scheme decisions are made regarding the measurements reported by the secondary user demanding access to the primary band. It has been shown that cooperative sensing provides reliable detection if the number of cooperating sensors is large enough [16]. In addition, cooperative sensing also shortens the sensing time of the spectrum and improves the overall sensitivity [17]. However, in related literature it is not clarified the optimum decision criteria to follow. A comparison between hard decision – *i.e.* decision only based on threshold levels– and soft decision –every measurement has a weight in the final decision– is provided in [18], which came to the conclusion that soft decisions are better-suited for OSA. In the same direction, Xiao et al. suggested a soft cooperative spectrum sensing mechanism based on Signal-to-Noise Ratio (SNR) measurement reports that showed high performance [19].

After sensing, measurements must be reported to the entity that decides on opportunistic access. Concerning information exchange for cooperative sensing in CR networks, Pan *et al.* provided a solution that consists in transmitting low-data control information in a wideband channel in order not to interfere with the licensed activity [20]. For the same purpose, Masri *et al.* suggested the implementation of a common control channel in opportunistic networks using Ultra Wide Band (UWB) [21]. However, in literature there are missing some implementations of feasible message exchange mechanisms among nodes.

Once channel status is known, the geo-localization of these measurements is of great value for a cognitive radio network in many ways [22], especially in the case of dynamic OSA. In the existing literature, it is possible to find different schemes that introduce location information in OSA procedures. The Federal Communications Commission (FCC) suggested two alternatives well-suited for a static scenario [23]-[24]: 1) to check in a central database for free resources in the TV spectrum provided the specific cognitive user location; or 2) to broadcast locally information about these free channels. However, the inclusion of location in a dynamic OSA scenario is a quite recent research topic. In [25] it is proposed a resource allocation scheme based on the distance between primary and secondary users, predicting propagation effect and deriving the maximum allocated power. The main disadvantage of this proposal is that sensing is not incorporated and channel prediction models may lack the required accuracy.

I.3. *OBJECTIVE DEFINITION AND THESIS STRUCTURE*

This Master of Science degree thesis aims at providing a centralized dynamic spectrum access mechanism for LTE-A UEs[1]. This initiative is inspired by the CORAGE project, a Spanish project iTEAM collaborated with, which successfully described a feasible scheme to enhance the capacity of LTE deployments by locally exploiting permanently unoccupied portions of frequency bands as Digital TV channels or temporally unoccupied frequency bands as TETRA (TErrestrial Trunk RAdio) band. For such purpose, CORAGE system jointly implemented a large variety of tools. However, after the conclusion of the project, we considered that some improvements were still possible. The most urgent one was to strengthen the channel state declaration confidence. We considered that UEs in a given area shall report their perception of all the monitored channels to an entity in a LTE network which will coordinate the opportunistic access to the unlicensed spectrum according to the information reported from a local area.

This Master Thesis dissertation assesses the implementation of the abovementioned central entity, denoted as Cognitive Resource Manager (CRM), providing the LTE and cognitive radio mechanisms required. The proposed spectrum access to the unlicensed spectrum relies on two key aspects: one, UEs periodically sense the OSA candidate frequency bands and report the perceived interference status (power sensed, Signal-to-Noise Ratio...) of each band to the CRM via an application layer protocol described further; and, two, the CRM will locally decide about each resource vacuity according to the measures reported and will update a geo-located database which

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[1] UE*:* User Equipment, a user in 3GPP terminology.

contains the occupancy state information of all the OSA candidate resources at every eNodeB and UE location. In addition, UEs must be precisely located in order to not to interfere with other licensed or unlicensed systems.

This work is structured as follows. First, we present the CORAGE system architecture and its main tools, and motivate the centralized coordinated spectrum access to the unlicensed spectrum by providing several system performance results. Next, we introduce the LTE and cognitive radio mechanisms required for the CRM implementation. Then, we detail the opportunistic spectrum access procedure in the CRM context and we reveal the most significant performance results obtained from computer simulations. Finally, the conclusions from our work are made.

II. A REAL OPPORTUNISTIC SPECTRUM ACCESS SCHEME IN LTE

The research carried out within the CORAGE (COgnitive RAdio Generation) project aimed at establishing the conditions for the operation of IMT-Advanced (e.g. LTE) systems in the band called Digital Dividend and resulting from the switchover from analogue TV to digital system or DTV (Digital Television). This migration and the subsequent frequency reallocation is already a fact in Spain, giving rise to a new regulatory paradigm where broadcasters play an important role in the provision of future mobile communications services. In this situation, the feasibility of deploying new communication networks in the mentioned bands is of particular interest to broadcasters and equipment suppliers. Therefore, at the mentioned scenario, we want to assess the suitability and the benefits of deploying LTE system that can operate flexibly in different bands in order to use the available spectrum more efficiently. In addition to the mentioned digital dividend, another potential band to exploit is TETRA, which is only used in emergencies. The key feature in LTE-Advanced systems Carrier Aggregation (CA) enables to increase the total assigned bandwidth and, hence, the transmission rate.

II.1. *CORAGE SYSTEM ARCHITECTURE*

CORAGE system is schematized in Fig.1, where it can be seen a TETRA system access network and the LTE-based CORAGE access network. Both networks are interconnected at backbone level in order to jointly provide emergency services and applications, as well as connectivity to other networks (Internet, PSTN, etc.) and session control by IMS.

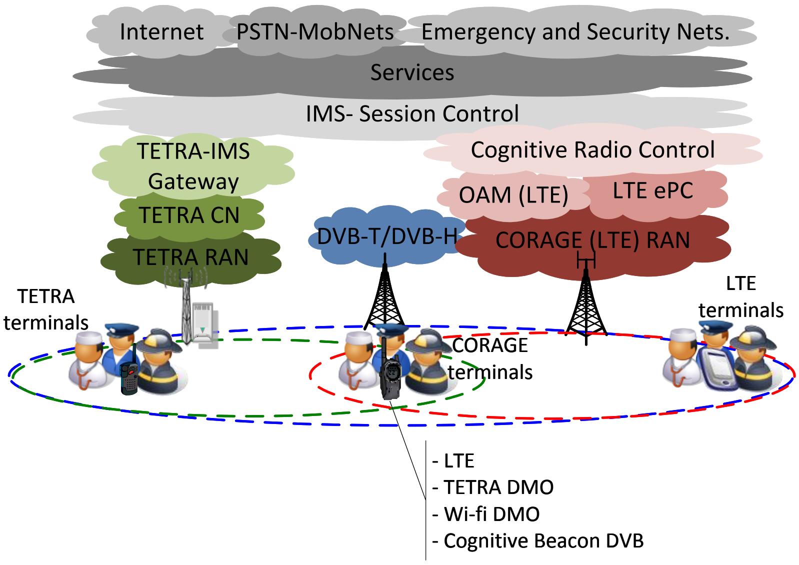


Fig.1. CORAGE functional view.

In detail, CORAGE's cognitive radio access system adapts its working frequency and bandwidth to the primary services and interference conditions. In order to perform such adaptation, this cognitive system uses different tools: geo-located databases, cognitive carrier and spectrum sensing. The DVB-T/DVB-H broadcasting network provides the mechanisms that allow the adaptation to the changing systems, being the CPC (Cognitive Pilot Channel) one of the most essential channel-status information sources [26]. LTE radio access system and DVB-T/DVB-H broadcasting network are backbone-interconnected, providing operation and maintenance functionalities or OAM (Operation And Maintenance) and cognitive radio control. In addition, CORAGE system must also be compatible with TETRA. Thus, a TETRA-IMS gateway must be implemented.

Within CORAGE system, Radio Access Network (RAN) and terminals can operate with several wireless systems working concurrently in order to maximize the availability of the Emergency and Security (E&S) services. Thus, different types of RAN, different types of terminals and common elements on top of both RAN and terminals may interact within areas served by a CORAGE system, as shown in Fig. 9 [26] [27]:

- TETRA RAN: It provides TETRA coverage for terminals for E&S terminals that only operate on a TETRA standard.
- TETRA CN: It performs switching between the different base stations in order to provide services to the terminals located inside the coverage area.
- CORAGE LTE RAN: It's the main CORAGE network. It adapts its frequency and bandwidth depending on the primary use of the band and, therefore, on the interference conditions.

- DVB-T/DVB-H broadcasting network: DVB-T/DVB-H network plays a very important role, locating the CPC in one of its subcarriers. The Cognitive Radio Control will supply CPC information in order to provide a correct cognitive performance on the system.
- LTE ePC (evolved Packet Core): It provides the required connectivity between LTE RAN and Internet, application and services, commuted networks and mobile 2G/3G networks. It is also responsible of users, quality of service, mobility and security management.
- OAM (Operation and Maintenance): It manages supervision, configuration and monitorization issues for the correct operation of the LTE access network
- Cognitive Radio Control: It manages both the LTE access network elements and the ePC in order to make a flexible and efficient use of the available radio resources.
- IMS-Session Control: It manages features as user autentification, authorization and register, as well as user privacy, SIP messages routing and network interconnection support.
- Services and Applications Layer: It consists on servers, which provide services (voice, data transmission…) to final users

II.2. *SCENARIO DESCRIPTION*

Considering the architecture introduced, we want to characterize the radio access in unlicensed radio bands (or cognitive) by adapting a LTE-based system. It is known that LTE implements OFDMA as the medium access protocol, which is highly recommended for cognitive systems due to its agility and flexibility.

In this sense, we simulated a LTE downlink operating in its licensed band and also in white spaces in a flexible way, for instance, in the UHF band. Fig.2 is a possible scenario for cognitive operation on unlicensed bands considering the TV channels allocation in a certain area. In the chart it can be appreciated the previous and future channel allocation after the analog TV migration to digital DVB-T, resulting in the called Digital Dividend. In this scenario we want to cognitively use the Digital Dividend and the white spaces resulting from the non-contiguous TV channel assignation.

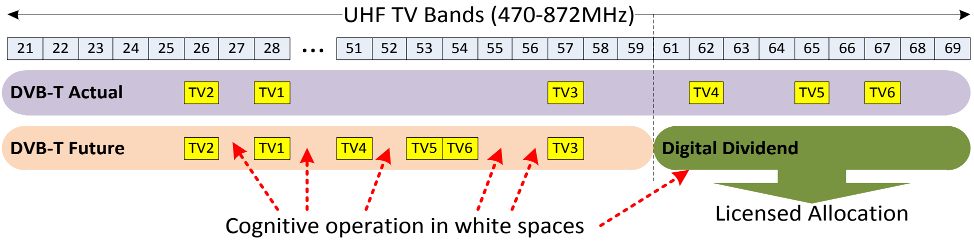


Fig.2. Cognitive operation on real white spaces

The real scenario where the CORAGE system was implemented is the Murcia Region. And real emplacement information was provided. There are 37 LTE eNodeBs, 16 of them share emplacement with DVB-T base stations, and 21 with TETRA transmitters. In addition, real information about the base stations geographical position, terrain and antenna heights, cell azimuth directions, tilts, radiation diagrams, transmission powers and LTE bandwidth was provided. Moreover, LTE and DVB-T coverage maps were also available (see Fig.3).

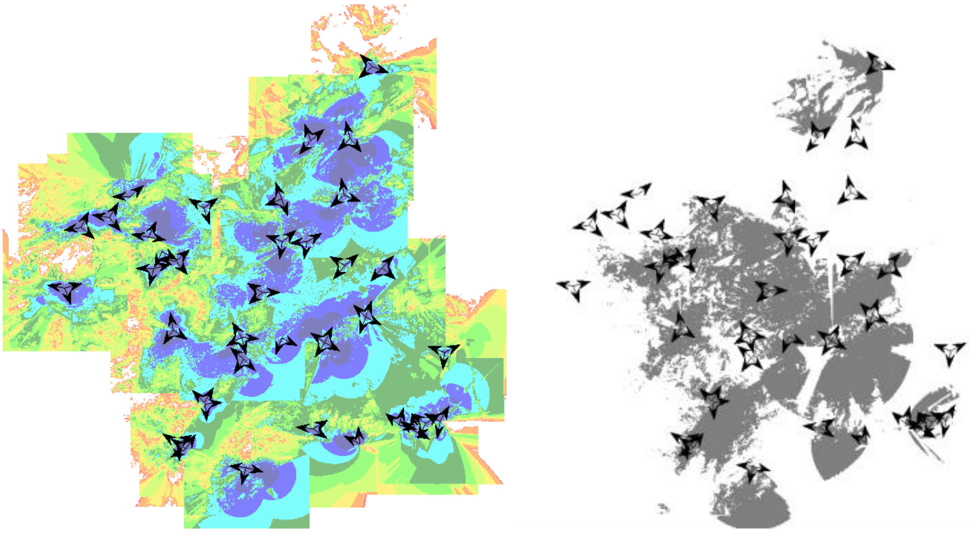


Fig.3. Real coverage maps

We evaluated the system operation and user experience using three different videos with different bit-rates and resolutions. Table 1 shows the main characteristics of the video used in the simulations.

Type	Resolution	Codification	Container	FPS	Bit-Rate (kbps)
1	320x240	h.264	MP4	12	65
2	640x480	h.264	MP4	12	200
3	800x600	h.264	MP4	12	750

Table 1. Characteristics of the evaluated videos.

In the proposed scenario we want to evaluate the assignation of Physical Resource Blocks (PRB), or just Resource Blocks (RB), to the different cognitive users. The Geo-DB will inform where and which digital TV channels are being used. In addition, the system will sense the TETRA band to opportunistically occupy it. This information is spread to cognitive users and base stations using the CPC.

In the following subsections, the most relevant results obtained from testing the CORAGE system by means of computer simulations are shown. First, mean throughput results per cell and user (average and video user) are displayed. In this analysis we consider all the possible LTE bandwidths in the scenario (1.4MHz, 3MHz, 5MHz, 10MHz and 15 MHz), and all the possible combinations of cognitive bands exploited (TETRA and DVB-T). Note that from all the cognitive users spread over the whole scenario, only one was receiving video, and the other users were generating traffic and consuming all the resources available, *i.e.* full-buffer users. Then, we evaluate the user experience in terms of mean frame delay. We conclude this section by performing a parametric survey aimed to find out the effect of the different cognitive parameters on the system performance.

II.3. *TRAFFIC ANALYSIS*

First, we study the effect of the available LTE bandwidth and the unlicensed bands used on the transmit throughput per user and cell. Note that the given throughput rates are effective values: lost and retransmitted packets are considered.

Fig.4 depicts the average throughput a user experiences receiving one of the three videos considered. Results for different combination of unlicensed bands used (DVB only, TETRA only and both bands) are provided. It can be seen that the system reserves resources enough to guarantee the offered service whenever it is possible. If not, the system adapts the user's throughput to the amount of total RBs available.

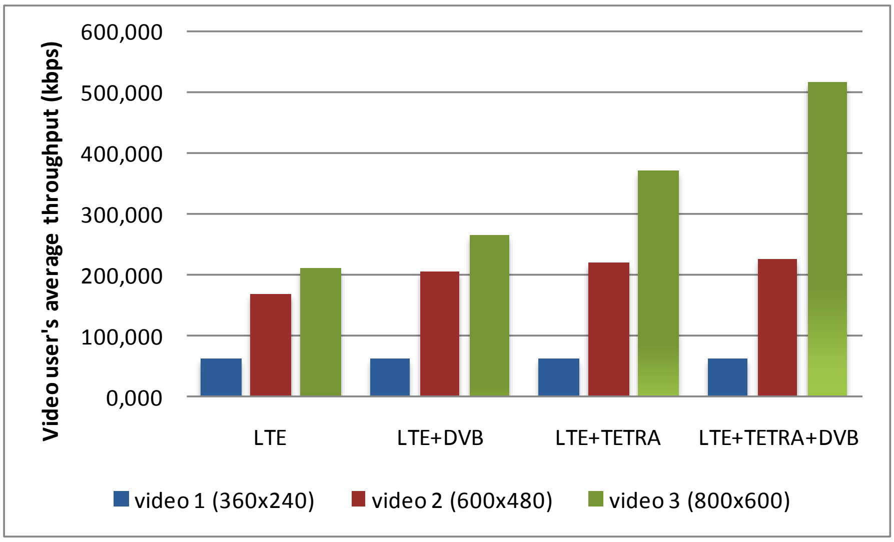


Fig.4. Video user's mean throughput behavior depending on the cognitive bands used

Fig.5 shows the average throughput per cell for different bandwidths and unlicensed bands opportunistically exploited. Note that this throughput is not affected by the transmitted video bit-rate. As mentioned before, users are full-buffer and they consume all the resources available, licensed and unlicensed. Therefore, the throughput increases within the number of available RBs, *i.e.* with the total bandwidth.

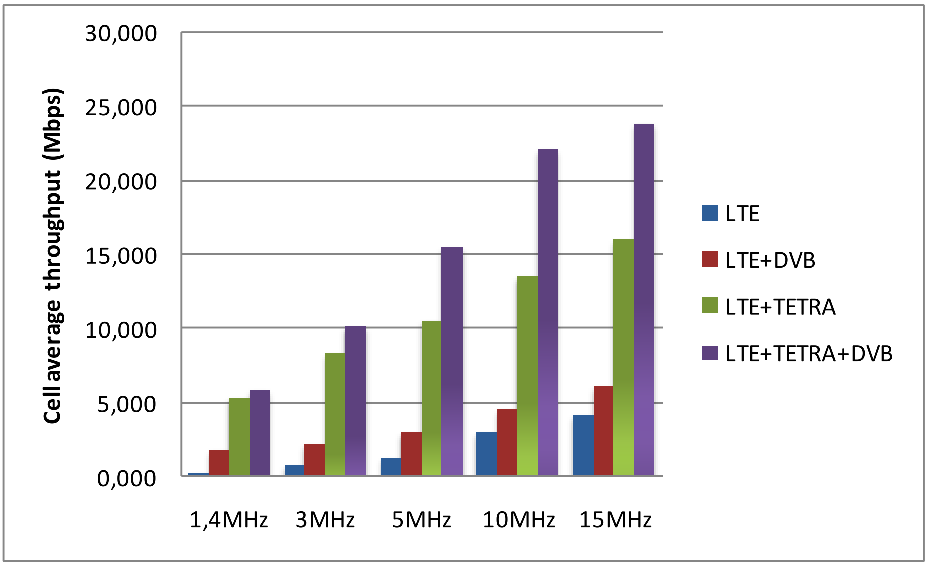


Fig.5. Mean throughput per cell for different bandwidths and cognitive bands used

II.4. *USER EXPERIENCE*

In general, video transmission experiences small losses in all the scenarios considered. QoE (Quality of Experience) metrics such as PSNR (Peak Signal-to-Noise Ratio) and MOS (Mean Opinion Score) reveal that video quality is not compromised: an average MOS value close to 5 (no quality degradation perceived) in every transmitted video was obtained.

For this reason, we focused on evaluating the average frame delay in every type of video for different LTE bandwidths, and the delay decreased as the number of RBs increased. And such reduction is greater if an unlicensed band is opportunistically used. The most data-consumer videos experience larger delays, especially when the LTE bandwidth is small and no cognitive bands are able to be used. The expected average frame delay for different videos and system setups (use of cognitive bands) for a fixed LTE bandwidth of 10MHz is depicted in Fig.6.

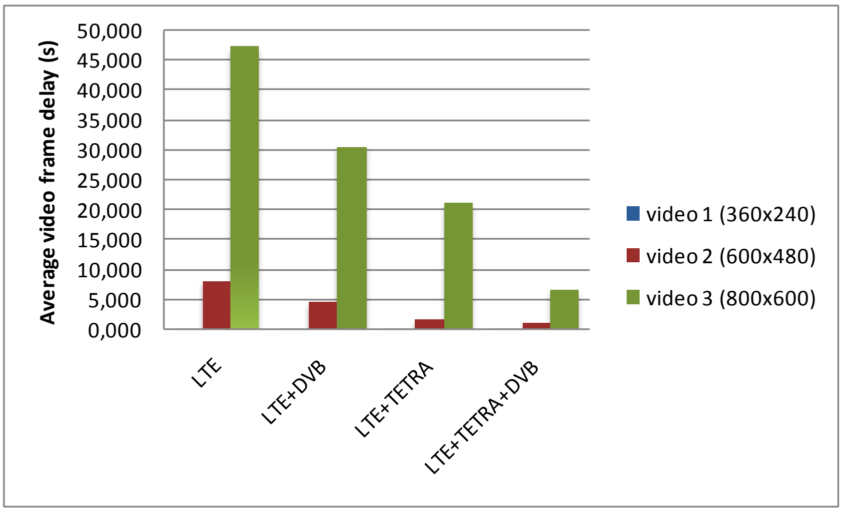


Fig.6. Average video frame delay per video and system setup.

Real-time video is considered when the video can be played without interruptions once the reproduction has started: we consider that video is in real time if the average frame delay is shorter than one second. Before the handset starts the video reproduction, a previous pre-buffering is always necessary. So, the video will start after the first frame is received. Considering high rate-videos, real-time video condition is not satisfied if only the LTE band is used. In fact, that condition is never met even if TETRA or DVB bands are occupied, but video delay is significantly reduced (see Fig.6). In general, and according to the simulation results, real-time videos are possible in scenarios where LTE bandwidths are larger than 10MHz and cognitive usage of spectrum is possible.

II.5. *PARAMETRIC SURVEY*

It is also interesting to analyze the effect on the performance experienced by LTE users of the choice of certain cognitive parameters on the user's side concerning sensing procedures, in order to optimize or improve the system performance. In this work, we focused on studying the effects of three parameters. The results shown below were obtained from simulations which LTE bandwidth was 5MHz and video 2 was aired.

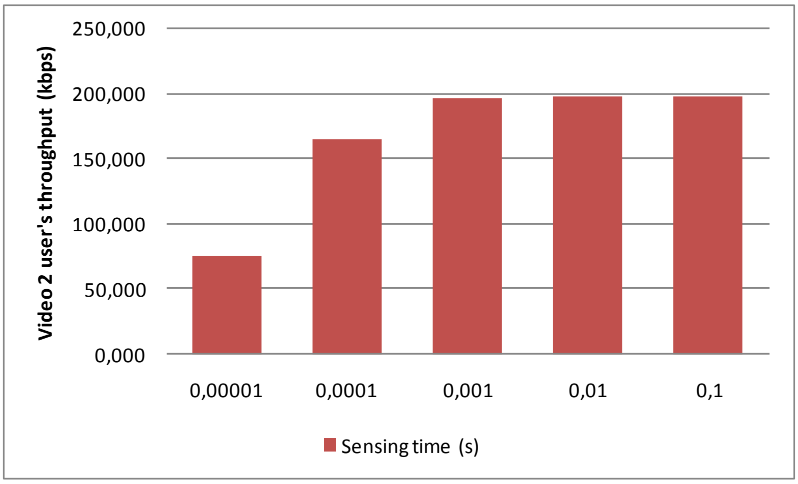


Fig.7. Effect on transmitted video rate by the sensing time

The first of these parameters is the sensing time of the secondary bands, *i.e.*, the period of time when users check the status of the frequency bands in order to determine if they are free and able to use them. Sensing values T_S of 10μs, 100μs, 1ms, 10ms and 100ms were taken. Fig.7 shows for each value of sensing time the measured throughput for video 2. Short sensing times, below the millisecond, provide throughputs lower than the video rate. This is because the shorter the time monitoring the spectrum and deciding its state, the less accuracy, so the probability of collisions is much higher. Increasing collisions increases the number of retransmissions, which reduces the effective throughput and increases the packet delay. According to the results, it is desirable to use sensing times of milliseconds; longer times are inefficient since data rate keeps constant and power consumption is increased.

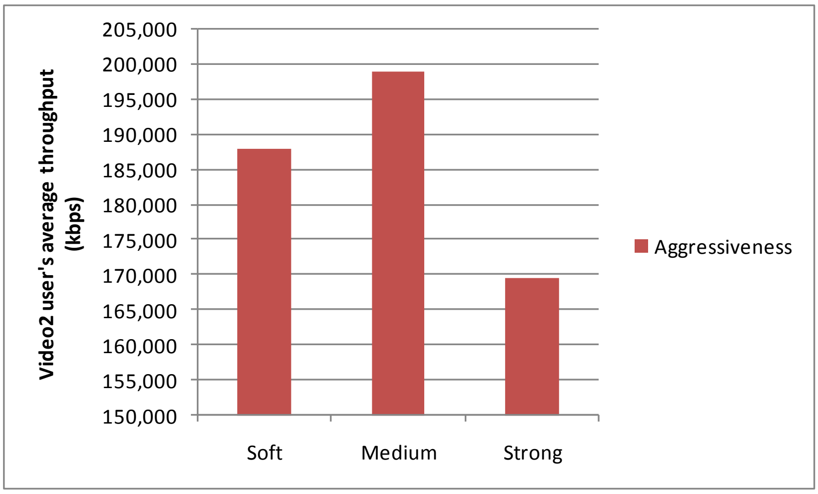


Fig.8. Average video 2 user's throughput depending on system's aggressiveness

The second parameter we analyze is the system aggressiveness. System aggressive stands for the behaviour of the system in the declaration of free channels, which directly affects the probability of not detecting the primary user or missed detection (MD). In a soft aggressiveness configuration the system is wary of exploiting the other channels, lowering the likelihood of MD, while in a strong aggressiveness profile the opposite happens. Fig.8 and Fig.9 show the average video user throughput and the average frame delay experienced based on the aggressiveness scheme adopted: light, medium and strong. Our study shows that the highest rate was achieved with a moderate aggressiveness. With the light scheme the whole capacity is not used, so the maximum bit-rate is never achieved. But a strong aggressiveness scheme is negative to the system, increasing the number of collisions and, thus, the number of retransmissions, which reduces the effective bit-rate and increase the delay significantly.

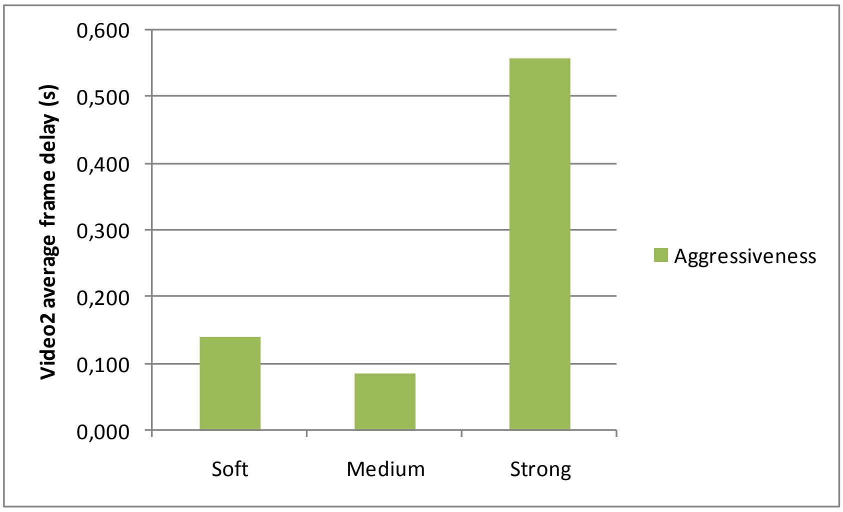


Fig.9. Average video2 frame delay depending on system's aggressiveness.

We also analyzed the behaviour of the system depending on the probability the cognitive users access the TETRA band. In the following results we have determined access to the free channel probabilities from 0 to 0.9 with 0.1 intervals. A probability of zero means that the system will never exploit the cognitive band. So, the average throughput both cell and user will reach corresponds to the LTE-only system configuration, without using any cognitive band. On the other hand, with a 0.9 access probability the system will exploit the TETRA band with a high probability. Figure 10 shows the average cell throughput based on the TETRA band access probability. It can be seen that the number of available RBs increment as a result of exploiting the TETRA band, regardless of the access probability, both cell and video user throughputs are increased. From 0 to 0.3, both rates gradually increase until they stabilize. But the cell throughput begins to fall from 0.6 probabilities. This decreasing trend is consequence of larger number of collisions to the primary band that reduce the effective rate. For instance, in the video 2 case, it is needed a clear channel probability higher than 20% in order to reach the video transmission rate. For higher quality videos it is necessary that the TETRA channel is available more frequently to achieve the top rate. And concerning the average delay per frame, the fact of using TETRA channel in a cognitive way the average delay is reduced by 90%.

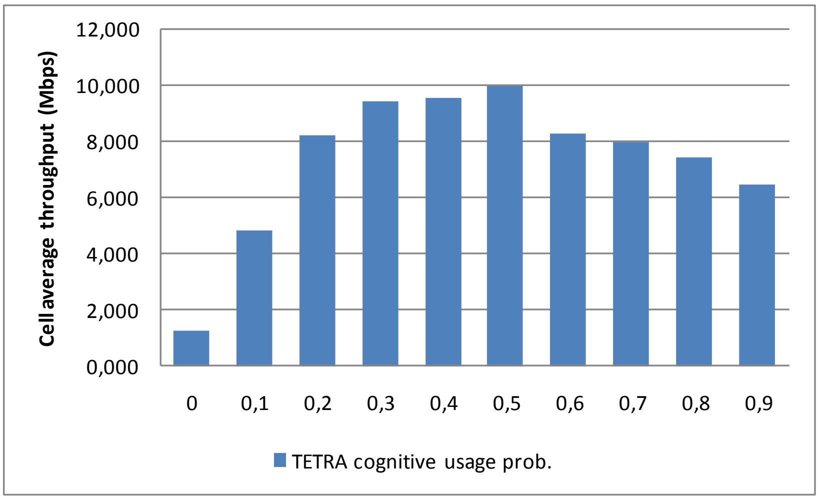


Fig.10. Average cell throughput depending on the cognitive use of TETRA band

III. LTE-ADVANCED AND COGNITIVE RADIO FEATURES ENABLING OSA

III.1. *SPECTRUM SENSING*

The success of OSA depends on the correct channel state detection. Cognitive users must only transmit when the licensed channel is idle so as to not interfere with the primary system. Willing to avoid those interferences and to maximize the secondary transmission opportunities, this subsection analyzes the spectrum sensing capabilities of LTE-A.

In general, the spectrum sensing task is characterized by the sensing time (T_S) and the sensing period (T_P). Sensing time refers to the time spent to determine the signal strength for a certain frequency band whereas the sensing period determines how often a particular band is monitored by the cognitive user. Some of the user measurement capabilities considered by the LTE-A standard for handover purposes can be exploited to sense the primary channel state. In fact, 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), respectively [28]. These two parameters are represented in Fig.11.

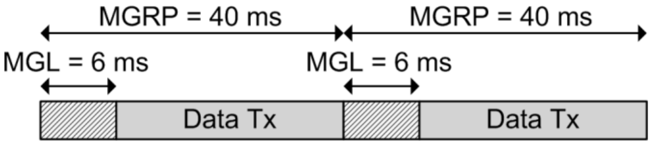
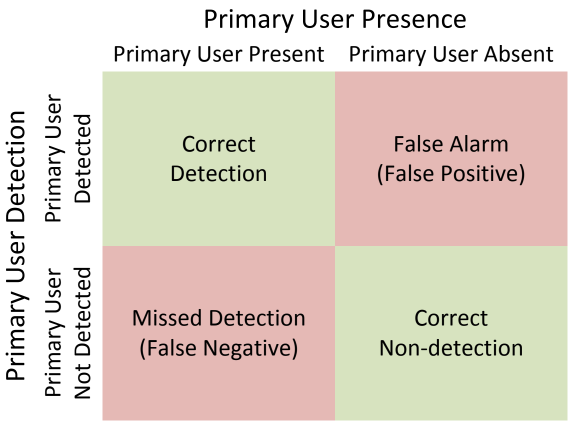


Fig.11. Gap pattern for spectrum sensing in LTE-A.

During sensing –*i.e.* the gap time period– the scheduler does not allocate resources to the user, which can tune its receiver on other carrier frequencies. According to the standard, 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) signalling, which also guarantees the synchronization between scheduling at the eNodeB –*i.e.* base station– and sensing at the UE.

The choice of the MGRP should not be made lightly since the system performance depends on this parameter. In detail, the greater this periodicity is, the lesser frequent the channel status is acquired and the more likely the information in the Geo-DB is outdated. As a result, the probability of allocate an occupied primary Resource Block (RB) to secondary users, that is, the interference or collision probability, is increased. In contrast, higher periodicity means more overhead, reducing data throughput. The effects of changing this parameter will be studied in the Section V, giving an optimum value for the considered scenario.

Moreover, LTE-A UEs are capable of measuring the so-called Received Signal Strength Indicator (RSSI). This measurement allows detecting activity/inactivity in the primary band during the measurement gap. Taking into account the re-tuning time required at the beginning and at the end of the measurement gap, it is possible to take samples in a certain bandwidth during an effective period of 5.166ms [29]. In the sensing approach proposed in this Master Thesis work, each measurement gap the UE senses one RB –*i.e.* bandwidth chunk of 180 kHz– in the licensed band. For example, considering a hypothetic primary band of 10MHz –50 RBs– and a MGRP of 40ms, the whole band will be sensed every 2 seconds. All these measurements must be reported to a logical entity that manages and updates the Geo-DB. A proposal for this reporting procedure is given in Subsection III.2.



		Primary User Presence	
		Primary User Present	Primary User Absent
Primary User Detection	Primary User Detected	Correct Detection	False Alarm (False Positive)
	Primary User Not Detected	Missed Detection (False Negative)	Correct Non-detection

Fig.12. Primary user detection (sensing).

In general, the inevitable spectrum sensing inaccuracy may result in erroneous channel occupancy information. Fig.12 shows all possible outcomes that the spectrum sensing mechanism can provide given the presence –*i.e.* activity– of a primary user in its licensed frequency band. In general, the detection errors –dark-gray areas– are classified into two groups: false positive error or False Alarm (FA) and false negative errors or Missed Detection (MD). FA happens when the presence of an inexistent primary user is detected whereas MD occurs when the cognitive user is unable to detect the primary activity. The consequences of FA and MD errors are different. A MD error will assign RBs occupied by a licensee to a secondary user, with the consequent interference –or collision– between primary and secondary systems. In contrast, a FA error will lead to spectrum underutilization. We will model the detector performance using the Receiver Operating Characteristic (ROC) curves for an energy detector as calculated in [30]-[31]. ROC curves represent the FA probability (ε) as a function of the MD probability (δ) given the channel model (AWGN, Rayleigh, Ricean, Nakagami, etc), the Signal-to-Noise Ratio (SNR) and the time-bandwidth product (TBP or m). As its own name suggest, TBP is defined as the bandwidth considered for detection (W) multiplied by the time spent for detection (T) or, in other words, $m = T \cdot W$. In general, as it can be seen from Fig.13, larger TBP values provide better detection system performance; this is, reduced FA and MD probabilities. Logically, channel conditions such as channel model and SNR restricts the maximum achievable performance and, from a certain point, increasing the TBP will not provide any improvement. For the LTE particular case, we can consider W as a single RB's bandwidth ($W = 180$), and T is a configurable value as long as a multiple of a Time Transmission Interval (TTI) is chosen.

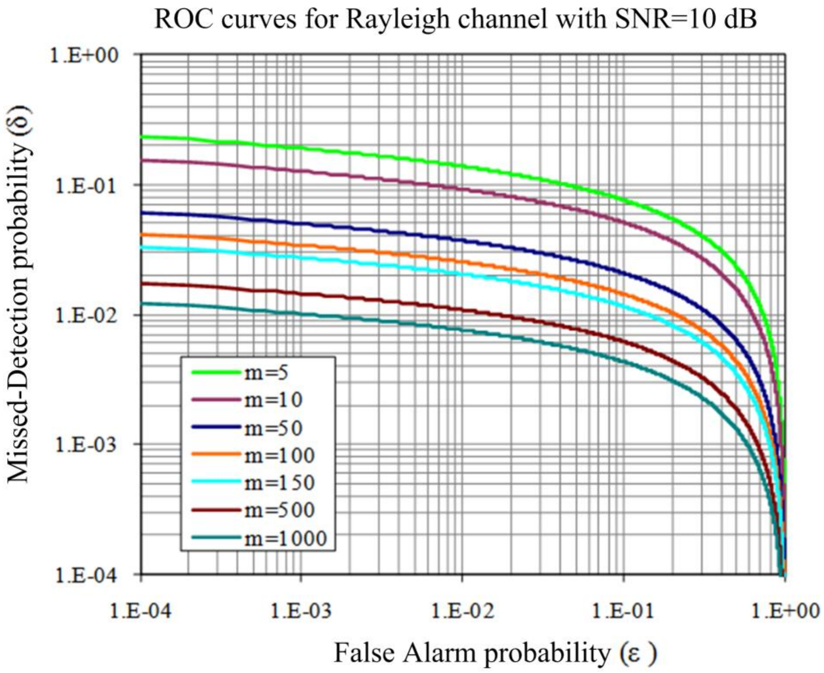


Fig.13. ROC curves for a Rayleigh-type channel with average SNR of 10 dB for different time-bandwidth product values (from 5 to 1000).

III.2. *MEAUSERE INFORMATION EXCHANGE*

The entire spectrum sensing information obtained by the secondary user must be transmitted to the CRM for further process. However, the reporting procedure required for the OSA operation is not specified. One solution could be to use a proprietary communication protocol but this will reduce the viability of OSA in LTE-A. Conversely, we propose the usage of the IEEE 802.21 protocol given its popularity and the availability of open source implementations. The IEEE 802.21 or Media-Independent Handover (MIH) standard specifies an application-layer protocol aimed to provide soft handover between different 802.xx architectures [32]-[33]. Mainly, MIH is based on the exchange of messages reporting a subset of PHY layer events. The MIH functions are enabled by an entity called MIH Function (MIHF), which provides MIH Event Services (MIES), MIH Command Services (MICS), and MIH Information Services (MIIS). In this work, only the MIES are of particular interest, in which a local MIHF receives event notifications from a set of well-configured remote MIHFs.

The CRM must include a MIHF entity that manages the event notification subscription and also receives and processes all notifications that concerns spectrum sensing in order to build the Geo-DB. Since the CRM does not perform any sensing task and only compiles MIH event notifications from remote entities, it is necessary to implement a remote MIHF in every LTE-A UE. With the aim of keeping the Geo-DB updated, the CRM needs to know when a cognitive user measures that the RSSI in the licensed band crosses a specific power level or threshold. Therefore, after the attachment procedure, the CRM must send to the active user a `MIH_Event_Subscribe` message with the list of RBs to be monitored. Moreover, with the `MIH_Link_Configure_Thresholds` primitive the CRM specifies the thresholds associated with this list.

Using RRC signalling the network can query LTE UEs to periodically sense the spectrum. Therefore, via the appropriate service access point, the MIHF implemented in the UE can access the measured signal levels and generate notifications according to the sensing information. When the licensed power level crosses the defined threshold, a `MIH_Link_Parameters_Report.indication` is forwarded to the MIHF in the CRM, which will finally notify it to the upper layers. Fig.14 depicts this data flow from the UE to the CRM.

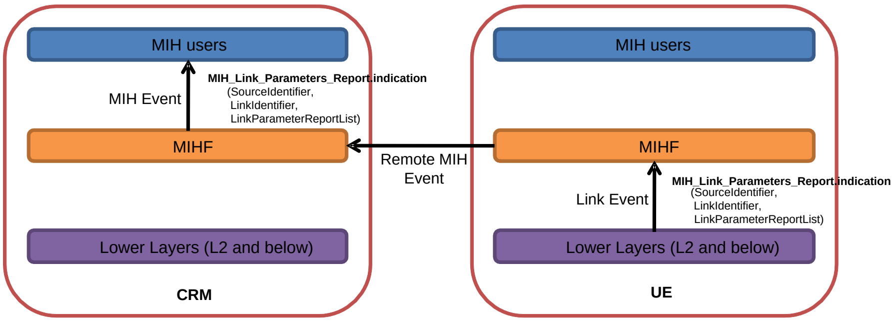


Fig.14. Remote `MIH_Link_Parameters_Report.indication` event flow.

The notification event exchange among cognitive users and the CRM is granted using the Default EPS Bearer allocated to any active user in LTE-A. The Default EPS Bearer assigns a unique IP (Internet Protocol) address to LTE-A users and provides connectivity, at least, to any node inside the LTE-A network.

III.3. *USER POSITIONING*

In the OSA framework, the main objective of user positioning is the collection of dynamic geo-located information of white spaces in the licensed band. This information will help the scheduler make an opportunistic allocation of resources that could even work when primary activity is detected in distant areas. Subsection IV.2 deals with this OSA procedure in more detail.

LTE-A specification considers UE localization through the LTE Positioning Protocol (LPP) and LPP Annex (LPPa) [34]-[36]. Several different positioning methods are mentioned in the standard, namely: Observed Time Difference of Arrival (OTDoA), Assisted-Global Navigation Satellite System (A-GNSS) and Enhanced-Cell ID (E-CID). Implementation details are omitted here but the interested reader can refer to the standard for further information. All of these positioning methods are based on measurements collected by the UE or the eNodeB. The Mobility Management Entity (MME) is the entity that receives the request for the localization of a UE from another entity such as another UE, eNodeB or other nodes. Then, the MME sends a location service request to the

Enhanced Serving Mobile Location Centre (E-SMLC), which will execute the positioning procedure through LPP and LPPa protocols. The SLs interface defined between E-SMLC and MME serves as a tunnel for the E-SMLC to transparently carry LPP and LPPa protocols through the MME, in addition to transport the Location Services Application Protocol (LCS-AP) messages and parameters.

The E-SMLC acts as a location server that computes user position using the measurements provided by one or several of the positioning methods. This entity interacts with the UE (using LPP) or the eNodeB (using LPPa) through the MME to obtain these measurements. For example, in the case of the E-CID method, the possible measurements, collected by the E-SMLC, are: Evolved Cell Global Identifier (ECGI)/Physical Cell ID, Reference Signal Received Power (RSRP), Reference Signal Received Quality (RSRQ), UE Rx – Tx time difference, Timing Advance (TA) and Angle of Arrival (AoA). In addition to collecting this information, the E-SMLC can provide assistance data in the particular cases of A-GNSS and OTDoA methods. It is also specified the usage of Positioning Reference Signals (PRS) for OTDoA positioning purposes.

If the UE lacks A-GNSS functionality, the E-SMLC might combine information from the serving and the neighbouring cells in order to triangulate user's geographical position. Both RSRP and TA permit estimating the distance from the UE to the serving cell, whereas distance to neighbouring cells can be derived just from the RSRP values. AoA measures, if available, add more precision to the triangulation process. Table 2 shows the reporting granularity of the measurements involved in the positioning methods [28], which directly affect the precision of the obtained positioning. It is worth noting that, in the case of TA and UE Rx–Tx time difference measurements, the resolution can be as good as twice the sensing period, *i.e.* $2T_s$, which corresponds to a spatial resolution of around 10 m.

Measurement	Reporting granularity
Evolved Cell Global Identifier (ECGI)/Physical Cell ID	N.A. (Not Applicable)
RSRP	1 dB
RSRQ	0.5 dB
UE Rx – Tx time difference	If value <$4096T_s$ then $2T_s$. Otherwise, $8T_s$
TA Rx – Tx time difference (T_{ADV})	$2T_s$
AoA	0.5º

Table 2. Measurements reporting granularity.

In the proposed scheme, the CRM and E-SMLC are interconnected using the MME, as shown in Fig.15. The CRM is the entity that requests the location service to the MME, which will activate the E-SMLC service. The resulting location calculated by the E-SMLC is sent to the MME that finally forwards it to the CRM. With the obtained information, the CRM can map sensing reports and location to build the Geo-DB.

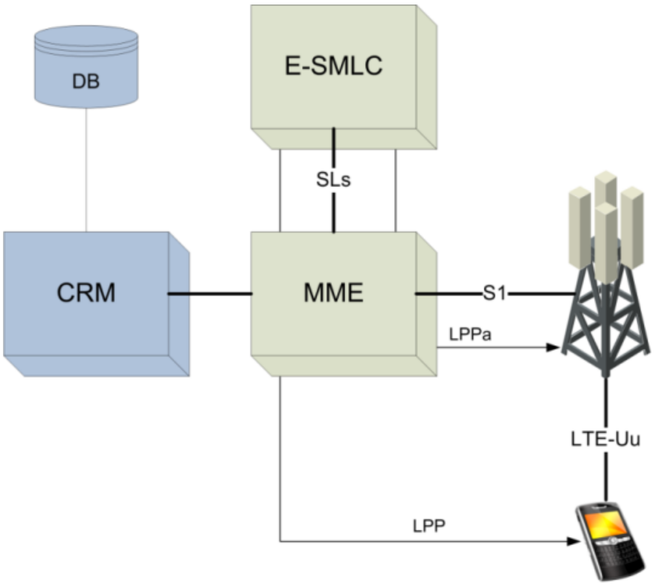


Fig.15. Scheme of the nodes implicated in the Geo-DB maintenance.

III.4. *GEO-LOCATED DATABASE*

Owing to users' positioning capability, the Geo-DB will contain valuable information about which frequency bands can be used by a given eNodeB at a specific moment of time and the maximum coverage range in order not to interfere with the primary system. Fig.11 illustrates the process of calculating the Geo-DB. The CRM collects the sensing information from the UEs and the positioning information from the location service provided by the MME and updates the database after making the cooperative decision, which will be explained further in Section IV.1. Once this process is finished, the CRM possesses the location of every opportunistic UE and which RBs are suitable for OSA (green squares) and which not (red squares).

The Geo-DB will contain information about the occupation of the different RBs in the licensed system spectrum on a per-cell basis, indicating also the maximum coverage distance from the eNodeB, as shown in Table 3. This way, an eNodeB, identified in the table by its Cell-ID, is able to opportunistically use those RBs with reduced transmission power in case the maximum range is detailed in the corresponding register. Otherwise, the maximum range field is flagged N.A. and the corresponding resource can be used without restrictions regarding the transmission power. The maximum range field is expressed in terms of Dist_T_{ADV}, which defines 10 m width ranges, and represents the maximum distance between the eNodeB and any candidate user. In addition to the data provided in Table 3, the Geo-DB also contains the final decision concerning the different resources as detailed later in Section IV.1.

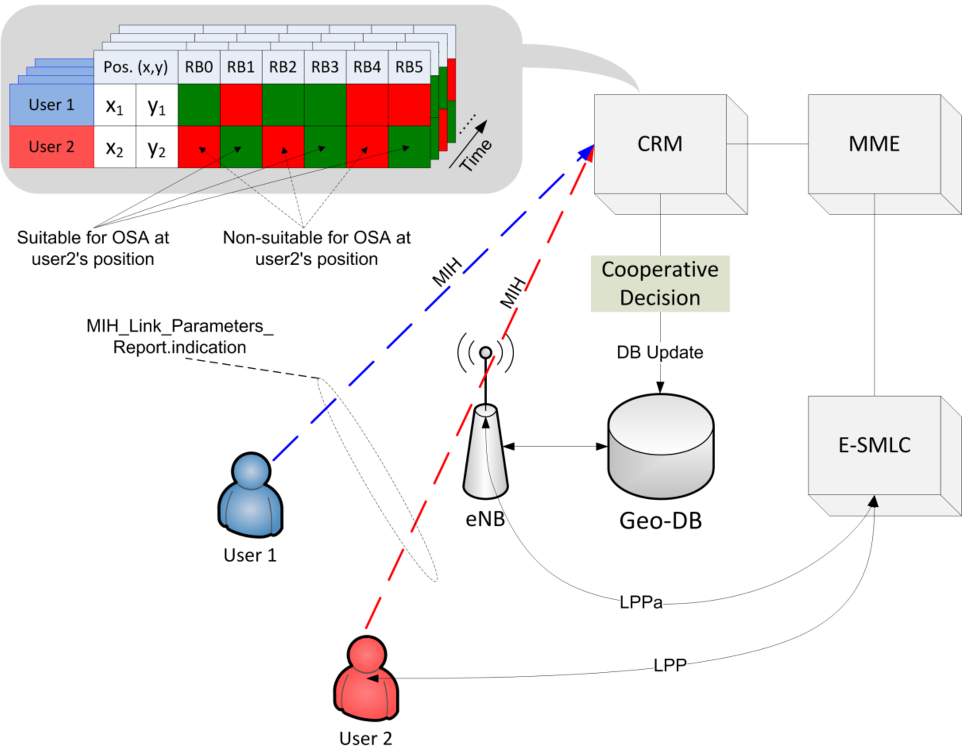


Fig.16. Cognitive spectrum access based on geo-located data.

The information contained in the Geo-DB must be periodically updated in order to consider the possible changes in the licensed spectrum, especially if those changes are due to the primary system activity. As stated in Subsection II.1, it takes 2 seconds for a user to sense a bandwidth of 10 MHz. A cooperative decision made taking into account the information provided by all the users inside a certain range would allow increasing the sensing accuracy. An up-to-date database will reduce the collision probability that could be caused by the lack of synchronization between the real state of the primary spectrum and the availability information stored in the database.

Cell-ID	*RB*	*Max. Range*
…		
10001AX	0	$10\cdot \mathrm{Dist}\_T_{ADV}$
10001AX	1	$12\cdot \mathrm{Dist}\_T_{ADV}$
…		
10002AX	0	N.A.
10002AX	1	$9\cdot \mathrm{Dist}\_T_{ADV}$
…		

Table 3. An example of some of the data available in the Geo-DB.

IV. OPPORTUNISTIC SPECTRUM ACCESS PROCEDURE IN CRM CONTEXT

The proposed OSA procedure relies on the cognitive radio tools described in the Section II and involves executing the processes detailed in this section. The cooperative decision about primary system activity in the different monitored channels, the way the free primary system resources are allocated to the users and the transmission of control information sent to the allocated users to inform them about the opportunistic resources are the three steps followed in this procedure.

IV.1. *COOPERATIVE DECISION*

Influenced by mobile channel factors such as noise, shadowing and multipath fading, single sensor measurements are prone to errors. In order to overcome this problem, cooperative spectrum sensing among multiple nodes in different locations is suggested. As mentioned in Subsection III.1, we propose the implementation of a centralized cooperative spectrum sensing in order to improve the channel status awareness. The cooperative decision making mechanism will be implemented in the CRM. For a more efficient use of the available spectrum and to fully exploit the opportunistic nature of our scheme, we consider monitoring and making decisions on a per-RB basis instead of per frequency band (*i.e.* containing several RBs). The input data considered by the decision mechanism consists of all the sensed channel state reports from UEs served by the same eNodeB and the geographical position obtained using the available location services. Every channel state notification creates a new entry in the CRM containing the identifier of the UE, the estimated geographical location of the UE, the channel or resource monitored, the licensed activity state sensed in that resource and the time in seconds when the channel state report was received. Once all this data is collected from different UEs, the CRM can make decisions about the vacuity of the monitored resources in different locations. The collected sensing reports are classified by their distance to the eNodeB in different ranges, whose width is given by a multiple of the TA resolution ($\text{Dist\_}T_{\text{ADV}} = 10\ m$). For each range and RB, an independent cooperative decision will be made.

Multiple samples of this sensed data from different UEs obtained in different channels are combined in order to update the Geo-DB. For the same UE and sensed resource, only the most recently collected data is used in the cooperative decision calculation (in this work, only measurement reports received no further than 2 s before the decision is made are considered). The pre-processing carried out by the CRM to update the database is briefly described as follows:

```
Geo-DB update algorithm
For each cell:
    For each TA range:
        Select measurements of UEs inside the TA range
        Calculate cooperative decision
        Insert the resulting data into the Geo-DB
```

Two simple measure fusion techniques or rules for cooperative decision making are considered in [18]. Therein, the OR-rule states the channel as not free if at least a single UE senses the primary activity. Conversely, the AND-rule decides that the considered resource is occupied if all the reports sense that such RB is occupied. In a similar way, we introduce two similar hard-decision rules: conservative and aggressive rules. The conservative rule declares the resource as free from licensed activity if all the UEs report such state; otherwise the channel is considered to be occupied. On the other hand, the aggressive strategy declares the resource as idle if just a single UE senses the channel as free. However, due to the abovementioned single sensor measurement uncertainty, the different measurements reported over time must be considered in the final decision. That is to say, old measurements must not have the same importance in the final decision as the newest reports due to the fast-changing radio-channel state conditions. Soft-based cooperative decision stands on this idea and, in addition to the abovementioned hard-decision rules, will be also considered in our study.

In soft-based cooperative decision, every reported measure has a weight associated to it. Following the weighted cooperative spectrum sensing described in [19], instead of weights depending on the measured primary SNR, we propose to weight the up-to-date notifications according to the time when the measurements were triggered and the coherence of the measurements taken inside the same TA range. The CRM will combine the information of the resource state with the weights and will make a decision by comparing the result with a defined threshold. Each resource state notification is weighted according to the elapsed time between the moment the notification was received by the CRM –*i.e.* the *i-th* notification is received at time t_i– and the instant when the channel state decision is made –t_{now}– as seen in Equation (1.a). T_{MAX} refers to the time elapsed between two consecutive measures of a specific primary resource, that is, T_p times the number of primary resources to sense. In addition to this linear weight equation, we will also analyze in Subsection V.2 the quadratic –Equation (1.b) – and the square root –Equation (1.c) – version of the formula in order to optimize the performance of the decision algorithm.

$$\omega_i = \frac{T_{MAX} - (t_{now} - t_i)}{T_{MAX}} \tag{1.a}$$

$$\omega_i = \left(\frac{T_{MAX} - (t_{now} - t_i)}{T_{MAX}}\right)^2 \tag{1.b}$$

$$\omega_i = \sqrt{\frac{T_{MAX} - (t_{now} - t_i)}{T_{MAX}}} \tag{1.c}$$

The decision regarding the resource availability for opportunistic access will be taken according to the value of the spectrum decision metric on a given RB, defined as:

$$U = \sum_{i=0}^{N-1} \frac{(-1)^{d_i} \cdot N_{di} \cdot \omega_i}{N^2}, \tag{2}$$

where d_i is the state of the monitored resource reported in the *i-th* notification expressed as:

$$d_i = \begin{cases} 0, & if\ resource\ is\ sensed\ as\ idle \\ 1, & if\ resource\ is\ sensed\ as\ occupied \end{cases} \tag{3}$$

N is the number of notification events considered in the decision making mechanism, including free resource notifications, N_0, and occupied resource notifications, N_1. N_{di} is the number of measurements that agree with the state of the resource notified in the *i-th* measurement report: N_0 if the resource was sensed occupied, N_1 otherwise.

The cooperative spectrum state decision U will depend on the number of measurements taken into consideration, the weight of each measurement and the most reported single-sensor measurement (2). If most of the measurement agree on the resource vacuity, a positive value of U is obtained. On the contrary, if the majority of measurements reports that the resource was occupied, a negative value of U is obtained. In order to normalize the equation, it is needed to divide it by the second power of N, in such a way that $-1 \leq U \leq 1$.

Depending on the value of U, the considered resource is stated as a candidate for OSA (H_0) if that result is greater than a certain threshold, denoted as γ. Otherwise, the resource is not available for opportunistic usage (H_1). The decision threshold γ must be tuned in order to provide the largest OSA probability without exceeding the interfering limit.

$$Decision = \begin{cases} H_0, & U \geq \gamma \\ H_1, & U < \gamma \end{cases} \tag{4}$$

IV.2. *RESOURCE ALLOCATION FOR INTERFERENCE MITIGATION*

As already mentioned, one of the main concerns in CR is the interference minimization towards the licensed system. To this respect, OSA in the licensed band will be only possible inside areas where the mentioned channel is assumed idle. With this aim, the amount of power transmitted in these resources must be dynamically controlled by the non-licensed system. This philosophy is known in literature as Power Control (PC) [37].

Once the Geo-DB is updated and the opportunistic availability of the licensed system resources is confirmed, it is possible to assign these free frequencies –in the form of free RBs– to increment the existing resources available in the LTE system. The dynamic and unpredictable behaviour of the licensed channel vacuity forces to set an irregular transmit power profile for the opportunistic resources allocated to each user depending on its distance from the licensed system –power must be low enough so as not to interfere with the primary system. It may happen that no licensed activity is detected in the area served by a given eNodeB. In that case, the LTE system can opportunistically use the available licensed resources in the whole coverage area without power restrictions. On the contrary, if one or several UEs detect the primary activity at any position under the eNodeB coverage area, transmit power must be limited, trying to minimize the interference caused to the primary system. That minimum prohibited distance defines the radius of a circumference inside which OSA is available. Fig.17 explains this concept showing a primary system and an OSA-capable LTE-A system. In this example, the primary and secondary coverage areas –dashed-line ellipses– partially overlap, being OSA feasible –solid-line ellipse– in $2Dist\_T_{ADV}$ meters away from the LTE-A eNodeB, and the opportunistic signal must not exceed the limits of the OSA area.

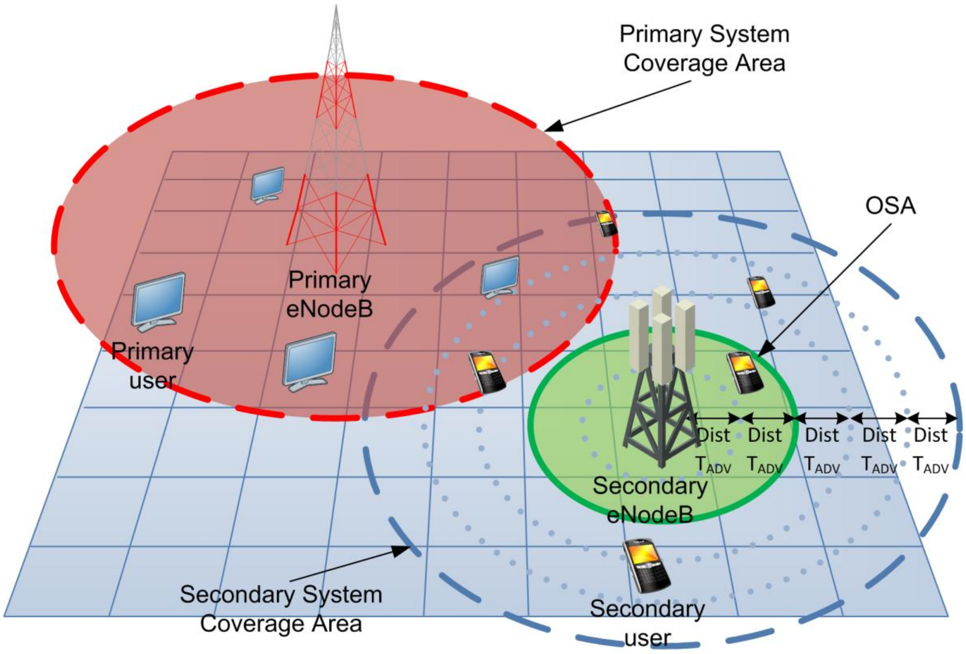


Fig.17. Example of a possible scenario where a LTE system opportunistically operates in another licensed frequency band without interfering.

Each eNodeB has a maximum transmit power to be distributed among all available RBs. This means that opportunistic resources that are going to be allocated must be taken into account in the distribution of power. Our proposed system will query the Geo-DB to discover which licensed resources the LTE system can use in an opportunistic way and, then, the scheduler will eventually decide when to use them. Once the system knows the total amount of resources to be allocated in a given eNodeB, it also knows the maximum power transmission per RB, just by dividing the total transmit power available in the eNodeB and the number of RBs to allocate. For the opportunistic RBs, power restrictions may apply if stated in the Geo-DB and the scheduler must adjust the transmission power according to the maximum distance the LTE signal must not exceed. The procedure to adjust the transmission implies reducing the maximum transmission power considering the difference in propagation losses between the maximum coverage distance of the

LTE cell –given by the 95%-tile of the distance of located users, extracted from off-line statistics– and the maximum distance where the opportunistic resource can be used.

In order to investigate the advantages of such PC strategy, it will be compared with a non-PC procedure in Subsection V.3. As its name suggests, non-PC consists of not adjusting the transmit power of the opportunistic signal and hence the eNodeB transmits with the maximum power available whenever the cooperative decision-making mechanism concludes the resource is free.

A reduction of the transmission power must be followed by a correction of the CQI reported by the UE in order to use the right Modulation and Coding Scheme (MCS) for that power. Note that according to specifications, decreasing the transmission power by 2 dB corresponds to decreasing the CQI by 1 [29].

Once resources –*i.e.* the RBs– have been assigned to opportunistic users, one additional problem is users' mobility that generates a large dynamism the system will have to deal with. Moreover, the localization procedure reports user position with some inaccuracy. Both aspects may lead opportunistic users to interfere with the primary activity. A survey about the impact of the location precision error in the system performance is detailed in Subsection V.3.

IV.3. *SPECTRUM ACCESS PROCEDURE*

As stated in the introduction, in LTE-A the amount of resources can be increased by aggregating continuous or discontinuous portions of spectrum –referred to as Component Carrier (CC)– in order to provide higher data rates. In the context of cognitive radio, CA concept can be extended and additional portions of spectrum can be used on an opportunistic and non-interfering basis by adding the detected spectrum holes or white spaces. This is the main concept OSA relies on, and provides extended capabilities and improved flexibility in the aggregation of spectrum resources, enhancing both data rate and spectrum efficiency.

On each CC, it is necessary to adjust the opportunistic transmission parameters –e.g. transmit power, modulation and coding schemes…– to the available spectrum holes. As a result, separate Hybrid Automatic Repeat reQuest (HARQ) processing and its associated control signalling is required for each CC. In this situation, the proper design of the control signalling channel is crucial. In general, according to 3GPP internal discussions there are three possible implementations of the control channel in CA [38]: a) each CC can have its own coded control channel and minor modifications of the control structure in LTE systems are required (Fig.18.a), b) the control channels of different CCs can be jointly coded and transmitted in a dedicated CC (Fig.18.b), and c) multiple control channels for different CCs are jointly coded and then transmitted over the entire frequency band formed by the licensed LTE band and the CC added (Fig.18.c). Approaches a) and c) are incompatible with OSA since prior LTE signalling transmission is required in each CC in the licensed band before knowing if that specific CC is idle, increasing collisions and interference with the licensed activity. Therefore, the proposed system requires the implementation of the control signalling scheme b), where the signalling from all the added CC is carried in the licensed LTE control channel. Opportunistic users will read their signalling information in the licensed LTE band and then, according to that information, transmit or receive data in the opportunistic CCs. This procedure must be performed periodically in order to release the opportunistic resources if the primary activity returns. LTE handsets can carry out this operation when all the CCs are contiguous, including the licensed LTE band [2]. However, in case that CCs are discontinuous and assuming that mobile devices only have a single radio interface, once the opportunistic user reads the control channel and finds out its allocated resources, the handset has to tune its working frequency to the allocated CC, synchronize to the LTE system to start data transmission or reception and, after a specific time interval, re-tune the radio to the licensed LTE band and read the control channel again. This situation is impractical in the ambit of OSA since the required time between re-tunes must be very short in order to provide updated information of the opportunistic resources availability and, even if the handset is able to perform fast re-tuning, there is no useful time left to exploit those frequencies. A feasible solution to this problem is to implement a semi-persistent scheduling [39] where the signalling check periodicity is extended (up to several seconds) without taking into account the licensed channel state. The longer the time the opportunistic user does not consult the control channel, the higher the probability that licensed and unlicensed activities collide. Thus, signalling consulting period and collision probability trade-off must be met.

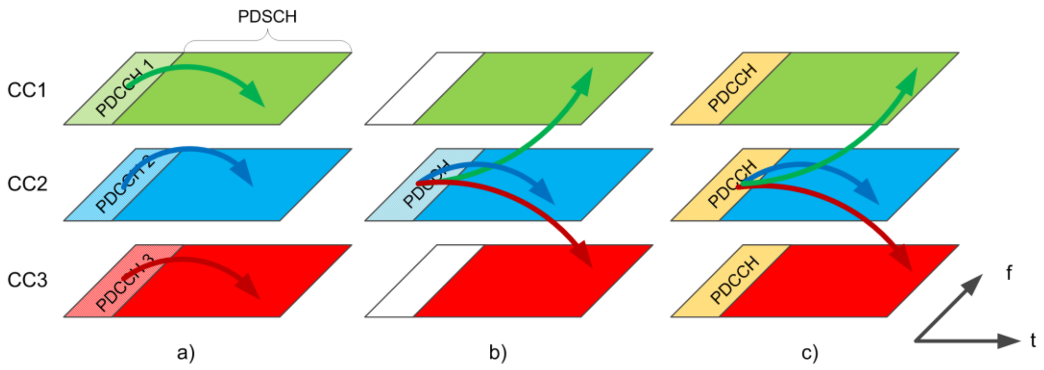


Fig.18. PDCCH designs for LTE-A when CA is enabled.

The use of OFDM-based opportunistic systems comes at a reduced cost because a particular set of subcarriers may be fed by zeroes in the corresponding transmitter Inverse Fast Fourier Transform (IFFT) input to prevent interference with the primary system. At the receiver, the FFT operation implemented to recover the transmitted data will still be valid for the OSA operation mode, with no extra cost. In [40], an efficient implementation of a Non-Contiguous OFDMA (NC-OFDMA) transceiver is presented for cognitive radio applications.

V. CRM PERFORMANCE RESULTS

First, we analyze the performance of the CRM in several configurations aiming at finding the combination that optimize the throughput – interference trade-off.

V.1. *SIMULATION SCENARIO AND PARAMETER SETUP*

Before going into detail with the CRM performance results, it is necessary to define the simulation scenario and make clear the assumptions we made.

For testing the CRM, we considered a scenario where a single LTE-A eNodeB and a licensed base station coexist. The primary system exploits the Industrial, Scientific and Medical (ISM) frequency band (2.4 GHz) while the LTE-A system carrier frequency is 2 GHz. The coverage area of both systems overlaps in such a way that this overlap affects a certain percentage of the area farthest from the LTE-A transmitter. The overlapping parameter can be varied in order to study to what extent OSA provides substantial improvement of capacity depending on the distance between the primary and the secondary system. Opportunistic LTE-A users were randomly spread throughout the LTE-A system coverage area. Primary system transmissions were randomly generated following the semi-Markov ON-OFF Pareto-distribution [41]. Its probability distribution function $f(x)$ is defined (5), where k is referred to as the shape parameter and x_m is the scale parameter of the Pareto distribution. Note that different combinations of these two parameters result in different primary activity periodicities T_{PA}, *i.e.* different average ON-OFF intervals in the primary system. In the simulator, the primary activity is modelled by the primary activity factor (F_{PA}), which normalizes the T_{PA} to the simulation time. Table 4 shows the most relevant simulation parameters used in this work.

$$f(x) = k\frac{x_m^k}{x^{k+1}}\,, \qquad x \geq x_m \tag{5}$$

Two different metrics are used in order to quantize the CRM performance: the maximum throughput served by the eNodeB with full-buffer UEs and the collision ratio that models the probability that the LTE-A activity interferes with the licensed system. Collision ratio is calculated as the ratio of the number of times a secondary UE in the coverage area of both licensed and non-licensed system uses opportunistically a licensed RB to the number of times OSA is performed when the licensee is active (6). We target an arbitrary collision ratio lesser than 10%.

$$Collision\ ratio = \frac{\#\ of\ times\ OSA\ is\ performed\ in\ the\ overlapping\ area}{\#\ of\ times\ OSA\ is\ performed\ when\ the\ licensed\ system\ is\ active} \tag{6}$$

Parameter	*Value*
Cell layout	1omni-directional cell / 1 primary transmitter
# users	100
LTE-A carrier frequency / bandwidth	2 GHz / 5 MHz (25RBs)
Primary carrier frequency / bandwidth	2.4 GHz / 5 MHz (25RBs)
Scheduling	Round Robin (LTE-A band) / MaxCIR[2] (Opportunistic band)
Propagation model	Urban Macro (UMa) [43]
k	2
x_m	60
Average primary system ON-OFF interval (T_{PA})	50 s
HARQ candidates	10
Mobility	Static users
False alarm / Missed detection Probabilities	0.028 / 0.01
Simulation time	100 s

Table 4. Simulation parameters

V.2. *SENSING CALIBRATION*

Before obtaining performance results from the implementation of the suggested opportunistic tools in a LTE-A system, first it is necessary to optimize the cooperative spectrum sensing mechanism in order to provide the best OSA performance. This optimization requires setting the most suitable decision threshold for the soft-decision cooperative spectrum sensing algorithm described in Subsection IV.1 and, according to this threshold, setting an appropriate resource sensing periodicity for UEs, T_p.

In Fig.19 it is shown the performance of the opportunistic LTE-A system in terms of cell throughput and collision ratio for a decision threshold γ ranging from -1 to 1. This figure compares the performance of the soft-based cooperative decision procedure assuming linear weights –Equation (1.a)–, but also the quadratic –Equation (1.b)– and the square root version –Equation (1.c)–. In this analysis, resource sensing periodicity was set to 40 ms. Lower decision thresholds imply to be less confident on the channel vacuity before using this resources, what increases collision probability. Conversely, higher decision thresholds entail less collisions but also a significant reduction in capacity because the OSA capability is wasted. As it can be seen, a good choice providing maximum throughput along with low collision probability is to make γ equal to zero. This value will be used in the following. It can also be appreciated that similar results are achieved with linear and quadratic weight formulas at $\gamma = 0$. So, it is suggested to use the linear version provided its lower complexity.

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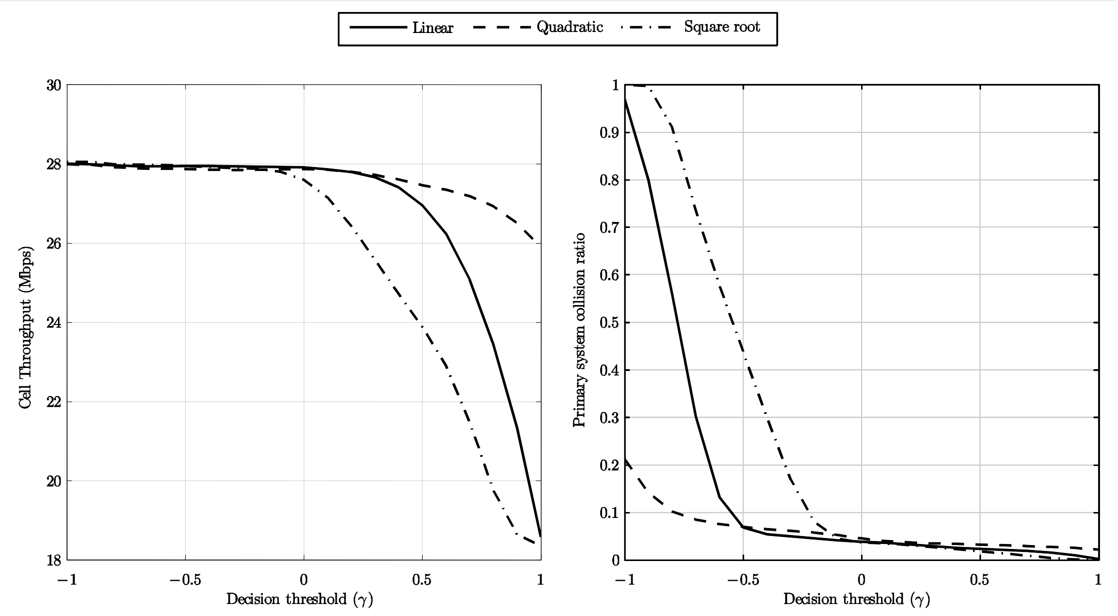
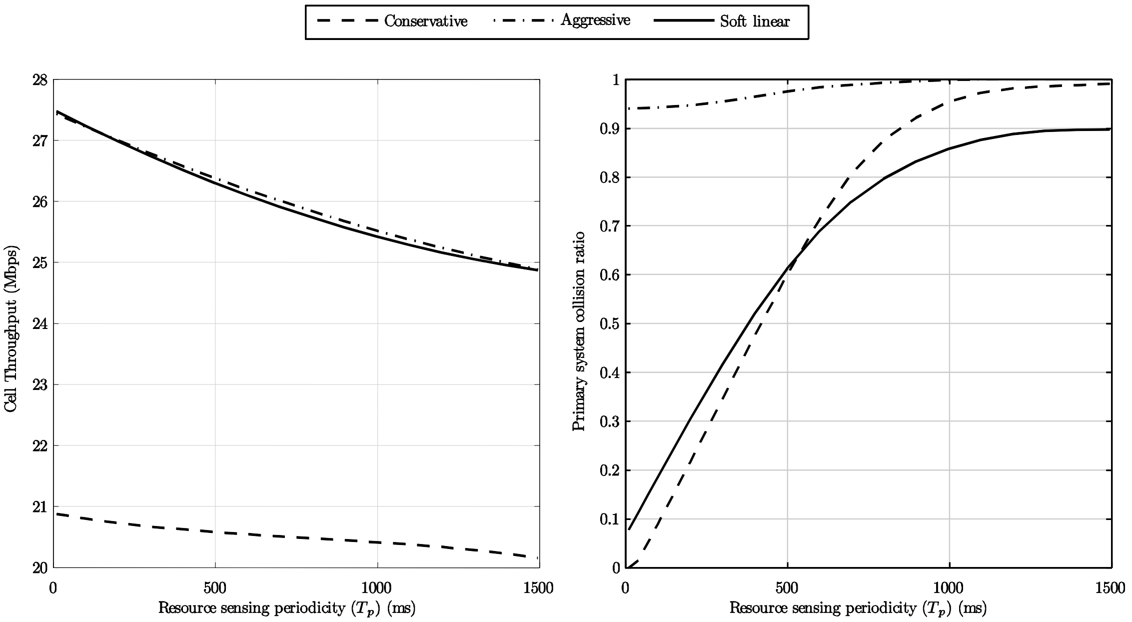
[2] *i.e.* Maximum Carrier-to-Interference Ratio. This scheduler prioritizes users with the highest received Signal-to-Interference power Ratio (SIR) (the received SIR is measured using the common pilot channel (CPICH) at the UE).



(a) (b)

Fig.19. System performance in terms of (a) cell throughput and (b) collision ratio for increasing decision thresholds when the linear, quadratic and square root versions are used.

Once the optimum decision threshold is set, it is necessary to check the benefits of soft-decisions as compared with hard decisions. For this purpose, Fig.20 depicts the experienced system performance (in terms of cell throughput and collision ratio) for different sensing periodicities, *i.e.* different values of T_p, with the three decision-making algorithms detailed in Section IV.1. Solid curves correspond to the soft-decision algorithm proposed in this Master Thesis work, the dashed curve is for the conservative strategy and, finally, the dash-dotted line is for the aggressive strategy. Fig.20(a) shows that the proposed soft-decision algorithm provides similar cell throughput as compared with the aggressive strategy, due to the fact that UEs sensing intervals, *i.e.* the 6ms-long time intervals –see MGL in Subsection III.1 – when the UE perform the spectrum sensing task, are desynchronized and some user can consume resources while others are sensing. However, longer sensing periods increase the channel uncertainty and make opportunistic users collide with the primary system. It can be also seen that increasing the sensing periodicity, which reduces the number of spectrum queries for a given time, does not enhance data throughput as it may be expected. Moreover, if the sensing periodicity is too high, channel state information is outdated and the number of collisions rises, see Fig.20(b), reducing the throughput. In the following, T_P will be assumed equal to 10ms since this value implies the highest cell throughput and lowest possible collision ratio according to the standard [28], which specifies that MGRP, T_P in this case, is configurable in multiples of the frame length –*i.e.* 10ms– (see Fig.11).

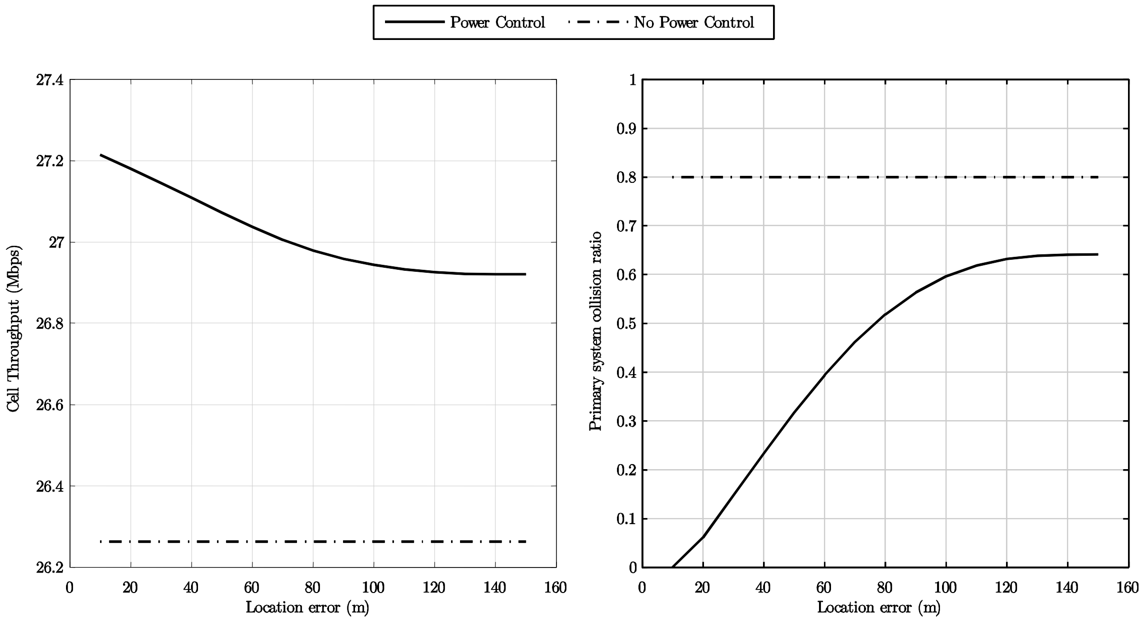


(a) (b)

Fig.20. Comparison of cell throughput (a) and collision ratio (b) among the conservative (dashed), aggressive (dotted-dashed) and soft-cooperative (solid) decision-making mechanisms considered for different sensing periodicities (T_P).

V.3. *COOPERATIVE ALGORITHM EVALUATION*

Another critical aspect in OSA techniques relying on Geo-DBs is the accuracy of the adopted UE location method. If a given UE is incorrectly supposed to be in an area where OSA is allowed, but its real location is in a forbidden OSA area, occupied opportunistic resources will be allocated to that user and the licensed system will be interfered. In addition, more problems associated to the precision error of the localization method may come up when the power of the opportunistic activity in the licensed band has to be limited because of detection of primary activity. In case the maximum range of the opportunistic signal is over-dimensioned, the number of collisions will increase. As a result, the performance provided by the PC mechanism –see Section IV.2– and, hence, the OSA, may be compromised. Aiming at studying the impact of the precision error of the UE localization method, a precision error modelled as a Gaussian distribution was introduced. In this way, Fig.21 shows the difference between either implementing PC (solid curve) or not (dashed lines) for different location errors. As it can be expected, the lack of a mechanism that controls the power of the opportunistic system provokes harmful interferences with the licensee, increasing the collision ratio, and limiting the potential throughput. On the other hand, simulation results show that the average cell throughput is slightly affected by the precision of the UE positioning. Positioning precision mainly affects the collision probability in the LTE-A system for the users that are far away from the eNodeB, for which transmission power is reduced to the minimum. In Fig.21(b) it can be seen that the maximum location error allowed in order to have a collision ratio lower than 10% is 30 m. In any case, there is a significant difference between implementing the PC and the Non-PC strategies for the allocation of resources in OSA. In the Non-PC case, the eNodeB transmits with the maximum power per RB, without power control, when it is cooperatively decided that there is no primary activity, increasing the number of collisions. As the scheduler used for the opportunistic resources tries to maximize the throughput (MaxCIR), the opportunistic resources will be normally scheduled for users close to the eNodeB and the collision probability in the LTE-A system will be small. Despite this, in the event of scheduling users far from the eNodeB, as they are closer to the primary system, their MCS will be more robust hence reducing the amount of transmitted data. Although this data was lost, this will affect the global throughput just slightly.



(a) (b)

Fig.21. (a) Cell throughput and (b) primary collision ratio for different location precision errors, with and without power control.

V.4. *OVERLAPPING AND PRIMARY SYSTEM ACTIVITY IMPACT*

In a real scenario, base stations are spread so as to cover the whole service. For this reason, the distance between eNodeBs and the primary system may change from one site to other. This may result in a lower or higher degree of overlap between the primary and the opportunistic systems or even they might not overlap. Therefore, it is necessary to evaluate the performance of the opportunistic tools described in this work for different overlapping situations. The overlapping factor (OF) is defined as the percentage of users under the LTE-A coverage area that are also able to detect the primary system activity (7). In addition, the primary system activity in a certain period of time depends on the primary system and its specific type of traffic. This section is dedicated to assess the dependence of the proposed OSA upon these two parameters

$$OF = \frac{\#\ of\ opportunistic\ users\ that\ sense\ the\ licensee}{\#\ of\ opportunisitc\ UEs\ spread\ over\ the\ scenario} \quad (7)$$

Fig.22 depicts the cell throughput of LTE-A with increasing OF for different primary activity factors –see F_{PA} definition in Section V.1–. Results show that with more activity in the primary system fewer resources are available for OSA and, thus, the achieved bit rate is lower. The overlapping factor also impacts on the experienced performance, especially for primary activity periodicities greater than 40% of the simulation time. However, the number of collisions is not affected by the overlapping area but by the primary system activity, as shown in Fig.23. Indeed, collision ratio increases when primary activity time decreases. The reason for this is that collisions are due to the sudden changes in the primary activity state.

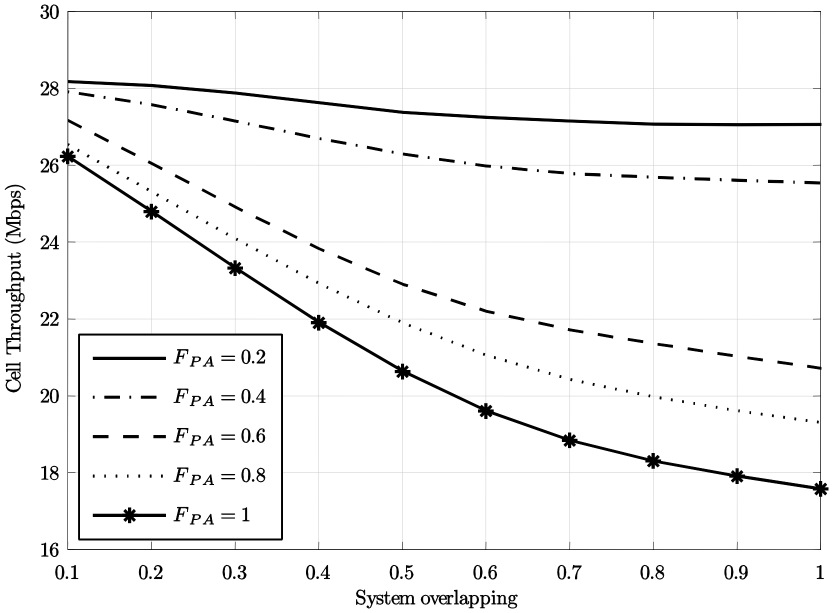


Fig.22. Experienced cell throughput for different system overlapping (OF) and primary system activity factor (F_{PA}) values.

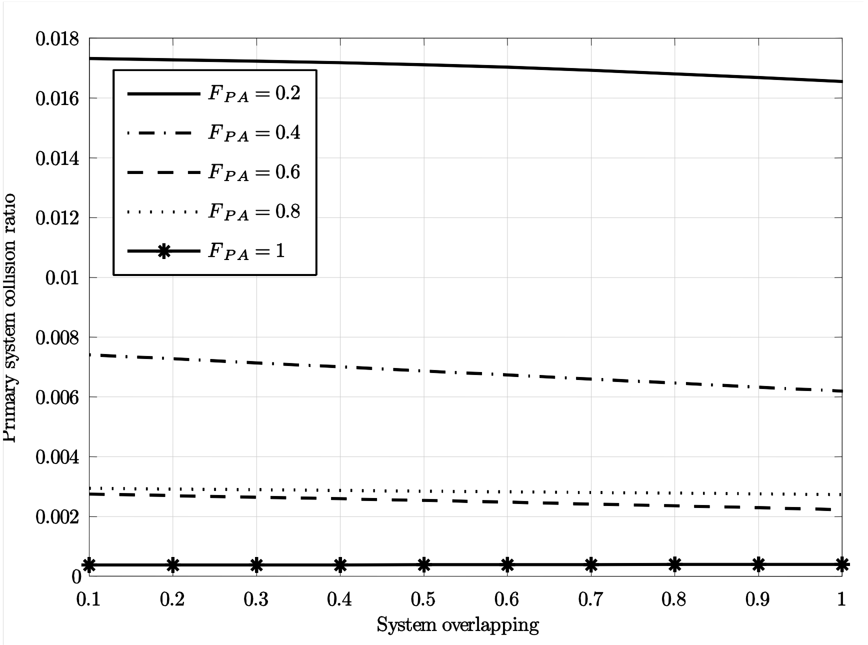


Fig.23. Expected primary collision ratio for different system overlapping (OF) and primary system activity factor (F_{PA}) values.

VI. CONCLUSIONS

This dissertation has proposed a set of tools and procedures to include opportunistic spectrum access in a LTE-A system. A new LTE network entity aiming at coordinating opportunistic access to unlicensed spectrum for cognitive UEs has been introduced. We have suggested a possible way to implement that coordinator, mixing the available LTE mechanisms and providing extra cognitive radio mechanisms. In addition, the proposed system is a low-cost solution because no modifications of the LTE-A system architecture are required for its implementation.

The implementation of this opportunistic access strategy in LTE-A certainly enhances the overall system performance. However, the opportunistic mechanisms must be set up carefully and several aspects have been discussed throughout the work. First, sensing periods must be as small as possible to increase accuracy. Only using cooperative decision-making mechanism these sensing periods can be increased. Moreover, several mechanisms for cooperative decision have been compared. It has been proved that the cooperative soft decision-making algorithm proposed in this dissertation work provides better performance than other hard decision mechanisms found in the literature. Similar rates to the aggressive strategy are achieved with the soft criterion, but with an evident reduction of the number of collisions with the licensed system, even lower than that achieved with the conservative strategy. Therefore, the suggested soft-decision algorithm takes advantage of the positive aspects of the two hard-decision criteria if an appropriate decision threshold is chosen. Finally, the UE location mechanism must be accurate enough in order to avoid interferences with the primary system. Specific figures have been provided for this level of accuracy.

We have also assessed the possibility of transmitting video with different qualities throughout a LTE-A system implementing cognitive mechanisms. It has been confirmed that video broadcasting over LTE-based systems is feasible, but the available system's bandwidth limits the characteristics of the transmitted video and the user's experience. If it is intended to go beyond LTE system capabilities, then a good solution is the implementation of cognitive elements, which allow monitoring other channels and using them in an opportunistic way when they are not busy, without interfering with other licensed systems. This study has shown that increasing the number of radio resources by using alternative frequency bands an increase in cell and user traffic rate is experienced. This performance improvement allows higher quality in video transmission, that implies higher bit-rate, and to accommodate a larger number of users. Furthermore, video delay is greatly reduced, and in some cases real-time experiences are possible, such as medium-quality video transmitted on a 10MHz LTE bandwidth system using TETRA.

The benefits, either in terms of increased throughput or delay reduction, are lower when using DVB band only than only TETRA, since the last slice of spectrum has larger bandwidth. The use of both cognitive bands provides the best performance: the more radio resources provided the better performance. However, indiscriminate use of these resources is not desirable. It has been demonstrated the need of a moderate aggressiveness scheme to occupy these licensed bands, but very aggressive systems would caused numerous collisions, degrading user experience and the effective traffic. Therefore the choice of cognitive parameters is critical, since a bad choice reduces the performance. Therefore, it is necessary to optimize certain parameters of the system. For example, this study has shown that cognitive bands should be monitored during a time long enough, about one millisecond, so that the system acquires sufficient and accurate information of the environment.

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