UNIVERSITAT POLITÈCNICA DE CATALUNYA
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Escola Tècnica Superior d'Enginyeria
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GAME THEORY-BASED CHANNEL SELECTION FOR LTE-U

A Master's Thesis

Submitted to the Faculty of the

Escola Tècnica d'Enginyeria de Telecomunicació de Barcelona

Universitat Politècnica de Catalunya

by

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In partial fulfilment

of the requirements for the degree of

MASTER IN TELECOMMUNICATIONS ENGINEERING

Advisor at UPC: Jordi Pérez-Romero

Barcelona, February 2016

Title of the thesis: Game Theory-based Channel Selection for LTE-U

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Abstract

The main topic of this thesis project is the study of a channel selection strategy for LTE-U based on the game theory. The method consists on a repeated game where each small cell is a player with the purpose of finding the best channel where to set up the LTE-U carrier and it uses the ITEL-BA algorithm in order to make the system to converge to a Nash Equilibrium state. The aim is to evaluate the performance of the system in terms of achieved throughput and convergence time depending on the variation of some parameters, which are the exploration rate, the achieved throughput and the non-stationarity condition. The work environment consists of a software that simulate the scenario where several small cells apply this strategy.

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Introduction

For some time now, the number of mobile broadband subscriptions have grown significantly, reaching billions of connections in the last few years. At the same time, also the amount of data usage per person increased, due to the increasing popularity of smartphones and to the evolution of the wireless technology. Consequently, the global mobile data traffic has faced a huge rise and a high proportion of the total demand is from 4G networks. That is why the wireless communication infrastructure is facing a great challenge with the expanding demand for wireless broadband access to Internet.

The matter that follows is to understand whether LTE (*Long Term Evolution*), which is the predominant 4G radio access technology, is evolving fast enough in order to guarantee the service to the whole demand.

Today, a number of access technologies, such as Wi-Fi, Bluetooth and ZigBee, are used in 2.4GHz ISM (*Industrial, Scientific and Medical*) and 5GHz U-NII (*Unlicensed National Information Infrastructure*) bands, known as “Unlicensed” or “Licensed-Exempt” bands.

In a companion publication (‘Extending LTE Advanced to unlicensed Spectrum’, Qualcomm Inc. December 2013), Qualcomm Inc. introduced a system, known as LTE-U (*LTE-Unlicensed*), which enables data offloads initially in unlicensed U-NII band, leveraging LTE CA (*Carrier Aggregation*) and SDL (*Supplemental Downlink*) protocols. More, several workshops to study the use of unlicensed spectrum with LTE alongside licensed spectrum were the basis of part of the 3GPP (*3rd Generation Partnership Project*) Release 13, also known as LAA (*Licensed Assisted Access*).

Aim of this thesis project is the evaluation of the performance of a channel selection strategy for LTE-U based on the game theory. Game theory is the formal study of conflict and cooperation. The channel selection strategy is modeled as a repeated game where each small cell is a player, in competition with the others, and the ITEL-BA (*Iterative Trial and Error Learning – Best Action*) learning algorithm is utilized in order to converge to a Nash Equilibrium state. The evaluation of the performance is made studying the impact of some parameters on the convergence time and the achieved throughput of the system.

The analysis was made by means of a software, run in MATLAB, which simulates a scenario where several small cells manage to find the best channel where to set up the LTE-U carrier. The simulations were of different typologies and different lengths, depending on the analysis willing to execute.

The work started with the reading of some papers for understanding the state of the art, deepening the topic of LTE-U and of the game theory-based channel selection strategy. The next step was the knowledge of the used tools for the development of the method, consisting of the software, run in MATLAB, which simulates the scenario for the analysis. After getting familiar with the program, modifications of the values of some parameters in the code were made in order to evaluate the performance of the system. In sequence, the impact of the exploration rate, of the activity period and of the non-stationarity on the performance of the system was studied. For each of them, the process consisted of setting up the parameters to launch the right simulation, obtaining and analyzing the results, discussing them and drawing up the conclusions. During the period of development of this project, the work load has been distributed as shown in the Gantt diagram below.

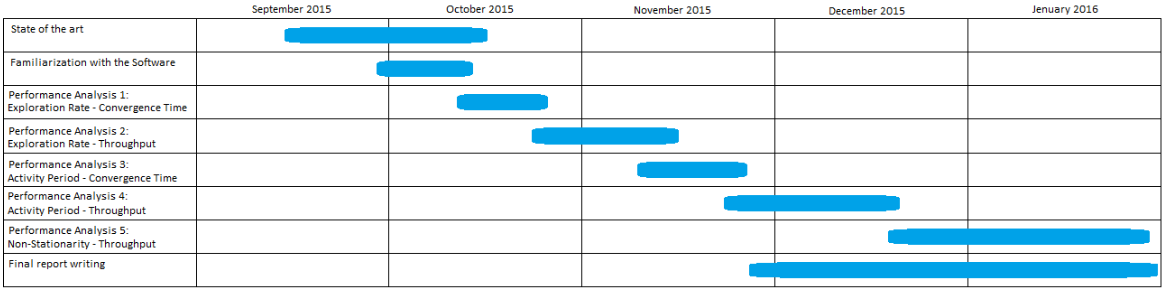


Figure A: Gantt diagram of the work load

The first two chapters present an overview of LTE and LTE-U, respectively, introducing the main features, the used technologies and the enhancements brought by these systems. The third chapter introduces the concept of game theory, presenting some applications to the wireless communications, and explains the game theory-based channel selection strategy studied in this project. In the fourth chapter, then, the purpose of the project is exposed and the work environment is presented. Chapter 5 presents the scenario with the tests performed and, then, discuss the results obtained. In the sixth chapter, at last, the conclusions are reached.

1. Long Term Evolution

1.1. Introduction to LTE

Mobile broadband usage, supported by the introduction of HSPA (*High Speed Packet Access*), is taking off, demanding improved services and increased capacity of mobile networks. To meet the increased demand for mobile broadband services, further improvements in the delivery of the service are required, such as higher data rates, shorter delays and even greater capacity. These are the targets of 3GPP radio access networks HSPA and LTE, of which the latter is the focus of this argumentation [1] [2]. LTE (both radio and core network evolution) is now on the market. Release 8 was frozen in December 2008 and this has been the basis for the first wave of LTE equipment. LTE specifications are very stable, with the added benefit of enhancements having been introduced in all subsequent 3GPP releases. The motivations for LTE are:

- Need to ensure the continuity of competitiveness of the 3G system for the future;
- User demand for higher data rates and quality of services;
- Packet Switch optimized system;
- Continued demand for cost reduction (CAPEX and OPEX);
- Low complexity;
- Avoid unnecessary fragmentation of technologies for paired and unpaired band operation [3].

LTE brings improved performance, compared to the early 3G system, including peak data rates exceeding 300Mbps, delays and latencies below 10ms and manifold spectrum efficiency gains. Moreover, LTE can be deployed in new and existing frequency bands, it has a flat architecture with few nodes and it facilitates simple operations and maintenance. In addition, LTE both targets a smooth evolution from legacy 3GPP and 3GPP2 systems and constitutes a major step toward IMT-Advanced (*International Mobile Telecommunications – Advanced*) systems. In fact, LTE includes many of the features originally considered for a 4G system [1] [2].

Figure 1.1: LTE logo [3]

LTE or the E-UTRAN (*Evolved - Universal Terrestrial Access Network*), introduced in 3GPP R8, is the access part of the EPS (*Evolved Packet System*). EPS is purely IP based. Both real time services and datacom services are carried by the IP protocol where the IP address is allocated when the mobile is switched on and released when it is switched off. The main requirements for this access network are high peak data rates, high spectral efficiency, short round trip time as well as flexibility in frequency and bandwidth [3].

1.2. Architecture

3GPP SAE (*System Architecture Evolution*) addresses the evolution of the overall system architecture including core network. Objective is to develop a framework for an evolution of the 3GPP system to higher-data-rate, lower-latency and packet-optimized system that supports multiple radio access technologies. The focus of this work is on the PS domain with the assumption that voice services are supported in this domain. Clear requirement is the support of heterogeneous access networks in terms of mobility and service continuity [4].

[Figure 1.2] provides a high-level view of LTE architecture. This is a snapshot of the part that most closely interacts with the UE (*User Equipment*), or mobile device, while the entire architecture is more complex [5]. The LTE access network is simply a network of base stations, also called eNB (*evolved NodeB*), generating a flat architecture. There is no a centralized controller but the intelligence is distributed among the base stations in order to speed up the connection set-up and reduce the time required for a handover [3]. In the network architecture showed in [Figure 1.2], the E-UTRAN consists of eNBs providing the E-UTRA user plane (PDPC/RLC/MAC/PHY) and control plane (RRC) protocol terminations towards the UE. The eNBs are interconnected among each other by means of the X2-interface and, moreover, they are also connected by means of the S1-interface to the EPC (*Evolved Packet Core*), more specifically to the MME (*Mobility Management Entity*) and to the S-GW (*Serving Gateway*) [4].

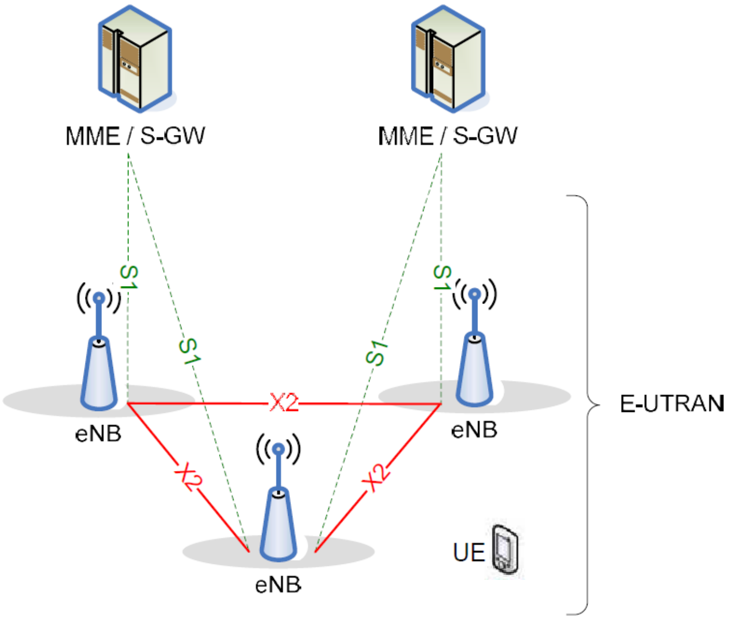


Figure 1.2: LTE network architecture [5]

[Figure 1.3] shows the functional split between E-UTRAN and EPC and, as it can be seen, the base station functionality has increased significantly in E-UTRAN. In fact, the eNB hosts functions for radio bearer control, admission control, uplink and downlink scheduling and measurement configuration [4].

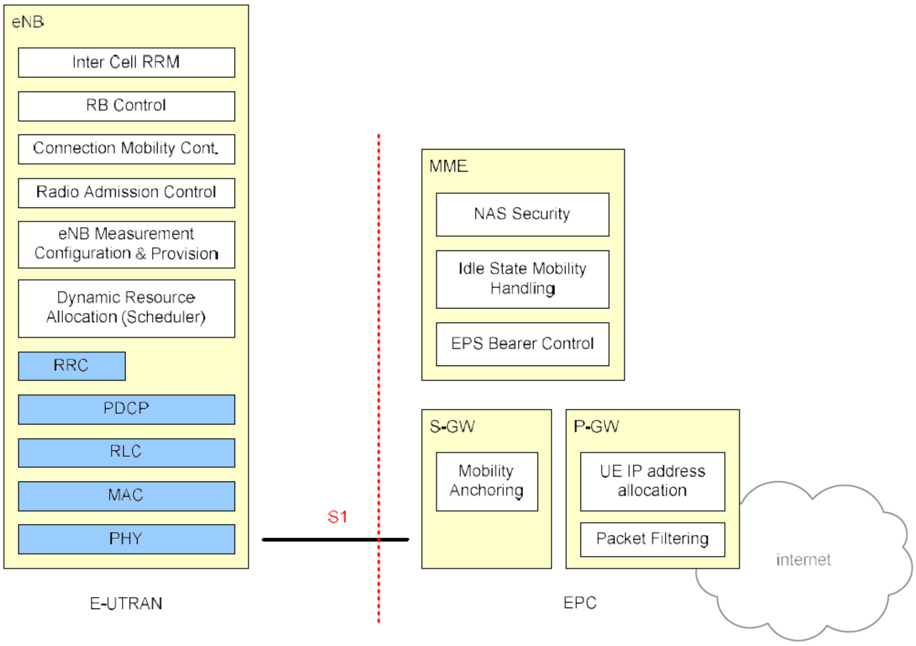


Figure 1.3: Functional split between E-UTRAN and EPC [4]

Another advantage of the distributed solution is that the MAC protocol layer, which is responsible for scheduling, is represented only in the UE and in the base station, leading to fast communications and decisions between the eNB and the UE. The scheduler is a key component for the achievement of a fast adjusted and efficiently utilized radio resource. The TTI (*Transmission Time Interval*) is set to only 1ms and, during each TTI, the eNB scheduler shall:

- Consider the physical radio environment per UE. Each UE reports its perceived radio quality, as an input to the scheduler, to decide which modulation (up to 64-QAM) and coding scheme to use;
- Prioritize the QoS service requirements amongst the UEs. LTE supports both delay sensitive real-time services as well as datacom services requiring high data peak rates;
- Inform the UEs of allocated radio resources. The eNb schedules the UEs both on the downlink and on the uplink; for each UE scheduled in a TTI the user data will be carried in a Transport Block (TB), which is delivered on a transport channel. In the downlink there can be a maximum of two TBs generated per TTI per UE. For the user plane there is only one shared transport channel in each direction [3].

1.3. Key Features

An intrinsic characteristic of radio communication is that the instantaneous radio-channel quality varies in time, space and frequency, including relatively rapid variations due to multipath propagation. Therefore, methods for mitigating these variations (diversity techniques) have been employed to maintain a constant data rate over the radio link. However, for packet-data services, end-users do not usually notice such rapid short-term variations. Consequently, one of the fundamental principles of LTE radio access is to exploit, rather than suppress, these rapid variations of the channel quality in order to make a more efficient use of the available radio resources [2]. In fact, in order to achieve high radio spectral efficiency as well as enable efficient scheduling in both time and frequency domain, a multicarrier approach for multiple access was chosen by 3GPP. For the downlink, OFDM (*Orthogonal Frequency Division Multiplexing*) was selected while for the uplink SC-FDMA (*Single Carrier – Frequency Division Multiple Access*), also known as DFT (*Discrete Fourier Transform*) spread OFDMA [3].

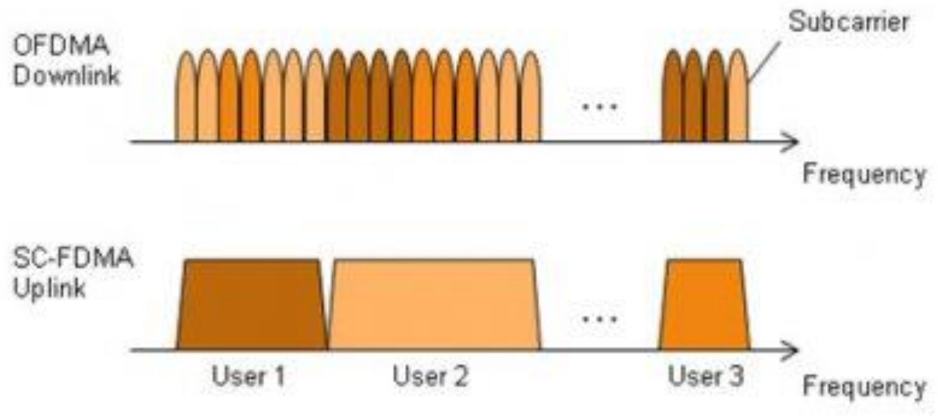


Figure 1.4: OFDMA and SC-FDMA [3]

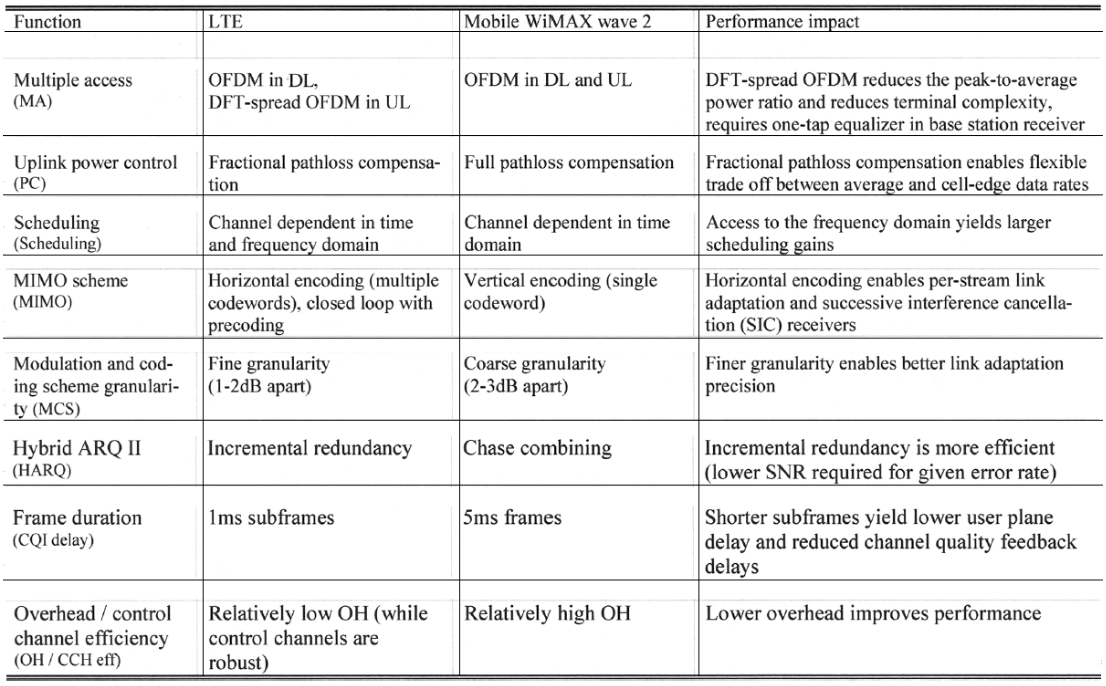
OFDMA is a multicarrier technology subdividing the available bandwidth into a multitude of mutual orthogonal narrowband subcarriers, which can be shared among multiple users. The numerology includes a subcarrier spacing of 15KHz, support for bandwidth up to 20MHz, and resource allocation granularity of 180KHz x 1ms. OFDM, in combination with high order modulation (up to 64-QAM), large bandwidths (up to 20MHz) and spatial multiplexing in the downlink (up to 4x4), makes it possible to achieve high data rates. The highest theoretical peak data rate on the transport channel is 75Mbps in the uplink and it can be as high as 300Mbps in the downlink, using spatial multiplexing [3].

Conventional OFDM with data transmitted over several parallel narrowband subcarriers lies at the core of LTE downlink radio transmission and the use of these subcarriers in combination with a cyclic prefix makes OFDM transmission relatively robust to time dispersion on the radio channel, eliminating the need for complex receiver-side channel equalization. This simplifies receiver baseband processing and thus reduces terminal costs and power consumption at receiver side. On the other hand, the OFDMA solution leads to high peak-to-average power ratio requiring expensive power amplifiers with high requirements on linearity, increasing the power consumption for the sender. Hence, another solution was chosen for the uplink. In this case, where there is less available transmission power than in downlink, an important factor is a power-efficient transmission scheme, in order to maximize the coverage and minimize terminal costs and power consumption.

Consequently, the LTE uplink employs, as mentioned above, SC-FDMA in order to limit the peak-to-average power ratio and, thereby, reducing terminal complexity and resulting more power-efficient. This technique generates a signal with single carrier characteristics, hence with a low peak-to-average power ratio [3].

In order to enable possible deployments around the world, supporting as many requirements as possible, LTE is developed for frequency bands ranging from 700MHz up to 2,7GHz and the available bandwidths are also flexible starting with 1,4MHz up to 20MHz. Furthermore, LTE supports both the TDD (*Time Division Duplexing*) and FDD (*Frequency Division Duplexing*) techniques. Also, added in R9, there were MBMS (*Multimedia Broadcast Multicast Service*), which is used to provide broadcast information to all users (e.g. advertisement) and multicast to a closed group subscribing to a specific service (e.g. streaming TV), and HeNBs (*Home eNB*), which are low power eNBs used in small cells (femto cells) and which provide coverage indoor (home or office) [3]. Moreover, several antenna concepts targeting different scenarios are included: diversity for improving robustness of control channel, beamforming for improving channel quality, multi-stream (MIMO) transmission for improving data rates [1].

Some of the more fundamental features discussed above are not unique to LTE, e.g. OFDM, multi-antenna transmission or adaptive modulation and coding are standard techniques used by other systems. However, LTE distinguishes itself by using more sophisticated solutions than other systems. A list of such characteristics is shown in [Figure 1.5] where, for each reference, the corresponding solutions used in more basic systems are also listed. This is represented by Mobile WiMAX Wave 2 [1].



Function	LTE	Mobile WiMAX wave 2	Performance impact
Multiple access (MA)	OFDM in DL, DFT-spread OFDM in UL	OFDM in DL and UL	DFT-spread OFDM reduces the peak-to-average power ratio and reduces terminal complexity, requires one-tap equalizer in base station receiver
Uplink power control (PC)	Fractional pathloss compensation	Full pathloss compensation	Fractional pathloss compensation enables flexible trade off between average and cell-edge data rates
Scheduling (Scheduling)	Channel dependent in time and frequency domain	Channel dependent in time domain	Access to the frequency domain yields larger scheduling gains
MIMO scheme (MIMO)	Horizontal encoding (multiple codewords), closed loop with precoding	Vertical encoding (single codeword)	Horizontal encoding enables per-stream link adaptation and successive interference cancellation (SIC) receivers
Modulation and coding scheme granularity (MCS)	Fine granularity (1-2dB apart)	Coarse granularity (2-3dB apart)	Finer granularity enables better link adaptation precision
Hybrid ARQ II (HARQ)	Incremental redundancy	Chase combining	Incremental redundancy is more efficient (lower SNR required for given error rate)
Frame duration (CQI delay)	1ms subframes	5ms frames	Shorter subframes yield lower user plane delay and reduced channel quality feedback delays
Overhead / control channel efficiency (OH / CCH eff)	Relatively low OH (while control channels are robust)	Relatively high OH	Lower overhead improves performance

Figure 1.5: LTE key characteristics [1]

In the following, it is exposed a description of several individual key features with the specific target they address.

Spectrum flexibility: Radio spectrum for mobile communications is available in different frequency bands in different bandwidths, and comes as both paired and unpaired spectrum. Spectrum flexibility enables operations under all these conditions. As mentioned above, LTE can be developed with bandwidths ranging from 1,25MHz up to 20 MHz, approximately, and it can operate in both paired and unpaired spectrum by providing a single radio-access technology that supports FDD as well as TDD operations. Where terminals are concerned, FDD can be used both in full- and half-duplex modes. Half-duplex FDD is useful because it allows terminals to operate with relaxed duplex-filter requirements, reducing cost of terminals and making possible to exploit FDD frequency bands which cannot otherwise be used (too narrow duplex distance). These solutions make LTE fit nearly arbitrary spectrum allocation [2].

Multi-antenna transmission: The use of this technique in mobile communication systems enhances system performance, service capabilities, or both. At its highest level, LTE multi antenna transmission can be divided into:

- Transmit diversity;
- (pre-coder-based) multistream transmission including beamforming as a special case.

LTE transmit diversity is based on SFBC (*Space-Frequency Block Coding*) techniques complemented with FSTD (*Frequency-Shift Time Diversity*) when four transmit antenna are used. This technique is intended for downlink channels that cannot make use of channel-dependent scheduling, or it can also be applied to user-data transmission (VoIP) when low user data rates do not justify the additional overhead associated with channel-dependent scheduling. In summary, it is used to increase system capacity and cell coverage range. On the other hand, multistream transmission develops multiple antennas at transmitter and receiver side in order to provide simultaneous transmission of parallel data streams over a single radio link. This technique increases the peak data rates over the radio link. In lightly loaded cell deployments, multistream transmissions lead to high data rates and more efficient radio resources utilization. In heavy loaded cells, this technique is best used for single stream beamforming in order to enhance the quality of the signal. In summary, when channel conditions are very good, up to four streams can be transmitted in parallel, leading to data rates up to 300Mbps in a 20MHz bandwidth; when channel conditions are less favorable, fewer parallel streams are used and a beamforming transmission scheme is used to improve the overall reception quality and, consequently, system capacity and coverage; to achieve good coverage, single stream beamforming transmission can be employed [2].

Scheduling and link adaptation: In LTE dynamic scheduling (1ms) is applied both to uplink and downlink. Channel-dependent scheduling is used to achieve high values of cell throughput. Transmissions can be carried out with higher data rates by transmitting on time or frequency resources with good channel conditions. In this way, fewer radio resources are consumed for any amount of information to be transferred, leading to a improved overall system efficiency. LTE applies also persistent scheduling, which implies that radio resources are allocated to a user for a given set of subframes. Link-adaptations techniques are utilized to make the most of instantaneous channel quality. They adapt the selection of modulation and channel coding schemes to current channel conditions, determining the datarate or error probabilities of each link [2].

Uplink power control: Power control is about setting transmit power levels with the aim of improving the system capacity, coverage, user quality and reducing power consumption. To reach these objectives, this technique usually attempts to maximize the received power while limiting interference. The LTE uplink is orthogonal so, in the ideal case, there is no interference among users of the same cell while the amount of interference with the neighbor cells depends on the position of the mobile terminal. The closer the terminal is to another cell, the higher the interference. Accordingly, terminals that are farther away from the neighboring cells may transmit with higher power and, moreover, there is a correlation between proximity to the serving cell and distance to the neighboring cells. The orthogonal LTE uplink makes possible to multiplex signals from terminals with different received uplink power in the same cell. Consequently, in the short term, instead of compensating for peaks in multipath fading by reducing power, these peaks can be exploited to increase the data rates by means of scheduling and link adaptation. In the long term, one can set the received power target based on the path gain to the serving cell, giving terminals that generate little interference a larger received power target [2].

Retransmission handling: In communications systems retransmission schemes are used to guarantee the quality of transferred data and to safeguard against occasional data transfer errors arising from, for example, noise, interference and fading. LTE supports a dynamic and efficient two-layered retransmission scheme: a fast HARQ (*Hybrid Automatic Repeat Request*) protocol with low overhead feedback and retransmission with incremental redundancy is complemented by a highly reliable selective repeat ARQ protocol. The HARQ protocol gives the receiver redundancy information that enables it to avoid a certain amount of errors, while the ARQ protocol provides a means of completely retransmitting packets which cannot be corrected by the HARQ protocol. This design leads to low latency and overhead without sacrificing reliability. In the LTE architecture, these two protocols are terminated in the eBNs, which gives tighter coupling between the HARQ and ARQ protocol layers; the benefits are manifold and include fast handling of residual HARQ errors and variable ARQ retransmission size [2].

It should be noted that there are several other features of LTE differing between these which are not listed, e.g. control signaling robustness, higher layer overhead and mobility aspects.

1.4. LTE evolution

LTE brought many improvements in terms of performance with respect to the previous network technologies and, along with those, new services and applications could have been developed. An important development, for instance, is the adoption of LTE as the technology supported by public safety communications. On the other hand, with the fast evolution of the cellular technologies and the phenomenal growth of the mobile data demand, new improved versions of LTE have been developed in order to fulfil these requirements; it is possible to refer to them with the terminologies LTE-A (*LTE-Advanced*) and LTE-U (*LTE-Unlicensed*).

In the following, a short overview of LTE-A is presented, while LTE-U, which is the technology at the basis of this project, will be explained in details in the next chapter.

1.4.1. LTE-Advanced

Along with the rapid development in cellular technology, there has also been a significant increase in its user demands. Even since LTE technology has been established in 2009, the work on its enhancements and requirements had begun and these have been fulfilled successfully by LTE-Advanced (LTE-A), the 3GPP Release 10, which has proven to be one of the fastest developing mobile technologies in the world [6].

In LTE-Advanced the focus is on higher capacity. LTE Release 10 was to provide higher bitrates in a cost efficient way and, at the same time, completely fulfil the requirements set by ITU for IMT-Advanced (*International Mobile Communications-Advanced*), also referred to as 4G. The improvements brought with LTE-A are:

- Increased peak data rate: downlink 3Gbps and uplink 1.5Gbps;
- Higher spectral efficiency: from a maximum of 16bps/Hz in R8 up to 30bps/Hz in R10;
- Increased numbers of simultaneously active subscribers;
- Improved performance at cell edges.

Its efficient interference management and reduced operational costs make LTE-A popular among operators. Its overall capacity, network management, quality of service management are the attributes that make LTE-A to give the best performance. The new main functionalities introduced in LTE-Advanced are Carrier Aggregation (CA), enhanced utilization of multi-antenna (MIMO) techniques and support for Relay Nodes (RN) [7].

Carrier aggregation: The most straightforward way to increase capacity is to add more bandwidth. Since it is important to keep backward compatibility with R8 and R9 mobiles, the increase in bandwidth in LTE-A is provided through aggregation of R8/R9 carriers. CA supports both TDD and FDD. Each aggregated carrier is referred to as a component carrier (CC). The component carrier can have a bandwidth of 1.4, 3, 5, 10, 15 or 20MHz and a maximum of five component carriers can be aggregated. Hence the maximum bandwidth is 100MHz. The number of aggregated carriers can be different in DL and UL, however, the number of aggregated components in UL is never larger than the number of aggregated carriers in DL. The individual component carriers can also be of different bandwidths [7].

In CA, broadband transmission is enabled through the communication of multiple CCs exceeding 20MHz of bandwidth. There are two types of carrier aggregation:

- Contiguous inter-band CA
- Contiguous intra-band CA and non-contiguous intra-band CA

In contiguous inter-band CA, the frequency arrangement is such that communication between CCs is achieved by a contiguous band greater than 20MHz. In non-contiguous intra-band CA, the communication is achieved by the use of two different carrier frequency bands, this helps in achieving higher throughput. In contiguous intra-band CA, communication is achieved by using multiple carriers in the same frequency bands [6]. Moreover, LTE-U is built upon the carrier aggregation capability of LTE-A. Essentially, CA seeks to increase the overall bandwidth available to a user equipment by enabling it to use more than one channel, either in the same band or within another band. In the next chapter it will be explained more in detail how carrier aggregation is exploited by LTE-U.

MIMO (*Multiple Input Multiple Output*) – or spatial multiplexing: MIMO is used to increase the overall bitrate through transmission of two (or more) different data streams on two (or more) different antennas – using the same resources in both frequency and time, separated only through use of different reference signals – to be received by two (or more) antennas [7]. LTE-Advanced supports the configuration of 8 antennas (8x8 MIMO) in the downlink and 4 antennas (4x4 MIMO) in the uplink. MIMO can be used when SNR (*Signal to Noise ratio*) is high, i.e. high quality radio channel. For situations with low SNR it is better to use other types of multi-antenna techniques in order to improve the SNR, e.g. by means of TX-diversity. Multiple antenna techniques play an important role in increasing spectral efficiency, average cell throughput and cell edge performance.

Relay nodes: In LTE-A the possibility for efficient heterogeneous network planning – i.e. a mix of large and small cells – is increased by introduction of Relay Nodes (RN). The relay node establishes wireless connection with radio access network via a DeNB (*Donor eNB*). The relay node is a low power base station that provides enhanced coverage and capacity at cell edges, and hot-spot areas and it can be also used to connect to remote areas without fiber connection. In addition, wireless relays can increase throughput, provide group mobility and capacity at cell edges.

2. LTE-Unlicensed

2.1. Introduction to LTE-U

The huge growth of demand has brought about increasing scarcity in available radio spectrum. Meanwhile, mobile customers pay more attention to their own experience, especially in communication reliability and service continuity on the move. To address these issues, LTE-U (*Long Term Evolution-Unlicensed*) is considered one of the latest groundbreaking innovations to provide high performance and seamless user experience under a unified radio technology by extending LTE to the readily available unlicensed spectrum [8].

LTE-Unlicensed is a promising enhancement in the 3GPP ecosystem that enables LTE to operate and coexist with other technologies in unlicensed bands. Although licensed spectrum remains 3GPP operators' top priority to deliver advanced services and better user experience (i.e. Quality of Service cannot be matched by unlicensed spectrum), the use of unlicensed spectrum will be an important complement to meet the ultra-high capacity foreseen to be needed by 4G and beyond [9]. LTE-U aims to offer mobile network operators a new approach to offload their traffic onto the unlicensed spectrum with seamless integration into their existing LTE evolved packet core (EPC) architecture. However, it will also introduce new challenges for other wireless networks operating on the same unlicensed bands, especially for the Wi-Fi network [10].

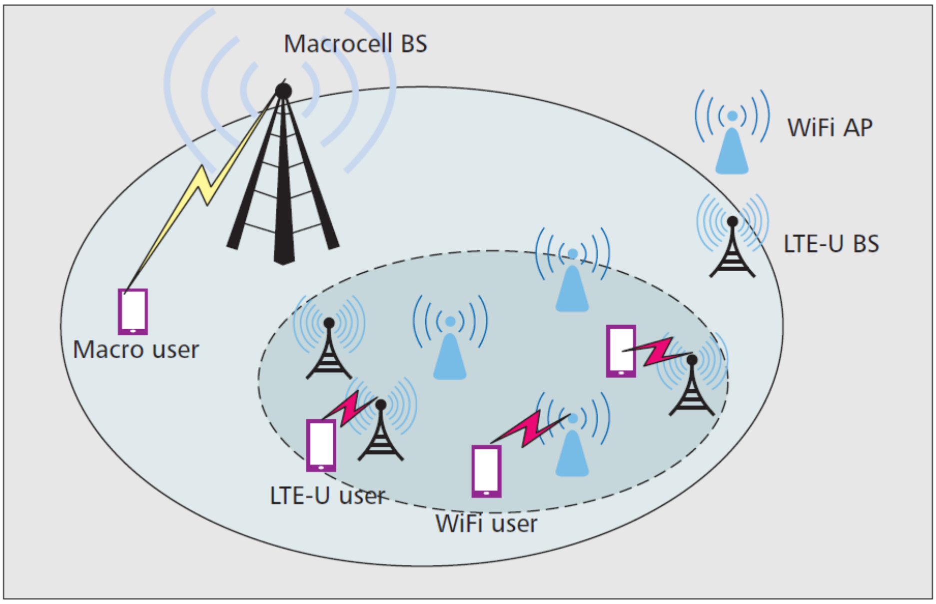


Figure 2.1: Example of LTE-U network topology [8]

However, compared to the usage of Wi-Fi in unlicensed spectrum, LTE-U offers several features that are attractive to operators:

- The spectrum efficiency and coverage with LTE is better than with Wi-Fi due to more advanced radio features such as FEC (*Forward Error Correction*), hybrid ARQ, interference coordination/avoidance, etc…;

- The same RAN (*Radio Access Network*) can provide LTE data access in licensed and unlicensed spectrum;
- A simplified network management and tracking of KPIs (*Key Performance Indicators*) through a single RAN can be achieved;
- Improved network management and load balancing through tighter integration;
- Instead of continue pursuing LTE – Wi-Fi interworking, LTE-U is well integrated to the existing operator network, thus solving all authentication, O&M (*Operations and Management*) and QoS issues;
- LTE ecosystem kinds of applications (e.g. machine-to-machine, device-to-device, etc.) are exploitable in LTE-U [9].

While having a bright future, LTE-U is still in its infancy and faces many challenges before being brought to fruition. The primary challenge, as mentioned above, is the coexistence between LTE-U systems and the incumbent unlicensed systems, for instance, user-deployed Wi-Fi systems. If left unrestrained, LTE-U transmissions can generate continuous interference to Wi-Fi systems, resulting in unceasing backoff of Wi-Fi nodes as the channel is detected to be busy most of the time. Hence, smart modifications to the resource management functionalities are indispensable on both sides to achieve harmonious coexistence. Second, the traffic offloading issues in the LTE-U scenario need to be revisited. Traffic offloading in LTE-U scenario needs to incorporate the user activities of the other unlicensed systems. To protect Wi-Fi performance, LTE performance in unlicensed spectrum will inevitably fluctuate with Wi-Fi activities, leading to considerable performance instability, which makes it challenging to provide LTE-U quality of service guarantee. Thus, a trade-off between offloading LTE user data to unlicensed spectrum and ensuring the QoS of LTE-U subscribers should be made. Last but not least, unlike the licensed spectrum, different operators may access the same portion of unlicensed spectrum bands. Negotiation and coordination polices need to be deliberately designed to realize efficient inter-operator spectrum sharing [8].

2.2. Technology and features

In 2014, the FCC voted unanimously to open up another 100MHz of spectrum to meet the ever increasing demand for unlicensed wireless services as the first step and an additional 195MHz in the next step, both in the 5GHz band. Compared to the 2.4GHz band, the 5GHz band is less congested and mainly used by Wi-Fi (11a) devices and, in addition, it has a shorter communication range due to higher pass loss but has wider available bandwidth. Therefore, for the sake of clearer channel conditions, wider spectrum and easier implementation, LTE-U currently focuses on 5GHz bands to provide broadband multimedia services. [Figure 2.2] shows the unlicensed spectrum layout in several different main regions at 5GHz [8].

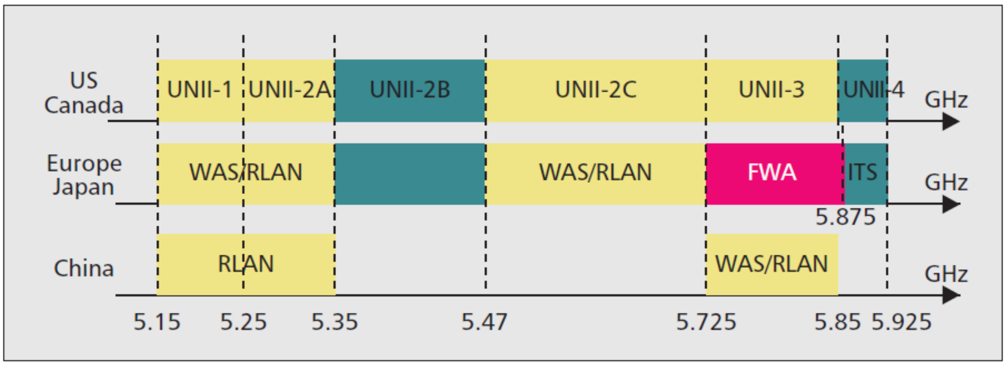


Figure 2.2: Unlicensed spectrum layout in different regions at 5GHz [8]

Although access to LTE over the unlicensed spectrum can be cost effective, some fundamental principles and regulations are imposed to guarantee harmonious coexistence between LTE-U and other incumbent systems.

Transmission power: The regulation of transmission power is a first issue in the use of unlicensed spectrum. It is specified to manage the interference among the users. For instance, there are maximum transmission power thresholds for indoor and outdoor usage. Besides the maximum transmission power, the 5.25-5.35GHz and 5.47-5.725GHz spectrum has mandated TPC (*Transmit Power Control*) mechanisms. TPC reduces the power of a radio transmitter to the minimum necessary in order to avoid interference to other users [8].

Radar Protection and Dynamic Frequency Selection: Meteorological radar systems also operate in the 5GHz unlicensed spectrum, thus, there may be interference on the radar transceiver. To better protect radars, an interference avoidance mechanism named DFS (*Dynamic Frequency Selection*) is adopted in 5.25-5.35GHz and 5.47-5.725GHz spectrum. Under DFS, LTE-U devices periodically detect whether there are radar signals and will switch the operating channel to one that is not interfering [8].

Listen Before Talk Feature: If LTE-U inherits the current MAC protocol without careful coexistence considerations, its operation would incur continuous interface to Wi-Fi systems since Wi-Fi adopts a contention-based MAC and will keep backing off when it detects LTE transmission. To coexist with incumbent unlicensed systems, LTE-U devices are required to detect before transmission whether the target channel is occupied by other systems at a millisecond scale. This is referred to as LBT (*Listen Before Talk*), meaning that one LTE-U device can transmit only when no ongoing transmission is observed for a specified period [8]. Also in WLANs sufficient care must be taken when deploying LAA. This is why LBT is discussed as a mandatory feature of LTE LAA system in order to guarantee fair and friendly coexistence in the unlicensed spectrum and to develop a single global solution. About this topic, focus of [11] is the design of LBT for LTE LAA operation.

Channel Sensing: Wi-Fi transmissions cannot be fully protected due to its CSMA (*Carrier Sensing Multiple Access*)-based random access protocol. Channel sensing requires equipment to check the presence of other occupants in the channel before transmitting. Since Wi-Fi is severely impacted by LTE transmissions in coexistence scenarios, adopting channel sensing methods in LTE-U is expected to be an effective way to avoid the significant degradation of Wi-Fi performance. An implementation of channel sensing in LTE-U is investigated in [10].

Due to the transmission power limitations in unlicensed spectrum, the LTE-U technology is more suitable for a small area. Hence, the deployment of most interest is the operator-deployed small cell, which provides access to both licensed and unlicensed spectrum for indoor environment and outdoor hotspots.

There are two different operation modes for LTE-U: SDL (*Supplemental Downlink*) and TDD (*Time Division Duplex*). The first one is the simplest form of LTE-U where the unlicensed spectrum is only used for downlink transmission, as downlink traffic is typically much heavier than uplink traffic. In TDD mode, on the other hand, the unlicensed spectrum is used for both downlink and uplink. This mode offers the flexibility to adjust the resource allocation between downlink and uplink, at the cost of extra implementation complexity on the user side, such as LBT features and radar detection requirements on the user equipment [8]. However, the first focus for LTE-U is on leveraging supplemental downlink capabilities over unlicensed spectrum. In this way, licensed band LTE provides reliable connection for mobility, signaling, voice and data in uplink and downlink, while LTE-U boosts data rates and capacity in downlink. Deployment scenarios can consider both licensed LTE-FDD (e.g. 1.8GHz) and licensed LTE-TDD (e.g. 2.6GHz) combined with LTE-U in downlink (e.g. 5GHz) [9].

2.3. Licensed Assisted Access

LAA (*Licensed Assisted Access*) is the 3GPP’s effort to standardize operations of LTE in unlicensed bands. This project has recently reached an important milestone with the completion of the feasibility study and the approval of the corresponding Technical Report 36.889 [12]. Based on the conclusion of the study, it has been decided to move the project to normative phase with the specification of LAA downlink operation in Rel.13 (uplink operation will be specified in a later release).

LTE-U and LAA are both part of the LTE unlicensed family. They are set to bring enhanced mobile experiences to customers by providing better wireless coverage, seamless mobility and increased capacity. These technologies rely on unlicensed spectrum – the foundation for permission-less innovation in wireless, allowing many technologies, including Wi-Fi and Bluetooth, to flourish [13].

It is possible to make a small comparison between LTE-U and LAA in order to see which the real differences are. First, LTE-U is a technology for the mobile operator deployments in USA, Korea and India, based on the 3GPP Rel.10/11/12, while LAA is for the mobile operator deployments in Europe and Japan, defined in the 3GPP Rel.13 and beyond, as mentioned above. Both of them protect and coexist well with Wi-Fi. They utilize a dynamic channel selection strategy, meaning that they dynamically select the unused channel with the least interference, avoiding Wi-Fi. In case there are no free channels, a fair and efficient coexistence must be achieved. LTE-U uses CSAT (*Carrier Sensing Adaptive Transmission*) to sense the other users and adjust on/off LTE cycling, with upgrade path to LAA, which, differently, abides by a region-specific LBT policy to sense channel availability and adjust on/off LTE cycling [13].

More, there might be the case of a shift from aggregated band to licensed band only. At low traffic loads, LTE-U/LAA turns off the transmission in the unlicensed spectrum, relying solely on the anchor of the licensed spectrum. Nevertheless, aggregation provides superior end-user benefits; in fact, with LWA (LTE/Wi-Fi link aggregation) and LTE-U/LAA carrier aggregation, end-users get improved coverage, extended mobility and increased capacity [13]. In particular, exploiting CA, component carriers in different frequency bands could be aggregated into wider virtual bandwidth to provide higher data rates. With CA, the control plane messages are always transmitted on the licensed band where the QoS is guaranteed. The user plane data can be transmitted on either licensed or unlicensed carriers. In this way, the crucial information can always be transmitted with QoS ensured [8].

2.4. Benefits and Challenges

Several advantages can be achieved by extending LTE to the unlicensed spectrum. In the following there are summarized some benefits brought by LTE-U, compared to the Wi-Fi system, which is the most commonly used system in unlicensed bands.

Boosts in data rates through CA: Thanks to CA technology, used to aggregate both licensed and unlicensed bands, a wider bandwidth can be used to achieve higher throughput. In addition, LTE-U can provide higher spectrum efficiency than Wi-Fi systems because LTE is a synchronous system which adopts scheduling-based channel access instead of contention-based random access. Other technologies of licensed LTE can be applied to the unlicensed spectrum (e.g. eICIC, CoMP, etc.) bringing significant increased data rates, which means smaller latency for real-time applications, higher quality and stability for video streaming. And thus considerably better user experience [8].

Reliable and Secure communication with a anchor in the Licensed band: The licensed LTE has defined nine QoS class identifiers for different application types, among which the control signaling are granted the highest priority. Control plane messages are transmitted properly between the BSs and the UEs. Since licensed and unlicensed bands are integrated on the same small cell BS, the network side has more global information, including the traffic load of each LTE-U BS, the LTE-U network topology, interfering Wi-Fi locations and so on, thus being able to facilitate the opportunistic unlicensed access. Then, LTE performs better than Wi-Fi in terms of user authentication and authorization techniques, providing subscribers with more secure transmission [8].

Seamless Mobility and Coverage: With LTE-U, the same LTE access method is used both for licensed and unlicensed spectrum, so UEs are operated within a unified network architecture. In this way, considerable overhead in the unlicensed spectrum can be saved, since control plane signaling can be transmitted over the licensed bands. More, this unification means synchronization on both spectrum types, through which interference can be handled better. Then, the PCC (*Primary Component Carrier*) in the licensed spectrum can always provide ubiquitous coverage for one UE. Last, LTE also offers a better and more robust air link structure designed specifically for mobility. Therefore, LTE-U has considerable advantages in preventing the UE from perceiving the impact of mobility [8].

Harmonious Coexistence with other Systems: The introduction of LTE-U is regulated to take considerable care to protect the performance of incumbent systems, especially Wi-Fi systems. By carefully protecting the Wi-Fi performance via LBT, LTE-U is able to achieve harmonious coexistence when sharing the same channels with Wi-Fi. The LBT feature will not allow LTE-U transmissions to occupy the channel all the time, but to share the resources with Wi-Fi in a fair and friendly manner [8].

Besides the many benefits brought by the LTE utilization of unlicensed spectrum, there are also many challenges which have to be faced in order to make possible the realization of such systems and in order to take advantage of these benefits. Some of the main challenging aspects to deal with are the dynamic channel selection, the co-channel coexistence with Wi-Fi systems, the intra-operator traffic offloading and the inter-operator spectrum sharing. Short overviews of these aspects are presented, except for the channel selection that will be discussed more in detail in the next paragraph, since it is main topic of this thesis project.

Coexistence is the key technical challenge to resolve for the deployment of LTE-U. There exist several mechanisms identified (e.g. channel selection, channel access, throughput characterization, etc…) to facilitate coexistence between different systems in the unlicensed 5GHz. In general these mechanisms exploit the frequency and the time domains, as illustrated in [Figure 2.3] [9].

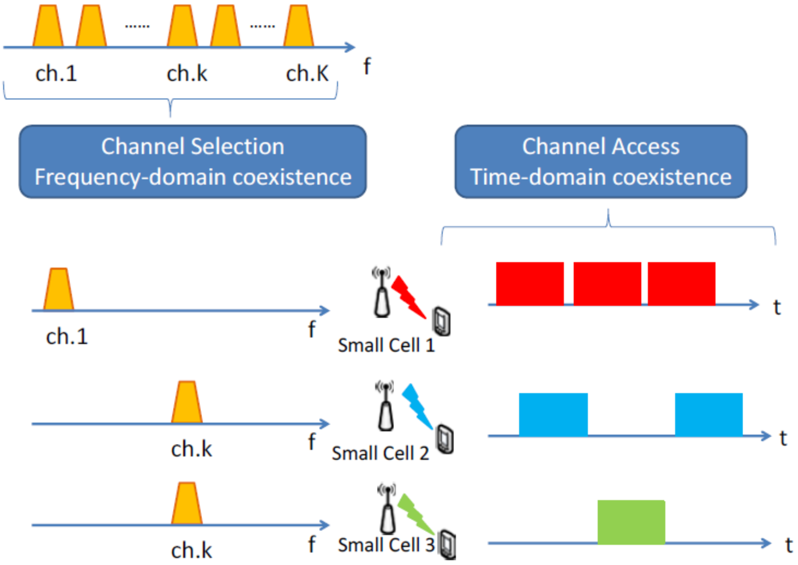


Figure 2.3: Frequency and time-domain coexistence mechanisms [9]

Channel Access: It is the mechanism used to decide actual transmissions on the selected channel. Channel access can be used as a time-domain coexistence mechanism to allow that multiple LTE-U small cells and Wi-Fi access points share the same operating channel by carrying out their transmissions in different time instants. In some markets, like Europe and Japan, it requires the support of a LBT (*Listen Before Talk*) scheme that operates at milliseconds scale, while in others, like US, Korea, India and China, there are no such LBT requirements, but only limitations in the maximum transmit power and out-of-band emissions are specified. In this second case, techniques that enable coexistence with Wi-Fi can be implemented without changing the LTE air interface protocol; as example, CSAT (*Carrier-Sensing Adaptive Transmission*) periodically activates and de-activates the transmission using LTE MAC control elements to adjust the duty cycle as a function of the measured activity in a channel. With LBT, on the other hand, a small cell using a LTE-U carrier will only transmit if it senses the channel as free during the CCA (*Clear Channel Assessment*) time, whose duration should be at least 18µs. Then, transmission will be done during a maximum time of 10ms followed by an idle period θ_{idle} of at least 5% of the channel occupancy time, after which the CCA will be executed again. Note that, if LBT is required, changes in the LTE air interface are needed [9].

Co-Channel Coexistence with Wi-Fi systems: It is possible that sometimes no clean channel is available so LTE-U and Wi-Fi have to share the same channel. In this case, some restrictions must be imposed on LTE resource allocation in order to protect the Wi-Fi performance. For these purpose, several techniques with or without LBT features can be used. Simple LBT, as it was mentioned above, requires radio transmitters first to sense the medium and then transmit only if the medium is sensed to be idle. In another LBT-based mechanism, sensing and backoff functions similar to Wi-Fi DCF (*Distributed Coordination Function*) are introduced on top of the original LTE MAC scheduling and, moreover, RTS/CTS (*Request-To-Send/Clear-To-Send*) functions are involved to reserve the channel. On the other hand, for techniques without LBT requirements, a mechanism which adopt CSAT (*Carrier-Sensing Adaptive Transmission*) for LTE-U MAC scheduling was proposed, where it was defined a TDM cycle during which a fraction of time is used for LTE small cell transmission and the rest is left for transmissions of other technologies. More, another mechanism is called LTE muting, where LTE is silent in *n* of every 5 subframes to abdicate the channel to Wi-Fi users. In addition to the time sharing methods, LTE transmit power control can be an alternative to assist LTE/Wi-Fi coexistence in the uplink. The conventional one is based on the UE path loss, but an improved one was proposed in order to involve the interference measurements in power control decisions [8].

Intra-Operator Traffic Offloading: The traffic offloading in LTE-U context should deliberately incorporate the impact of Wi-Fi activities. Mutual interference modeling is an unavoidable issue in designing the optimal traffic offloading strategy to unlicensed spectrum. Besides, the trade-offs between the licensed co-channel interference mitigation and the QoS provisioning of LTE-U users should also be considered. Some research have been made. A framework was proposed, where femtocells share the same unlicensed channel with Wi-Fi systems and access the unlicensed bands based on duty cycling. More, in an extended work, an optimal traffic balancing strategy was proposed to maximize the total user satisfaction of femto and Wi-Fi users while keeping the perceived interference of macro users below the desired level. For the intra-operator traffic offloading, future efforts could be focused on investigating the mutual interference modeling when different coexisting mechanisms are adopted, and considering the inter-femtocell interference in dense deployment scenarios [8].

Inter-Operator Spectrum Sharing: When LTE-U small cells of multiple operators exist in the same region, inter-operator coordination and negotiation is required. If the available spectrum is abundant, different operators can select different clean channels to access. On the other hand, in dense deployments where multiple with operators that have to use the same channels, two possible approaches can be exploited to mitigate the inter-operator interference. The first one is time sharing, where different operators can access the channel in different time durations. The second one may be FFR (*Fractional Frequency Reuse*), where small cell users of different operators are allowed to transmit on the channel simultaneously if they are close to their respective cell centers. FFR approach is more spectrum-efficient and flexible in resource allocation, but at the cost of higher computational complexity and control overhead [8].

To conclude, analytical modeling and theoretical studies are essential to find an effective mutual interference model for LTE and Wi-Fi coexistence. The PHY/MAC differences between the two systems need to be considered in modelling the mutual interference. At last, the inter-cell interference between macrocells and between LTE-U small cells should be incorporated in dense deployment scenario.

2.5. Channel Selection

As the unlicensed spectrum is bandwidth-rich, the large number of available unlicensed channels offers high probability for a LTE-U small cell to find an unused channel with very low-level interference. The interference can be avoided not only among small cells but also between the LTE and Wi-Fi devices. As discussed in [14], the interference measurements are performed at both equipment initialization and periodically during operation. There are two kind of interference detection. In one of them, the interference is measured by energy detection. In the other one, advanced RAT-specific measurements are performed in order to improve the detection sensitivity.

Channel selection is the mechanism used to decide the operating channel where a small cell sets up its LTE-U carrier. Therefore, it can be used as a frequency-domain coexistence mechanism to safeguard that LTE is a “good neighbor” in unlicensed bands without requiring modifications in LTE PHY/MA standards, e.g. by enabling SCs to choose the cleanest channel based on received power measurements. If interference is found in the operating channel and there is another cleaner channel available, the transmission can be switched to the new channel. This ensures that the interference is avoided between the small cell and its neighboring Wi-Fi devices and/or other LTE-U small cells. It is worth noting that, for certain bands such as 5.25-5.35GHz and 5.47-5.725GHz, there are further specific requirements imposed on channel selection mechanisms to allow the coexistence of unlicensed devices with radar systems (as discussed above) [9].

The design of a proper channel selection functionality can greatly improve the overall efficiency of the LTE-U operation. It can be derived from (1) that the decision-making applied to perform the channel selection for the i-th small cell will impact on the achieved throughput performance mainly through the terms $M(i,k)$ and $SINR_n(k)$. Thus, if the selected k-th channel is not used by other cells, higher throughput will follow. Similarly, if the selected k-th channel is affected by low interference levels, high $SINR_n(k)$ will be observed and higher throughputs will follow. Therefore, the channel selection for a given small cell should be able to dynamically identify and capture the relevant context information about the current status of utilization of the candidate channels so that the best one can be chosen. Consequently, smart solutions able to identify the best channels under each specific condition are of high interest for the materialization of all the potentials that LTE-U offers [9].

Different approaches for channel selection can be envisaged:

- Fully distributed case, where each small cell makes decisions on its own;
- Intra-operator coordination, where decisions for a given small cell take into consideration knowledge about other small cells’ configurations belonging to the same operator;
- Inter-operator coordination, where also information about small cells from other operators in the area is available;
- Coordination also with managed Wi-Fi systems in the area.

Clearly, higher coordination levels will ease the channel selection decision-making, however, they involve more demanding network coordination architectures, information exchange protocols and procedures, etc. Besides, from a decision-making logic point of view, exploiting learning from past experiences seems a pertinent principle in the LTE-U context. Each small cell may autonomously learn what channels are usually not being used by its neighbors and then tend to select such free channels. Thanks to this learning capability, general scanning procedures over the 5GHz band conducted systematically to look for the cleanest channel can be avoided or reduced to a minimum. Besides, learning from the own experience in using a channel can help in overcoming situations like the hidden node problem. Furthermore, the adaptability of the learning-based decision-making process will provide robustness to the solution and the capability to react to changes in the scenario (e.g. the deployment of a new small cell in the area) [9].

Two learning-based decision-making channel selection strategies have been studied. The first one is a distributed Q-learning mechanism that exploits prior experience and enables coexistence with other systems in a smart and efficient way. In the other one, based on the game theory, the problem is modeled using a non-cooperative repeated game and the ITEL-BA (*Iterative Trial and Error Learning – Best Action*) learning algorithm is used to drive convergence towards a Nash Equilibrium.

In the following, a short overview of the Q-learning mechanism is presented, while the game theory and the repeated game method are described in detail in the next chapters, as main topic of this project thesis.

2.5.1. Q-learning

Q-learning belongs to the category of Temporal Difference Reinforcement Learning (RL) techniques that consist in learning how to map situations to actions so as to maximize a scalar reward. The learning is achieved through the interaction with the environment, so that the learner discovers which actions yield the most reward by trying them. The idea is that each small cell progressively learns and selects the channels that provide the best performance based on the previous experience.

In the approach proposed in [9], each small cell i stores a value function $Q(i,k)$ that measures the expected reward that can be achieved by using each channel k according to the past experience. Whenever a channel k has been used by the small cell i, the value function $Q(i,k)$ is updated. Based on the $Q(i,k)$ value functions, the channel selection decision-making for the small cell i follows the softmax policy in which channel k is chosen with a certain probability.

In the papers [9] and [15], a performance analysis of the Q-learning method is presented by means the results obtained in indoor simulations both in stationary and non-stationary conditions.

3. Game Theory-based strategy

Game theory is the formal study of decision-making where several players must make choices that potentially affect the interests of the other players. It is the formal study of conflict and cooperation. Game theoretic concepts apply whenever the actions of several agents are interdependent. These agents may be individuals, groups, firms, or any combination of these. The concepts of game theory provide a language to formulate, structure, analyze and understand strategic scenarios [16].

The internal consistency and mathematical foundations of game theory make it a prime tool for modeling and designing decision-making processes in interactive environments. The automation of strategic choices enhances the need for these choices to be made efficiently, and to be robust against abuse. Game theory addresses these requirements. As a mathematical tool for the decision-maker the strength of game theory is the methodology it provides for structuring and analyzing problems of strategic choice. The process of formally modeling a situation as a game requires the decision-maker to enumerate explicitly the players and their strategic options, and to consider their preferences and reactions [16].

The object of study in game theory is the *game*, which is a formal model of an interactive situation. It typically involves several *players*; a game with only one player is usually called a *decision problem*. A *Nash Equilibrium*, also called strategic equilibrium, is a list of strategies, one for each player, which has the priority that no player can unilaterally change his strategy and get a better payoff. Games can be described formally at various levels of detail. A *cooperative* game is a high-level description, specifying only what payoffs each potential group, or coalition, can obtain by the cooperation of its members. What is not explicit is the process by which the coalition forms. *Cooperative game theory* investigates such coalitional games with respect to the relative amounts of power held by various players, or how a successful coalition should divide its proceeds. This is most applied in political science or international relations. In contrast, non-cooperative game theory is concerned with the analysis of strategic choices. The paradigm of *non-cooperative game theory* is that the details of the ordering and timing of players' choices are crucial to determining the outcome of a game. The term "non-cooperative" means this branch of game theory explicitly models the process of players making choices out of their own interest [16].

3.1. Literature

Wireless communications is a suitable scenario for the application of game theory. The importance of RRM (*Radio Resource Management*) has in fact emerged as a key issue in network design. Co-channel interference, due to the shared nature of the wireless medium, represents a major impairment to the performance of wireless communications. The resource competition can be investigated by modeling the network as an economic system, in which any action taken by a user affects the performance of others as well: just the main field of application of game theory [17]. Two examples of game theory-based applications will be presented in the following.

Network selection is a well-studied problem in which users (UEs) must decide to connect to one of several spatially co-located networks to maximize their data rate. The optimal network selection strategy for each user is a function of the network characteristics and behaviors of other UEs because UEs must share resources if connected to the same network. This problem lends itself well to a game theoretic analysis; in [18] it is analyzed the network selection process for co-located LTE-U and Wi-Fi networks as an infinitely repeated game between the UEs. Aim of that study was to make the following contributions:

- Find an optimal downlink network selection strategy for UE network selection for co-located Wi-Fi and LTE-U, assuming no information about the strategies of other UEs or when there are no other UEs in the network;
- Find a mixed strategy NE for a base case network with 1 LTE-U BS, 1 Wi-Fi AP and 2 UEs equidistant to the two BSs, parametrized by the LTE-U coexistence mechanism and Wi-Fi performance characteristics;
- For each case, evaluate the performance of different strategies against other UEs through simulation.

This project is innovative for several reason. First, no literature looks at the case in which the networks themselves are also co-located in space and frequency (network coexistence mechanisms). Second, this approach integrates strategies in which the network selections do not “converge”, but rather may keep changing indefinitely. Third, UEs cannot force other nodes to follow the strategy that achieves the NE because there may be constraints that prevent certain UEs from carrying out the optimal strategy [18].

Another study, reported in [19], was made about small cell deployment in licensed and unlicensed bands by means of a local interaction game framework. Each small cell has to decide which channels should be selected in licensed and unlicensed band. The local interaction game framework is introduced to solve the optimization problem. The game is proved to be an exact potential game and the optimal action profile for small cells constitutes a pure strategy NE. It is proposed a SAP (*Spatial Adaptive Play*)-based L/U channel selection algorithm to achieve the optimal action profile. The study was focused on a network of small cells which can access both licensed and unlicensed spectrum. And operating bandwidth constraint is considered for small cell eNB (SeNB). Each SeNB reserves a licensed channel set for its exclusive use and meanwhile it can also access the unlicensed spectrum. Though licensed spectrum can provide the QoS guarantee, SeNB has to pay for it. Oppositely, unlicensed spectrum is free to use but it is shared among all other SeNBs. The goal of the work is to maximize the network utility. Then resources allocation method for SeNB in licensed and unlicensed band becomes essential to the optimization problem. To solve this problem, a local interaction game framework is introduced. The optimal action profile for SeNBs is proved to be a pure strategy NE and can be acquired by the spatial adaptive play (SAP) based L/U channel selection algorithm [19].

On the other hand, the purpose of this thesis project is different from those of the mentioned studies, whose aims were the selection of the best network to maximize the data rate and the cell deployment to decide whether to use a channel in licensed or unlicensed band. This project focuses on a game theory-based channel selection strategy for LTE-U, where the aim is to evaluate the performance, in terms of throughput and convergence time, of this method utilized to find the optimal channel configuration for the SCs present in the scenario. The method is explained in the following.

3.2. Channel Selection as a Repeated Game

Taking into account the aforementioned fully distributed approach, the channel selection problem for LTE-U can be modeled based on game theory concepts, as studied in [20]. By characterizing the channel selection problem as a game, players' behaviors and actions can be analyzed in a formalized structure that facilitates the application of the existing theoretical achievements in game theory. In particular, the formulation of the channel selection problem in LTE-U considers a non-cooperative repeated game. Regarding the learning algorithm, the ITEL-BA algorithm is proposed, which was proved to converge to a pure Nash Equilibrium. ITEL-BA typically converges to a NE within a small number of iterations [20].

Here the system model of [20] is exposed. Let assume a set of *S* small cells (SCs) denoted as *Σ={1,…,S}* making use of the 5GHz unlicensed band as a supplemental downlink. The total band is considered to be organized in *K* channels of bandwidth *B*. Let denote by *A={1,…,K}* the set of available channels. The channel selection problem consists of the decision making process individually undertaken by each SC to decide the operating channel where it will set up an LTE-U carrier. The global process can be modeled as a repeated game, where each SC is a player in the game. Time is assumed to be organized in generic units denoted as "time steps" that specify the instant when the game is played. At the beginning of every time step, each player performs an action that consists in the selection of a channel to set-up an LTE-U carrier. Action $a_i(t) \epsilon A$ denotes the channel selected by SC *i* in time step *t*.

At the end of a time step, each SC obtains a reward or payoff as a result of the selections made by all the SCs. The reward of SC *i* is the normalized average throughput achieved in the selected channel by the SC:

$$r_i\left(a_i(t), \mathbf{a_{-i}}(t)\right) = \overline{R_i\left(a_i(t), \mathbf{a_{-i}}(t)\right)}/R_{max} \qquad (3.1)$$

Where $\overline{R_i\left(a_i(t), \mathbf{a_{-i}}(t)\right)}$ is the average throughput obtained by the *i*-th SC when it is operating in channel $a_i(t)$ and the rest of SCs are operating in the channels given by $\mathbf{a_{-i}}(t)$=[$a_i(t)$,…, $a_{i-1}(t)$, $a_{i+1}(t)$,…,$a_S(t)$], and *Rmax* is a normalization factor.

Each player selects an action with the objective of optimizing its own reward. In order to achieve this, each player will apply a learning technique to the action selection decision-making during the game. Each SC learns its own action selection strategy without having explicit knowledge on the strategy followed by the other SCs. Then, the learning is achieved through the interaction with the environment, so that the learner discovers which actions yield to highest reward by trying them. Furthermore, the learning process may lead the game to a state where none of the SCs can improve its throughput by unilaterally changing its selection. This is a Nash Equilibrium state [20].

3.2.1. Learning Strategy

The algorithm proposed in [20] for channel selection in LTE-U is the ITEL-BA. This is an extension of the ITEL, a simple but effective learning algorithm where players can only observe the results of their own actions. This approach significantly reduces the convergence time to an NE, under the assumption that players are able to gather additional information. It is assumed that players are able to measure interference in all the channels.

The learning is an iterative process where each iteration performed in a time step can be broadly divided into three phases:

- Selection of a new action according to a certain strategy;
- Observation of the environment by measuring the obtained reward resulting from the selected action, which gives the players an idea of how well they played;
- Improvement of the action selection strategy based on the current observation.

In the case of ITEL-BA, each player retains a benchmark action and the corresponding benchmark reward as a reference to evolve the action selection strategy.

Let denote as $a_{Bi}(t)$ and $r_{Bi}(t)$, respectively, the benchmark action and the benchmark reward of player *i* at the beginning of time step *t*. At this time, the operation of the algorithm considers that the player *i* selects an action $a_i(t)$, which can be the benchmark action or a different action within the set *A*. The action is chosen depending on the so-called mood of the player, which captures the degree of satisfaction of the player with the current benchmark action and benchmark reward. The *mood* of player *i* at the beginning of time step *t* is denoted as $m_i(t)$ and it can be *content*, *discontent*, *hopeful* or *watchful*.

As a result of the action selected by the *i*-th player, $a_i(t)$, and the action selected by the other players, $\mathbf{a_{-i}}(t)$, player *i* will measure the obtained reward $r_i\left(a_i(t), \mathbf{a_{-i}}(t)\right)$ at the end of time step *t*. The comparison between the obtained reward and the benchmark reward will in turn be used to update the mood, the benchmark action and the benchmark reward for the next time step, respectively $m_i(t+1)$, $a_{Bi}(t+1)$ and $r_{Bi}(t+1)$.

The general idea of the action selection strategy is that a *content* player will be selecting the benchmark action most of the time, and will occasionally experiment with new actions according to a probability $\varepsilon \ll 1$ called exploration rate. In the latter case, it will change the benchmark action/reward if the new action is better than the old one. Instead, a *discontent* player will try out new actions frequently, eventually becoming content with a probability that depends on how well the selected action is performing in terms of reward.

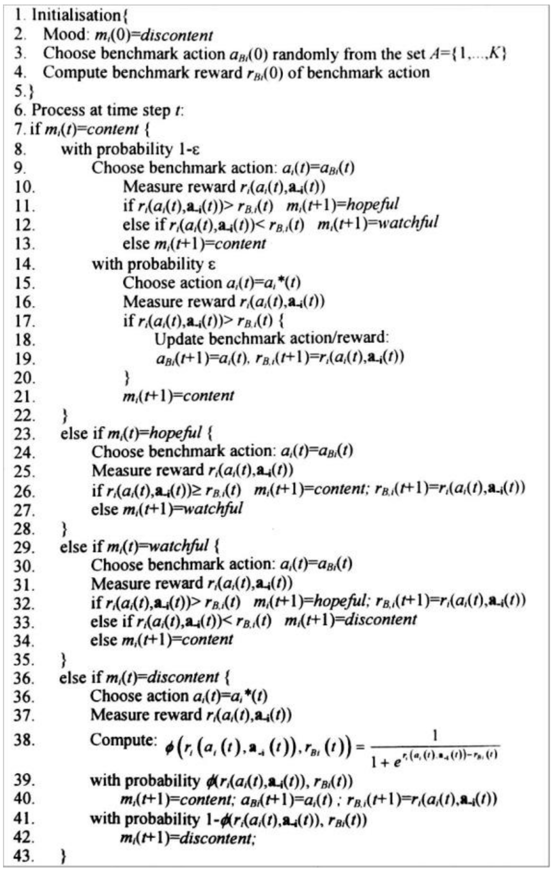
The *hopeful* and *watchful* moods correspond to transitional situations, triggered by changes in the behavior of other players. Specifically, if a *content* player selects its benchmark action and receives a different reward than the benchmark reward (e.g. because of some changings of other players' actions), then the player becomes *hopeful* if the reward increased or *watchful* if it decreased. If the player is *hopeful* and the reward of the benchmark action stays up for one more time step, the player will become *content* again and will update the benchmark reward to the new value. In turn, if the player is *watchful* and the reward stays down for one more time step, the player will become *discontent*.

Whenever a *discontent* player selects an action or when a *content* player experiments with new actions different from the benchmark, the action selections criterion used by the ITEL-BA algorithm is defined as:

$$a_i^*(t) = \arg\max_{a_i' \in A} \hat{r}_i\left(a_i', \mathbf{a}_{-\mathbf{i}}(t-1)\right) \qquad (3.2)$$

Where $\hat{r}_i\left(a_i', \mathbf{a}_{-\mathbf{i}}(t-1)\right)$ is an estimation of the hypothetical reward that the *i*-th SC would obtain by transmitting in channel a_i' during time step *t* assuming that the other SCs keep the same channels $\mathbf{a}_{-\mathbf{i}}(t-1)$ selected in the previous time step *t-1*. To compute this estimation the *i*-th SC needs to measure the existing interference in all the available channels *A* during time step *t-1*. These interference measurements will capture the usage of the channels done by the other SCs according to their selected actions $\mathbf{a}_{-\mathbf{i}}(t-1)$. Whenever there are multiple actions with the same maximum value of $\hat{r}_i\left(a_i', \mathbf{a}_{-\mathbf{i}}(t-1)\right)$, the selected action $a_i^*(t)$ will be chosen randomly among these ones. It must be noted that the *i*-th SC needs to compute $a_i^*(t)$ only when it wants to change its action, meaning that the SC will not measure the existing interference in all the available channels A all the time [20].

[Figure 3.1] presents the action selection process and update rules of the mood and benchmark action/reward of the ITEL-BA algorithm.



```
Initialisation{
  Mood: $m_i(0)=discontent$
  Choose benchmark action $a_{Bi}(0)$ randomly from the set $A=\{1,\dots,K\}$
  Compute benchmark reward $r_{Bi}(0)$ of benchmark action
}
Process at time step $t$:
if $m_i(t)=content$ {
    with probability 1-ε
        Choose benchmark action: $a_i(t)=a_{Bi}(t)$
            Measure reward $r_i(a_i(t),\mathbf{a}_{-i}(t))$
            if $r_i(a_i(t),\mathbf{a}_{-i}(t)) > r_{B,i}(t)$   $m_i(t+1)=hopeful$
            else if $r_i(a_i(t),\mathbf{a}_{-i}(t)) < r_{B,i}(t)$   $m_i(t+1)=watchful$
            else $m_i(t+1)=content$
        with probability ε
            Choose action $a_i(t)=a_i^*(t)$
            Measure reward $r_i(a_i(t),\mathbf{a}_{-i}(t))$
            if $r_i(a_i(t),\mathbf{a}_{-i}(t)) > r_{B,i}(t)$ {
                Update benchmark action/reward:
                $a_{Bi}(t+1)=a_i(t)$, $r_{B,i}(t+1)=r_i(a_i(t),\mathbf{a}_{-i}(t))$
            }
            $m_i(t+1)=content$
    }
    else if $m_i(t)=hopeful$ {
        Choose benchmark action: $a_i(t)=a_{Bi}(t)$
        Measure reward $r_i(a_i(t),\mathbf{a}_{-i}(t))$
        if $r_i(a_i(t),\mathbf{a}_{-i}(t)) \geq r_{B,i}(t)$   $m_i(t+1)=content$; $r_{B,i}(t+1)=r_i(a_i(t),\mathbf{a}_{-i}(t))$
        else $m_i(t+1)=watchful$
    }
    else if $m_i(t)=watchful$ {
        Choose benchmark action: $a_i(t)=a_{Bi}(t)$
        Measure reward $r_i(a_i(t),\mathbf{a}_{-i}(t))$
        if $r_i(a_i(t),\mathbf{a}_{-i}(t)) > r_{B,i}(t)$   $m_i(t+1)=hopeful$; $r_{B,i}(t+1)=r_i(a_i(t),\mathbf{a}_{-i}(t))$
        else if $r_i(a_i(t),\mathbf{a}_{-i}(t)) < r_{B,i}(t)$   $m_i(t+1)=discontent$
        else $m_i(t+1)=content$
    }
    else if $m_i(t)=discontent$ {
        Choose action $a_i(t)=a_i^*(t)$
        Measure reward $r_i(a_i(t),\mathbf{a}_{-i}(t))$
        Compute: $\phi\left(r_i\left(a_i(t),\mathbf{a}_{-i}(t)\right), r_{Bi}(t)\right) = \frac{1}{1+e^{r_i(a_i(t),\mathbf{a}_{-i}(t))-r_{Bi}(t)}}$
        with probability $\phi(r_i(a_i(t),\mathbf{a}_{-i}(t)), r_{Bi}(t))$
            $m_i(t+1)=content$; $a_{Bi}(t+1)=a_i(t)$ ; $r_{B,i}(t+1)=r_i(a_i(t),\mathbf{a}_{-i}(t))$
        with probability $1-\phi(r_i(a_i(t),\mathbf{a}_{-i}(t)), r_{Bi}(t))$
            $m_i(t+1)=discontent$;
    }
```

Figure 3.1: Pseudocode of the ITEL-BA algorithm [20]

4. Methodology and Approach

In this chapter the purpose of the study and the tools utilized to reach the results are described.

In the first part, it is explained the aim of the study, which consists in the evaluation of the performance of the system utilizing the aforementioned game theory-based strategy for the channel selection in a particular scenario. In the second part, it is described the software utilized to execute the simulations in order to obtain the results and to evaluate the impact on the performance.

4.1. Purpose

The purpose of this thesis project is the study of the behavior of the system that uses the game theory-based strategy for the channel selection in LTE-U. The impact of some specific parameters on the performance of the system is analyzed. In particular, the analyzed parameters are the exploration rate, the activity period of the small cells and the frequency of variation of the environment, respectively. For each of these studies, it was observed how the variation of these parameters affects the performance of the system, in term of convergence time and/or achieved throughput.

- With convergence time is meant the time, measured in time steps, needed to the system to reach a configuration where the SCs achieve an optimal channel allocation configuration, which is referred to as a Nash Equilibrium state.
- The throughput evaluation could be done in two different ways. The first one in steady case, which means measuring the achieved throughput after convergence has been reached. In the other case, conversely, the throughput is measured along the whole simulation, considering the periods before and after the convergence has been reached.

The exploration rate, ε, is the parameter which affects the probability, for a content player, of experimenting with new actions instead of the benchmark action. The higher the value of ε, the higher this probability. In this case, the impact of this parameter on the performance of the system in terms of throughput and convergence time is evaluated.

The activity period, T, of a SC determines the duration, in number of time steps, of a session of activity. More precisely, it affects the probability for a SC of ending the session in the next time step and, consequently, of making a new decision. Also in this case, it is studied the impact of the activity period on the throughput and the convergence time of the system.

The previous analysis were made in stationary conditions, meaning that in the scenario there were two different operators and a fixed number of SCs for each operator applying the ITEL-BA algorithm or utilizing other configurations, as it will be described in the following. There were no random external events bringing changings in the environment. The other analysis, on the other hand, was made in non-stationary conditions, observing how the game theory-based strategy behaves when there are random events which lead to changes in the environment. The impact of the non-stationarity was studied by means of the evaluation of the performance of the system in term of throughput.

4.2. Software tool

The analysis of the impact of these parameters on the performance of the system was made by means of a software, run in MATLAB, which simulate an indoor scenario where several SCs apply the aforementioned game theory-based strategy in order to find the best channel where to set up the LTE-U carrier. The simulations were made of different durations and with different configurations of the SCs, in order to evaluate different behaviors and to study different cases of interactions among the SCs, respectively. In the following, the MATLAB work environment is introduced and the used software is explained in detail, while the scenario and all the typologies of simulation are described in the next chapter, where also all the results are reported and discussed.

4.2.1. MATLAB work environment

MATLAB (*MATrix LABoratory*) is a multi-paradigm numerical computing environment and fourth-generation programming language. As proprietary programming language developed by MathWorks, MATLAB allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages, including C, C++, Java, Fortan and Python. MATLAB is the high-level language and interactive environment used by millions of engineers and scientists worldwide. It lets you explore and visualize ideas and collaborate across disciplines including signal and image processing, communications, control systems and computational finance. It can be used in projects such as modeling energy consumption to build smart power grids, developing control algorithms for hypersonic vehicles, analyzing weather data to visualize the track and intensity of hurricanes, and running millions of simulations to pinpoint optimal dosing for antibiotics [21]. Some key features are:

- High-level language for numerical computation, visualization and applications development;
- Interactive environment for interactive exploration, design and problem solving;
- Mathematical functions for linear algebra, statistics, Fourier analysis, filtering, optimization, numerical integration and solving ordinary differential equations;
- Built-in graphics for visualizing data and tools for creating custom plots;
- Development tools for improving code quality and maintainability and maximizing performance;
- Tools for building applications with custom graphical interfaces;
- Functions for integrating MATLAB based algorithms with external applications and languages [21].

4.2.2. Software source code

In this thesis project, the MATLAB environment was used in order to run the software that executes the simulations for the analysis of the performance of the system. This software was developed with the purpose of making simulations for the analysis of the Q-learning and game theory-based channel selection strategies for LTE-U. In this project, only the game theory-based strategy was analyzed. Here the structure of the software is explained and discussed.

First of all, it is possible to divide the code of the software into two parts. The first one, where there are the declaration of the variables and the initialization of the parameters, and the second part, that is the one which executes the experiments. Hence, before launching the program, the input parameters must be set up, in order to create the environment of the simulation that is going to be executed. By modifying these parameters it is possible to set up: the kind of environment (indoor or outdoor) and its dimension; the propagation model; the number of operators with the relative number of access point; the number of users; the LBT settings; the activity parameters per AP; the number of channel used and a possible fixed channel allocation for the APs; the type of evaluations requested to be executed in the simulation (evaluate optimum, Nash Equilibrium solutions, check convergence); the number of realization of the experiment to check the convergence behavior; the algorithm used by each operator; the exploration rate value; the maximum number of time steps; the maximum number of experiments. After all these parameters are set up, the program can be launched in order to execute the simulation.

Once the input parameters have been set and the program has been launched, the software starts to execute the code, first creating the scenario and then applying the game theory-based channel selection method with the learning strategy discussed in the previous chapter. The duration of the execution depends mainly on the value of three parameters: the maximum number of experiments (`Max_Experiments`), the number of realizations (`num_realizations_convergence_check`) and the maximum number of time steps (`Max_Time_Steps`). The second part of the code, in fact, is composed of three for cycles whose lengths depend on the value of these parameters, as shown in [Figure 4.1]. Changing the first one allows making multiple experiments for a given simulation; the second one gives the number of different realizations of the same experiment in order to check the convergence behavior; the third one gives the effective duration, in time steps, of each simulation.

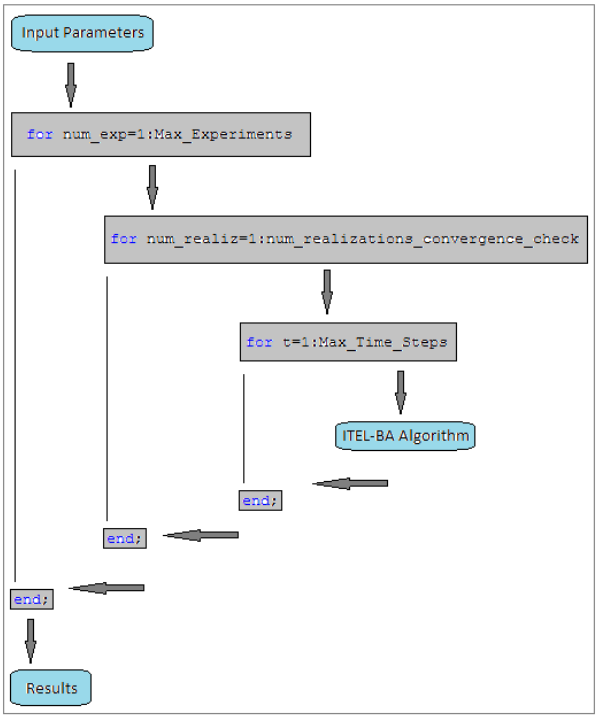


Figure 4.1: Structure of the code of the software

After reading the input parameters, the program enters the first cycle which allows to execute more experiments. Here, the scenario is created; the APs are initialized, positioned and the detection conditions among them are checked if they operate at the same frequency; the users are initialized, they are dropped randomly in the scenario and each of them is associated with the AP with lower `L_UE` (propagation loss between UE and AP). Then, the activities are initialized, setting up the session state in ON mode, and the channels are initialized. After, the simulation process starts, evaluating the optimum combinations and identifying the NE solutions. It is significant to observe that the distribution of the users in the scenario is done randomly by means of a random number generation function (`rng(seed)`) where the seed is different for each experiments, leading to different users distribution in each experiment.

After this step, the program enters the cycle of the different random realizations, where the ITEL-BA algorithm is initialized. Also in this case there is a `rng(seed)` function that allows to modify the behavior of the randomly selected actions in each realization. For the initialization of the algorithm, the benchmark actions are randomly selected and the respective rewards are computed.

At this point, the program is ready to start the simulation and it enters the last cycle whose length is given by the maximum number of time steps per simulation. In this section of the code the ITEL-BA algorithm is applied. At the beginning of each cycle, the rewards and the statistics for all the APs that are active in time step t are computed. More precisely, the noise plus interference seen by each user is computed, as well as the detection among the APs sharing the same channel. Then, there is an update of the measured rewards for the different actions based on the currently selected actions by the other APs. At this point, the convergence to a NE state is checked verifying the condition that all the APs should be in content state and their benchmark action should be the one with maximum reward. At last, the activity and the channel selections for the next time step are checked. For each AP, it is checked if the session state is ON or OFF. When the session state is ON, there are two cases:

- The session ends: first the reward is evaluated, then the benchmark action and the state of the AP are updated based on the obtained reward;
- The session does not end: it is checked if it is needed to change the selected channel (i.e. if the quality is bad).

It is significant to observe that it is possible to end a session and start a new one in the same time step, that is useful to guarantee continuous activity. When the session state is OFF, on the other hand, a new session is started, but if there are no served users, then no session can start. After that, a new cycle starts and all the steps are repeated.

Generally, the values of those three parameters are set depending on the type of analysis that is going to be done. When the aim of the study is to evaluate the convergence time or the throughput in steady case, the analysis consists of several different realization of the same experiment, such that the randomly chosen actions are selected differently in each realization. When the aim of the study is to evaluate the throughput along the whole simulation, conversely, the analysis is composed of multiple experiments for a given simulation, and in each of them the users are dropped differently. In the next chapter the typologies of simulations are explained along with the results obtained.

5. Tests and Results

The purpose of this thesis project, as mentioned above, was the evaluation of the performance of the system, mainly in terms of achieved throughput and convergence time, depending on the variation of some parameters. In this chapter the tests executed in order to evaluate the impact of the exploration rate, the activity period of the SCs and the non-stationarity condition on the performance of the system are explained. Furthermore, the results obtained are exposed, suggesting the best values of these parameters which lead to the best performance.

With respect to the analysis that was going to be made, different kinds of simulation were executed and, furthermore, different cases of SCs configuration were taken into account. In each of the next sections, the kind of simulation and the configurations involved are presented. Before discussing the results, nevertheless, the scenario considered in the simulations is described and the model for the throughput characterization is explained.

5.1. Simulation scenario

The considered scenario is based on the indoor scenario for LTE-U coexistence evaluations, as in the studies of [9], [15] and [20]. It consists of a single floor building where two operators deploy four small cells (SCs) each. SCs are equally spaced and centered along the shorter dimension of the building, as represented in [Figure 5.1].

Small cells SC1 to SC4 are owned by operator 1 (OP1), while SC5 to SC8 are owned by operator 2 (OP2). SCs are deployed at height 6m while the antenna height of each mobile terminal is 1,5m. A total of 10 terminals (users) per operator are randomly distributed inside the building. Each user is associated to the SC of its own operator that provides the highest received power. The SC-to-terminal and SC-to-SC path loss and shadowing are computed using the ITU InH model in [22].

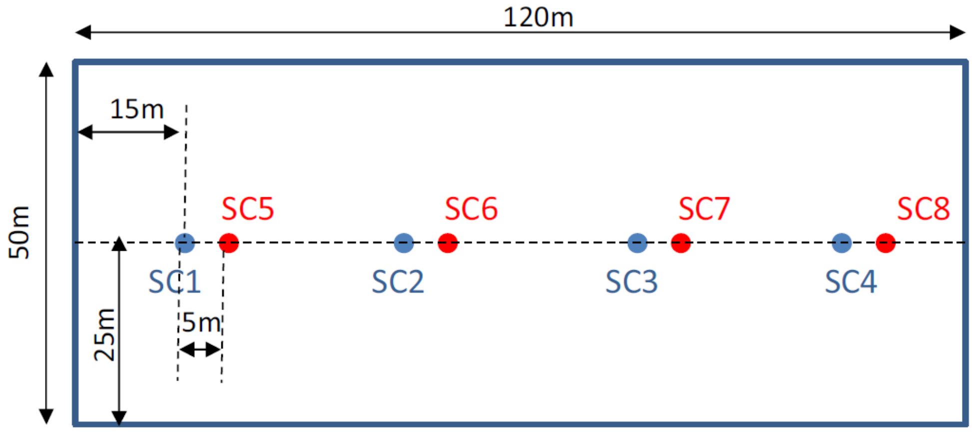


Figure 5.1: Layout of the floor building [20]

The carrier frequency is 5GHz and the band is organized in *K* channels of bandwidth B=20MHz, numbered as *k=1,…,K* channels. Each SC is configured to exploit one channel as supplemental downlink for extending the available capacity in the licensed band. The transmit power in one LTE-U carrier is 15dBm. Omnidirectional antenna patterns are assumed with a total antenna gain plus connector loss of 5dB, while the terminal noise figure is 9dB.

The computation of the average throughput $\overline{R_i\left(a_i(t), \mathbf{a_{-i}}(t)\right)}$ obtained by the *i*-th SC when it is operating in channel $a_i(t)$ and the other SCs operate in channels $a_{-i}(t)$ is done based on the model described in [9]. The model captures the use of a LBT scheme. In turn, the normalization factor R_{max} corresponds to the maximum throughput that a SC can achieve in a LTE-U channel. It is defined as $R_{max}=B \cdot S_{max} \cdot (1-\theta_{idle})$ where S_{max} is the maximum spectrum efficiency in b/s/Hz that the technology can achieve (assumed here to be $S_{max}=4{,}4 b/s/Hz$ [23]) and θ_{idle} is the fraction of time associated with the idle periods imposed by the LBT strategy (assumed here $\theta_{idle}=0{,}05$). The computation of the estimated hypothetical reward $\widehat{r_i}\left(a_i', \mathbf{a_{-i}}(t-1)\right)$ assumes that the *i*-th SC is able to measure the interference in each channel. The SINR and the opportunities of transmission given by the LBT scheme are estimated and the throughput is computed following [9].

In order to analyze the performance of the system, the SCs of OP1 always apply the ITEL-BA algorithm while for the SCs of OP2 different possibilities are considered:

- They can be inactive, meaning that there is no external influence to the SCs of OP which apply the algorithm;
- They can use a fixed channel allocation, meaning that the SCs of OP1 are influenced by fixed external constraints;
- They can apply the ITEL-BA algorithm, meaning that the SCs of OP1 and SCs of OP2 are all players of the game and so they are in competition;
- They can apply a RANDOM algorithm, simulating the presence of random events which lead the environment to be non-stationary.

In the following, the results of the tests regarding the exploration rate, the activity period of the SCs and the non-stationarity condition are exposed.

5.1.1. Throughput characterization

This section presents a model to assess the throughput that can be obtained in a LTE-U carrier. Let assume a number of small cells denoted as $i=1,\ldots,S$ making use of 5GHz unlicensed band. The total band is organized in channels of bandwidths B, numbered as $k=1,\ldots,K$. No radar signal is present. Considering that the channel selection functionality has chosen the k-th channel for carrying out LTE-U transmissions in the downlink of the i-th small cell, and that LBT is required, the total aggregated throughput served by this cell can be estimated as:

$$R(i,k) = \sum_{n=1}^{N(i)} \frac{B}{N(i)} S\left(SINR_n(i,k)\right) \frac{1-\theta_{idle}}{M(i,k)} \qquad (5.1)$$

Where $N(i)$ is the total number of users being served by the i-th small cell exploiting the supplemental downlink capacity offered by LTE-U; $SINR_n(i,k)$ is the signal to noise and interference ratio observed by the n-th user when downlink data is transmitted on the k-th channel; θ_{idle} is the fraction of time associated with the idle periods imposed by the LBT strategy; $M(i,k)$ is the number of small cells that are sharing in the time domain the k-th channel with the i-th small cell following the LBT strategy; $S(SINR_n(i,k))$ is a generic function ranging between 0 and S_{max} that provides the spectral efficiency in *b/s/Hz* as function of $SINR_n(i,k)$. Expression (5.1) assumes an equal sharing in the time domain between small cells. It could be modified to capture other scheduling strategies to share the bandwidth between users. Note also that (5.1) corresponds to the throughput achievable in one channel. In case that a small cell aggregates multiple channels, the total throughput would be the summation of (5.1) for all the channels [9].

5.2. Exploration Rate analysis

In this analysis, it was studied the impact of the exploration rate (ε) on the performance of the system both in terms of achieved throughput, along the whole simulation, and of convergence time, measured in time steps, needed to reach a state of Nash Equilibrium. In order to study the effect of the variation of ε on these two parameters, two different kinds of simulation were done. In one case, in order to check the convergence behavior each simulation was composed of one experiment:

- 100000 different random realizations of the same experiment;
- 1000 maximum number of time steps.

On the other hand, for the study of the throughput behavior multiple experiments for each simulation were made:

- 1000 experiments;
- each one with a duration 5000 time steps.

Then, in both cases, different configurations of the SCs were taken into account, depending on the number of channels considered and on the behavior of the SCs of the OP2, since the SCs of OP1 always apply the ITEL_BA algorithm. These configurations are shown in the following table.

Configurations			
K=4, no OP2	K=4, OP2 fixed	K=4, OP2 ITEL_BA	*Convergence Time*
-	K=4, OP2 fixed	K=4, OP2 ITEL_BA	*Achieved Throughput*

Table A: Configurations of the SCs and number of channels for the evaluation of Convergence Time and Achieved Throughput

At last, the values of the exploration rate considered for this experiment vary between 0 and 1 and the purpose is to observe how the convergence time and the achieved throughput behave depending on the variation of this parameter.

The graph in [Figure 5.2] represents the trend of the convergence time depending on the exploration rate, for all the above mentioned configurations. As it can be observed, for each configuration, the value of the time needed to reach a Nash Equilibrium state decreases quickly with the increase of the exploration rate for values of ε from 0,01 to 0,1. Then, the convergence time reaches its lowest value in the range of ε between 0,15 and 0,3, depending on the configuration. As it is shown, in the case with K=4 channels and where the SCs of the OP2 use the ITEL_BA algorithm, the value of convergence time is approximately 16 time steps, while all the other configurations reach a lower value of convergence time, approximately of 5-8 time steps. After that, it starts to slowly increase again for values of ε greater than 0,3. Taking into account only the case of K=4 channels, it is possible to say that when the SCs of both the operators (OP1 and OP2) apply the ITEL_BA algorithm, the time needed to converge to a NE state is much greater than the convergence time needed in the cases when the SCs of OP2 are inactive or use a fixed channel allocation.

Hence, the utilization of the ITEL_BA algorithm by both the operators introduces a higher value of convergence time and, on the other hand, a value of the exploration rate between 0,15 and 0,3 must be used in order to achieve the lowest value of convergence time as possible.

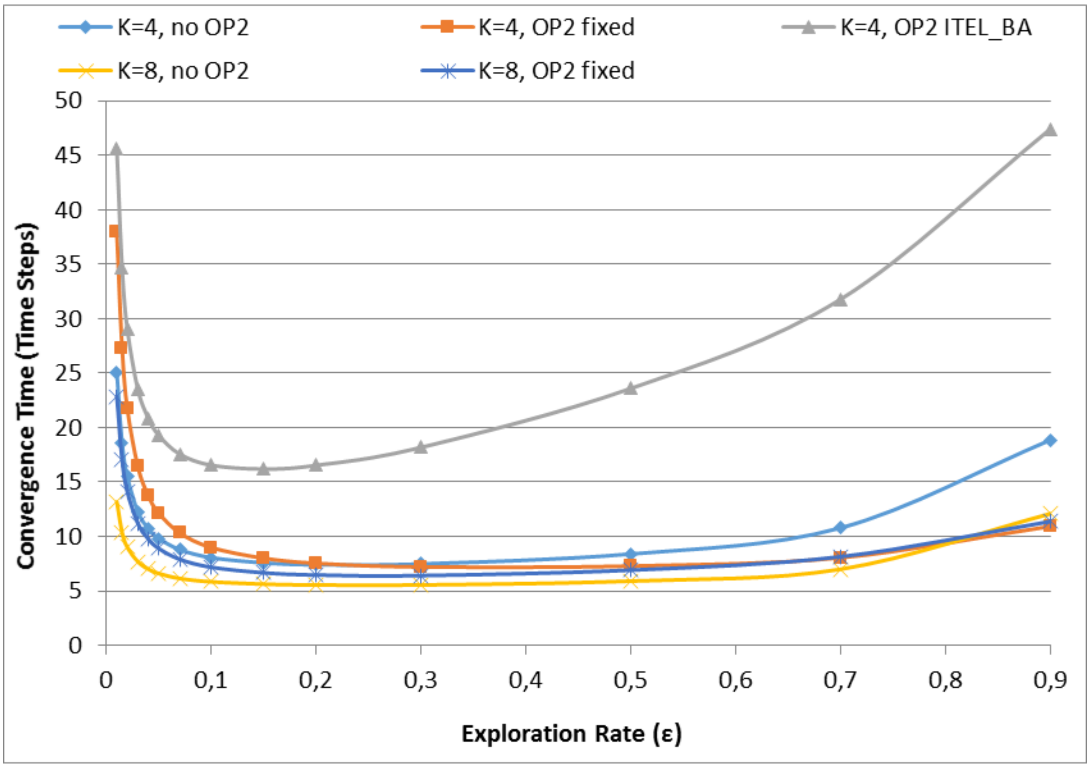


Figure 5.2: Convergence Time over Exploration Rate

The exploration rate affects the probability that a player, in this case a SC, will experiment new actions instead of selecting the benchmark action. Consequently, the higher the value of ε, the higher the probability that the player explores the environment, estimating the reward of another channel and then maybe selecting it. For this reason, the benchmark actions time evolution of the SCs may have different behaviors. Particularly, in the cases when both operators use the ITEL-BA algorithm, with 4 and 8 channels, it is possible to notice these differences due to the variation of the value of ε.

[Figure 5.3] and [Figure 5.4] show that, in order to reach a state of Nash Equilibrium, in the case of ε=0,9 the actions change more frequently than in the case of ε=0,01, especially when all the SCs apply the ITEL-BA algorithm and they are all in competition among each other.

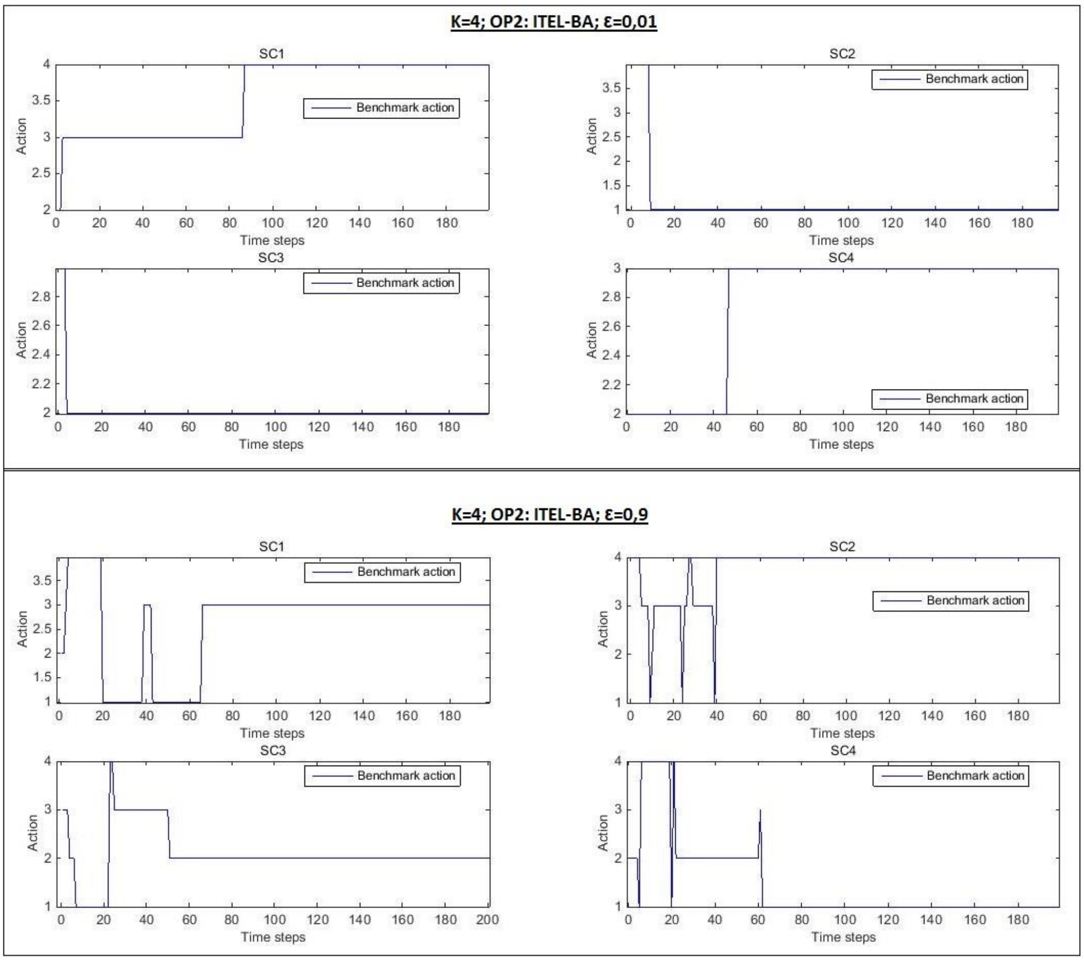


Figure 5.3: Time evolution of the benchmark actions of the SCs of OP1 with K=4

Depending on the configuration, there are different initial states and also different situations of competition among the SCs. First of all, if the SCs of the OP2 have a fixed channel assignment, only the SCs of the OP1 will have to compete each other in order to select the best channel, while in case that also OP2 uses the ITEL-BA algorithm, the competition is among all the SCs in the scenario. Moreover, if the channels are 4, at least some of them must be shared among the SCs, while in the case of 8 channels, each SC can have the channel for itself.

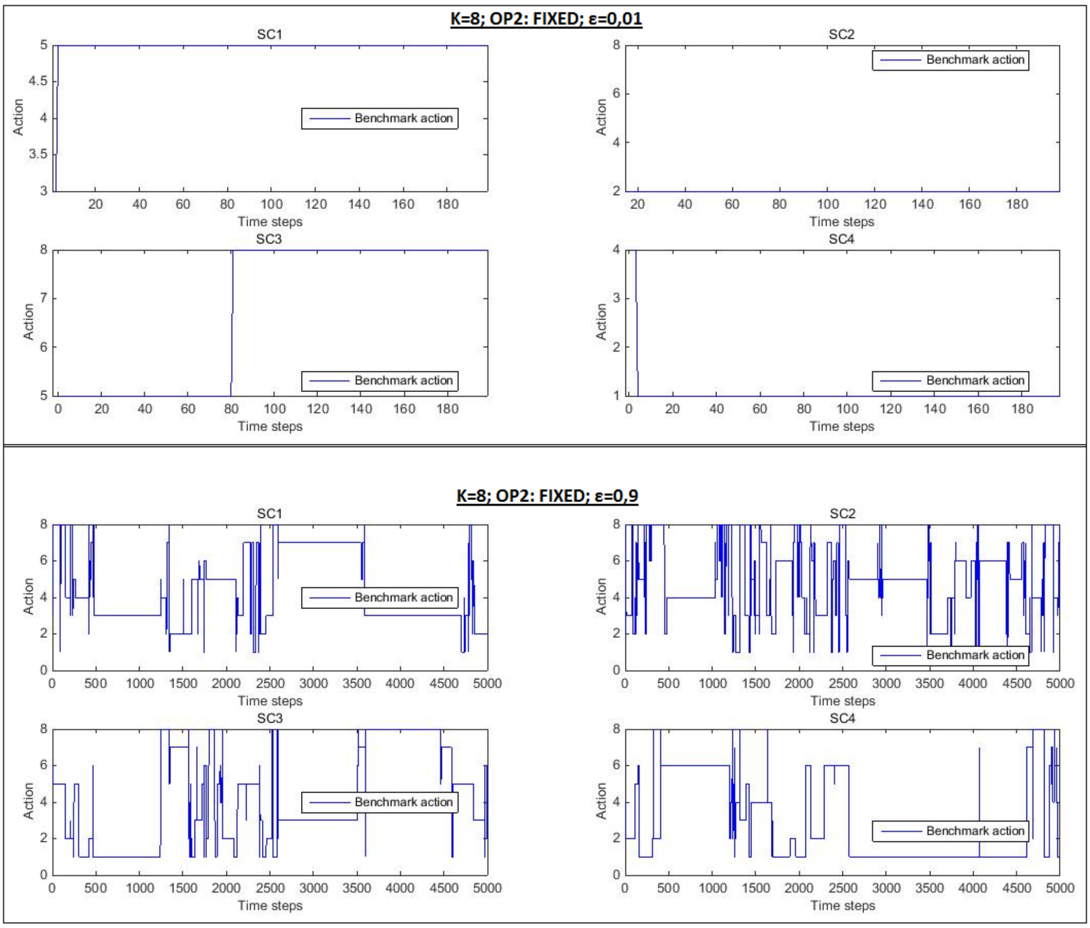


Figure 5.4: Time evolution of the benchmark actions of the SCs of OP1with K=8

In the case of K=4 channels and when the SCs of the OP2 have a fixed channel assignment, the SCs of OP1 have a clear estimation of the rewards of each channel since when they start to make the measurements at the beginning of the process; hence, there is not a tough competition and the convergence will be reached in few time steps, leading, furthermore, to high values of throughput. As it can be seen in [Figure 5.5], in fact, also for high values of ε this configuration keeps a high value of throughput, differently from the other configurations where, the increase of the value of the exploration rate leads to a decrease of the throughput.

Apart from this specific behavior for high values of ε, the graph in [Figure 5.5] shows a common shape, among the configurations, for the trend of the achieved throughput measured along the whole simulation depending on the exploration rate. Generally, the value of the throughput tends to quickly increase in the beginning until it reaches its maximum value and then it starts to decrease again, except for the above mentioned configuration (K4, OP2 fixed) which tends to keep high values of throughput.

Considering the case of K=4 channels, the maximum value of throughput with respect to the optimum case is achieved when the exploration rate is approximately 0,2 and it is about 96% when OP2 is fixed and 92% when OP2 uses ITEL-BA algorithm. On the other hand, in the case of K=8 channels, the curve increases earlier and the maximum value of throughput with respect to the optimum case is achieved when ε is between 0,01-0,02 and it is more than 99% for both the configurations. This may happen because in case of

8 channels there are more possible channel configurations which lead to a NE state, allowing the SCs to select easily a channel that returns an optimal reward; as a matter of fact the convergence time in the cases of 8 channels is lower than in those of 4 channels.

Hence, in order to achieve the maximum value of throughput the exploration rate has to be set in the range of [0,01;0,2] depending on the configuration that is being used.

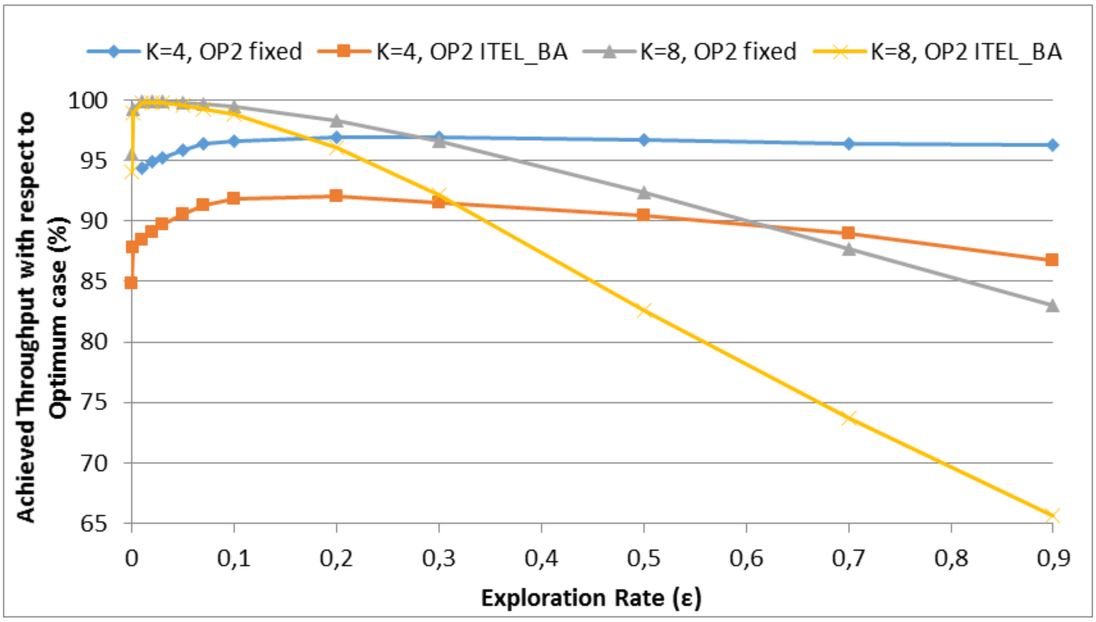


Figure 5.5: Achieved throughput with respect to the optimum case

It is also possible to observe in [Figure 5.5] that, in both cases K=4 and K=8, the curve relative to OP2 fixed is always above the curve relative to OP2 applying ITEL-BA, which means that the use of the algorithm by both the operators leads to lower values of throughput compared to those obtained when one of the operator has a fixed channel allocation. At last, comparing the graph in [Figure 5.2] with the one in [Figure 5.5], and consistently on what discussed above, it can be seen that the trends of the convergence time and of the throughput depending on the exploration rate are specular to each other; higher values of convergence time correspond to lower values of throughput and vice versa.

Summarizing the results obtained it is possible to say that:

- there is an inverse relation between convergence time and achieved throughput: higher values of one of them corresponds to lower values of the other;
- a value of ε in the range of [0,1; 0,3], depending on the configuration, leads to lower convergence time and higher achieved throughput;
- the utilization of the ITEL-BA algorithm by both the operators leads to higher convergence time and lower achieved throughput.

5.3. Activity Period analysis

In the following two sections, the studies of the impact of the activity period on the convergence time and on the achieved throughput are presented, respectively.

5.3.1. Convergence Time evaluation

In this analysis it was studied the impact of the Activity Period (T) on the time, measured in time steps, needed to reach a state of Nash Equilibrium. It is expected that this parameter affects significantly the performance of the system since it determines the time when the algorithm makes decisions. More precisely, it determines the probability with which a SC ends a session in the next time step and, consequently, makes a new channel selection. The higher the value of the activity period, the lower the probability of making a new decision in the next time step. In order to study the effect of T on the convergence time, different configurations of the SCs and different kinds of simulation were taken into account. Moreover, the case of four channels (K=4) only was studied, because more relevant and interesting than the case of eight channels, and the value of exploration rate ε=0,2 was selected, because in the previous experiments it was the value that led to a shorter convergence time. For what concerns the settings of the SCs, those of the OP1 always used the ITEL-BA algorithm, while those of the OP2 could be inactive (OFF), with a fixed channel allocation (FIXED) or using the ITEL-BA algorithm as well (ITEL_BA). The following configurations were studied and, from now on, they will be referred to as A, B, C, D:

- A) OP1: ITEL_BA, OP2: OFF, Channels K=4, Exploration rate ε = 0,2;
- B) OP1: ITEL_BA, OP2: FIXED, Channels K=4, Exploration rate ε = 0,2;
- OP1 and OP2: ITEL_BA, Channels K=4, Exploration rate ε = 0,2 with:
  - C) Activity Period OP2, T_2=1;
  - D) Activity Period OP2 equal to Activity Period OP1, T_2=T_1.

In the configuration where the SCs of both the operators used the ITEL-BA algorithm, two different cases were studied. In the first one, the SCs of OP2 used the algorithm but their activity period was fixed at T_2=1; in the second one, all the SCs of the scenario used the algorithm with the same activity period (T_1=T_2). This choice was made in order to observe how much the convergence time changes between these two configurations and, also, to observe the difference between the case of OP2 with fixed channel allocation (OP2: FIXED) and the case of OP2 using the ITEL-BA algorithm with the activity period fixed at T_2=1.

On the other hand, the simulations consisted in several random realizations of the same experiment but, depending on the kind of configuration and on different values of T, their lengths were different. In fact, the purpose of the experiment was to study the average time needed to reach a Nash Equilibrium state and, in order to do that, the SCs had to converge to a NE state in each realization. As it will be seen, some configurations require a longer convergence time compared to others and, moreover, the higher the value of activity period the longer the convergence time; for these reasons, the simulations had different number of realizations and different maximum number of time steps. More precisely, the number of maximum time steps was increased in order to reach a NE state in each realization but, consequently, the number of realization was decreased due to the computer time needed to execute the simulations, which, otherwise, would have taken very long time. In the following table the settings of all the simulations are reported.

A) OP1: ITEL_BA; OP2: OFF; Channels K=4; Exploration rate ε = 0,2		
Activity Period OP1, T=1	num_realizations: 100000	Max_Time_Steps: 1000
Activity Period OP1, T=5	num_realizations: 100000	Max_Time_Steps: 1000
Activity Period OP1, T=10	num_realizations: 100000	Max_Time_Steps: 1000
Activity Period OP1, T=20	num_realizations: 100000	Max_Time_Steps: 5000
Activity Period OP1, T=50	num_realizations: 5000	Max_Time_Steps: 10000
Activity Period OP1, T=100	num_realizations: 5000	Max_Time_Steps: 50000
B) OP1: ITEL_BA; OP2: FIXED; Channels K=4; Exploration rate ε = 0,2		
Activity Period OP1, T=1	num_realizations: 100000	Max_Time_Steps: 1000
Activity Period OP1, T=5	num_realizations: 100000	Max_Time_Steps: 1000
Activity Period OP1, T=10	num_realizations: 100000	Max_Time_Steps: 1000
Activity Period OP1, T=20	num_realizations: 100000	Max_Time_Steps: 1000
Activity Period OP1, T=50	num_realizations: 100000	Max_Time_Steps: 10000
Activity Period OP1, T=100	num_realizations: 100000	Max_Time_Steps: 20000
C) OP1: ITEL_BA; OP2: ITEL_BA; Channels K=4; Exploration rate ε = 0,2; T_2=1		
Activity Period OP1, T=1	num_realizations: 100000	Max_Time_Steps: 1000
Activity Period OP1, T=5	num_realizations: 100000	Max_Time_Steps: 1000
Activity Period OP1, T=10	num_realizations: 100000	Max_Time_Steps: 1000
Activity Period OP1, T=20	num_realizations: 100000	Max_Time_Steps: 5000
Activity Period OP1, T=50	num_realizations: 50000	Max_Time_Steps: 20000
Activity Period OP1, T=100	num_realizations: 50000	Max_Time_Steps: 30000
D) OP1: ITEL_BA; OP2: ITEL_BA; Channels K=4; Exploration rate ε = 0,2; T_2=T_1		
Activity Period OP1, T=1	num_realizations: 100000	Max_Time_Steps: 1000
Activity Period OP1, T=5	num_realizations: 100000	Max_Time_Steps: 1000
Activity Period OP1, T=10	num_realizations: 100000	Max_Time_Steps: 5000
Activity Period OP1, T=20	num_realizations: 1000	Max_Time_Steps: 60000
Activity Period OP1, T=50	num_realizations: 500	Max_Time_Steps: 500000
Activity Period OP1, T=100	num_realizations: 500	Max_Time_Steps: 1500000

Table B: Settings of the simulations for each configuration

Furthermore, as it can be seen in the table, the values of the activity period which were studied are T=[1;5;10;20;50;100] and for each of them the value of the convergence time was observed, when a convergence percentage of at least 99% was reached.

In the following, two parameters are analyzed. First, the values of convergence time were evaluated, in order to observe how they change depending on the values of activity period. In the following table are reported all the values of convergence time obtained from the simulations for all the configurations.

Activity Period (Time Steps)	K=4, no OP2	K=4, OP2 fixed	K=4, OP2 ITEL_BA $T_2=1$	K=4, OP2 ITEL_BA $T_2=T_1$
$T_1=1$	7,40415	7,54629	16,53713	16,53713
$T_1=5$	39,11818	36,23959	60,26765	134,832553
$T_1=10$	141,364258	101,207034	157,673056	1089,34701
$T_1=20$	505,204042	280,873605	426,568506	9202,9002
$T_1=50$	1855,40623	1565,06147	1712,81856	84414,9118
$T_1=100$	4000,636	3764,41666	4051,39432	216512,569

Table C: Values of the convergence time depending on the activity period

Another factor which was studied is the ratio between the convergence time and the activity period. More precisely, for each configuration and for each value of the activity period, it was evaluated the ratio between the convergence time generated by that activity period and the value of the activity period itself. This ratio reports the total number of time steps needed to converge to a NE state over the number of time steps of a period of activity, so it could be seen as the total number of channel selections which are needed to reach a NE state. Nevertheless, in the following table are reported all the values of this ratio obtained from the simulations for all the configurations.

Activity Period (Time Steps)	K=4, no OP2	K=4, OP2 fixed	K=4, OP2 ITEL_BA $T_2=1$	K=4, OP2 ITEL_BA $T_2=T_1$
$T_1=1$	7,40415	7,54629	16,53713	16,53713
$T_1=5$	7,823636	7,247918	12,05353	26,9665107
$T_1=10$	14,1364258	10,1207034	15,7673056	108,934701
$T_1=20$	25,2602021	14,0436802	21,3284253	460,14501
$T_1=50$	37,1081246	31,3012295	34,2563712	1688,29824
$T_1=100$	40,00636	37,6441666	40,5139432	2165,12569

Table D: Values of the ratio depending on the activity period

For both the analysis, the results obtained with the configurations A, B and C are discussed separately from the results of the configuration D.

Configurations A, B and C: The graphs in [Figure 5.6] represent the trends of the convergence time depending on the values of the activity period; the values of convergence time related to the first three configurations (A, B, C) are shown.

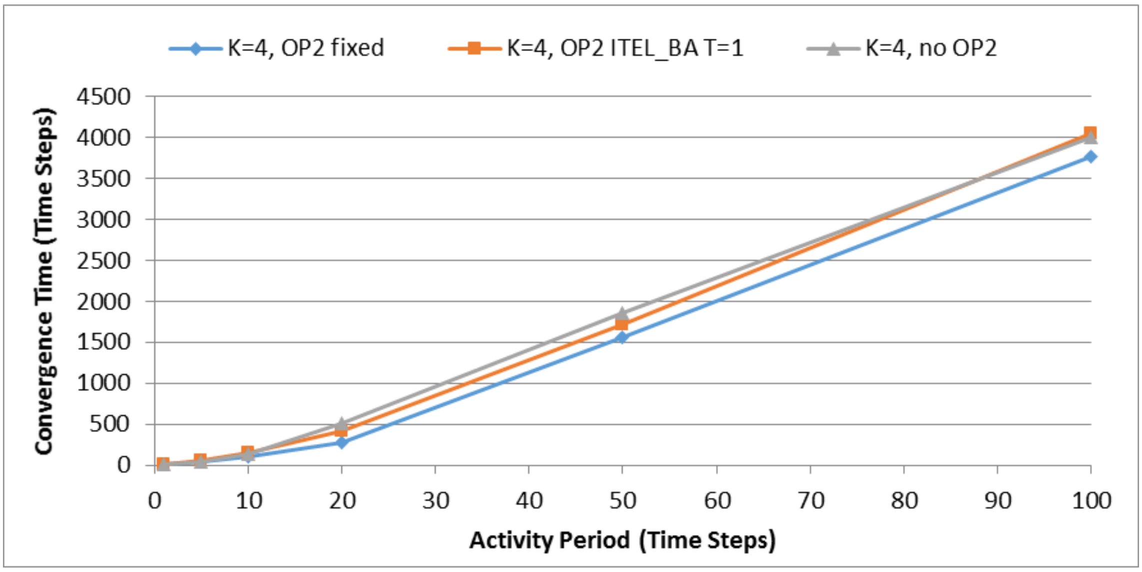


Figure 5.6: Convergence Time over Activity Period for configurations A, B and C

As it can be observed all the curves have the same behavior, they tend to increase for higher values of the activity period. This happens because with higher values of activity period, each SC has a lower probability of ending a session in the next time step and, consequently, of initiating a new one. This means that the SCs wait more time (T time steps) before executing a new action so in order to reach a NE state more time is needed. Looking at the graphs, it is possible to observe that in the cases of OP2 inactive (K=4, no OP2), OP2 fixed (K=4, OP2 fixed) and OP2 using ITEL-BA algorithm with activity period fixed at T2=1 (K=4, OP2 ITEL_BA, T=1) the values of convergence time are very similar; it is lower than 500 time steps for values of activity period equal to 1,5,10 and 20 time steps, then it increases up to values between 1500 and 2000 time steps for T=50 and, at last, it reaches values between 3500 and 4000 time steps for T=100.

In [Figure 5.7] the trends of the ratio between the convergence time and the activity period for the configurations A, B and C are represented.

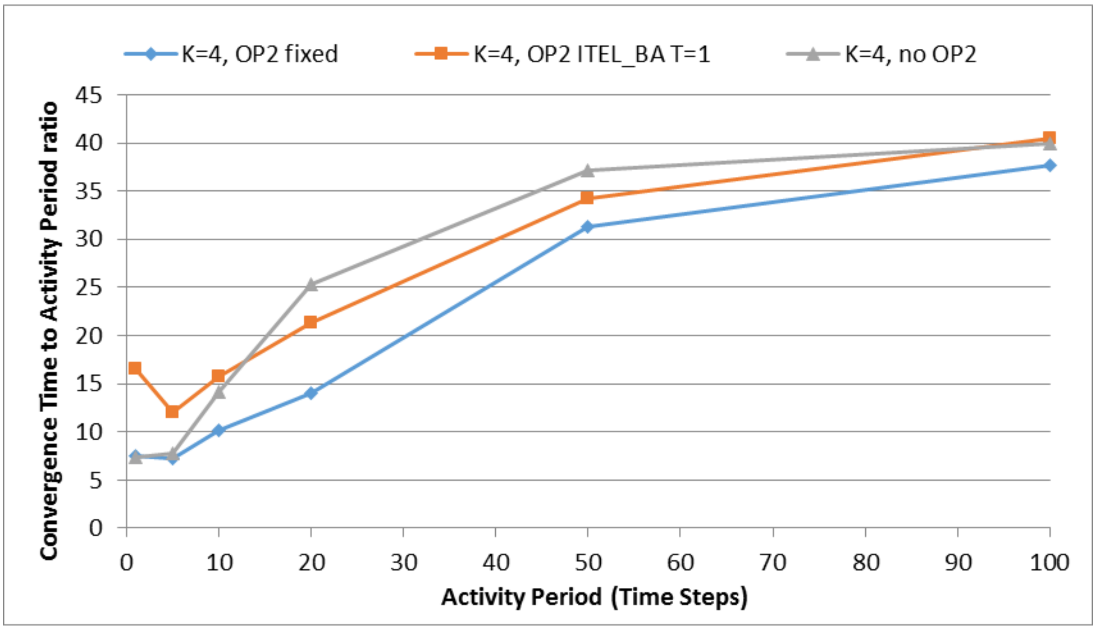


Figure 5.7: Convergence Time to Activity Period ratio for configurations A, B and C

It can be observed that, also in this case, all the curves have the same behavior and they tend to increase with higher values of the activity period. The explanation of this result is that in the case of lower values of activity period, the SCs execute their actions more often and, consequently, they may explore the environment faster; in this way, all the SCs experiment new actions more rapidly and they select the new channel. The criterion used to select the new channel is based on an estimation of the hypothetical reward that the SC would obtain by transmitting in that channel during a fixed time step and assuming that the other SCs keep the same channels that they selected in the previous time step [20]. For this reason, when the activities of the SCs are faster, these hypothetical rewards change faster and, consequently, the SCs can evaluate more channel allocation configurations in less time, leading to a shorter convergence time. On the other hand, when the activity period is higher, the SC tends to experiment new actions less often and, at the same time, it sees less changings of the other SCs; in this way, it takes more time to the SC to evaluate the several channel allocation configurations in order to find the optimal one.

Nevertheless, it is significant to observe that the curve of the configuration with the OP2 inactive (K=4, no OP2) at a certain point crosses the other two curves. This happens because when the OP2 is inactive, there are only four SCs, those of OP1, competing each other and there are less constraints to be respected. With constraint is meant the influence of a SC on the others: when a SC has to execute a channel selection, it first checks the presence of the other SCs in the channels and then it goes to select the best channel to use. Then, if there are only four SCs operating in the scenario, each time one of them has to make a selection, it has to check the other three SCs while in case of eight total SCs in the scenario, the checking must be done on other seven SCs. This means that when there are more cells, each time a SC has to select a new channel, it can obtain more information from the others, making, then, a better decision. As consequence, when also the OP2 is active, its cells create more constraints to the others, either if they use a fixed channel allocation or if they use the ITEL-BA algorithm, and the choice of the optimal channel allocation configuration can be reached easily.

However, for low values of activity period, the behavior due to the number of constraints is not present. This could be possible because of the high frequency with which the SCs make a new decision. When OP2 is inactive, also if the SCs get less information from the others, the low value of T makes possible to select a new channel very often and to reach the convergence in a short time. For higher values of activity period, conversely, the activity rate of the SC does not compensate the scarcity of information received from the other SCs and, then, the time needed to reach a NE state is higher.

Configuration D: The graph in [Figure 5.8] represents the trend of the convergence time depending on the value of the activity period in the case of the configuration D.

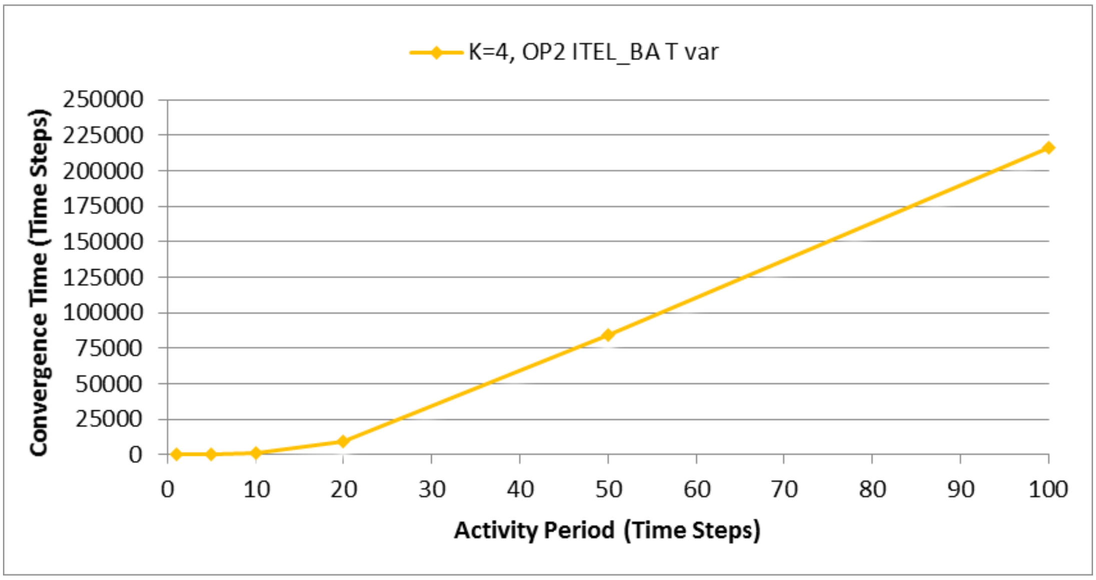


Figure 5.8: Convergence Time over Activity Period for configuration D

Also in this case, for the same reason of the previous ones, the curve tends to increase for higher values of the activity period. When the SCs of OP2 use the ITEL-BA algorithm with activity period equal to the SCs of OP1 (T_2=T_1), the convergence time has the same trend of the other configurations but its values are much higher. As it was observed in the configurations A, B and C, an increase of the activity period leads to longer convergence time; in configuration D, even more, it reaches very high values due to the fact that all the SCs of both the operators utilize higher value of the activity period and, consequently, they take more time to make a new decision. In this case, there are eight SCs in competition to each other and, differently from those in configuration C, all of them use a higher value of activity period. This means that each of them makes new decisions with lower frequency, leading to a longer time needed by each of them to find the best reward and, consequently, to a longer global time needed to find an optimal channel allocation configuration for the scenario.

The graph in [Figure 5.9] shows the trend of the ratio between convergence time and activity period in the case of configuration D.

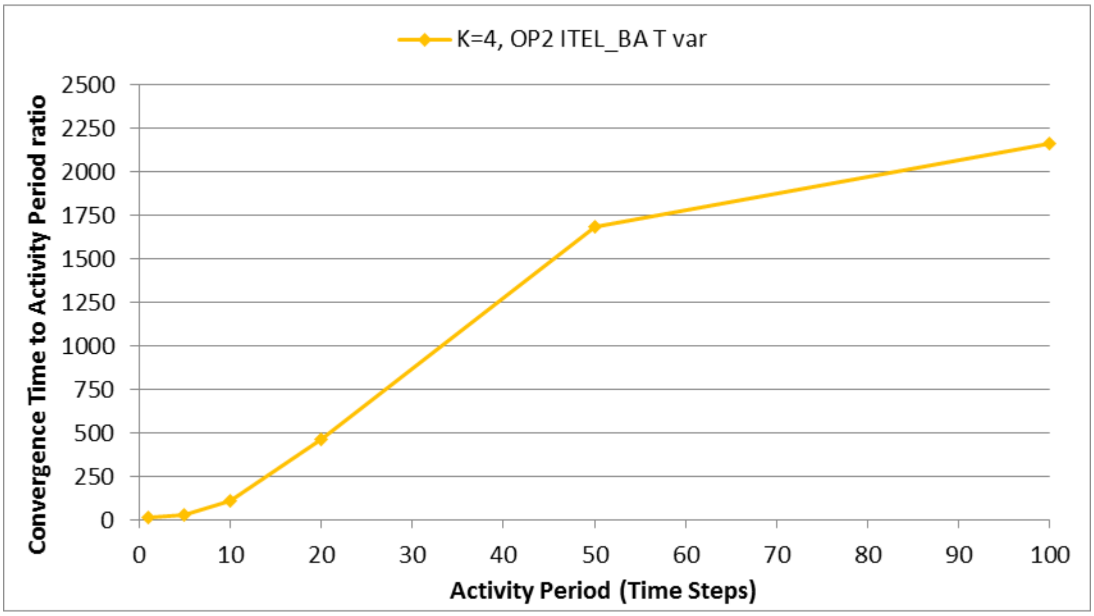


Figure 5.9: Convergence Time to Activity Period ratio for configuration D

Also in this evaluation, it can be observed that the trend of the curve is common to the other cases: it increases with the increase of the value of the activity period. Furthermore, there is a significant difference between the first three configurations (A, B and C), reported in the graph of [Figure 5.7], and the configuration D, where OP2 use the ITEL-BA algorithm with activity period equal to OP1 (T_2=T_1), reported in the graph of [Figure 5.9]. The values of the ratio obtained for this configuration are much higher compared to those obtained for the others (A, B and C). This is a consequence of what it was explained above: due to the higher values of convergence time in the case when the OP2 uses the ITEL-BA algorithm with T_2=T_1, also the values of the ratio for this configuration are higher than those related to the other configurations.

In conclusion, the increase of the value of activity period leads to an increase of the time needed to reach a Nash Equilibrium state; moreover, when the SCs of both the operators use the ITEL-BA algorithm with the same activity period, the value of the convergence time is much higher compared to those in the other configurations.

5.3.2. Achieved Throughput evaluation

In this analysis it was studied the impact of the variation of the activity period (T) on the performance of the system in terms of throughput. Two different kinds of evaluation were taken into account, one for evaluating the throughput in steady state and the other for the achieved throughput with respect to the optimum case (%) along the whole simulation. In the steady case, the experiments are long enough so that the system can always reach a NE state and then, after convergence has been reached, the throughput is measured. In the other case, the simulation includes the first short period of activity of the system, when the SCs are executing the channel selections in order to find the optimum allocation. Here the throughput is measured along the whole simulation, considering the periods before and after the convergence has been reached.

Consequently, two kinds of simulation were done, in order to obtain the results related to these two evaluations, respectively and, in both cases, different configurations were considered, depending on the behavior of the SCs of the OP2, since the SCs of OP1 always used the ITEL-BA algorithm.

At last, for all the configurations of both the studies, it was chosen to evaluate the performance only in the case of four channels (K=4), the more relevant and interesting, and it was set the value of exploration rate which, in the previous study, guaranteed a higher value of throughput (ε=0,2).

Throughput in steady case: for the study of the throughput behavior in steady state, each simulation was composed of:

- Several different random realizations of the same experiment;
- Fixed number of maximum time steps.

In this case the lengths of the simulations were different, depending on the case in examination; in fact, in order to evaluate the behavior of the throughput in steady state, the requirement was that the SCs had to converge to a NE state in each realization, which means having a convergence percentage as much as close to 100%. It is clear that this requirement was the same of the one needed for the study of the convergence time, in fact, the simulations done for these two studies were exactly the same. It is possible to see all the settings for all the configurations in [Table B] above.

The throughput in steady case is meant as the throughput after the convergence has been reached by the system. It was computed as the average reward that the SCs received after they had reached a NE state and it was evaluated as a sum of products of two parameters, as shown in the following formula:

$$\overline{Th} = \sum_{i \in NE(i)} Th\big(NE(i)\big) * Prob\big(NE(i)\big) \qquad (5.2)$$

The two parameters that were multiplied are:

- $Th\big(NE(i)\big)$: The average aggregated reward of each combination considering all the SCs except those without users or with fixed allocation;
- $Prob\big(NE(i)\big)$: Probability of converging to the *i*-th NE state, which is given by the number of time that the system has converged to that NE solution.

Hence, the average throughput is given by the sum of the products between the probability of converging to a NE state and the average reward of the SCs obtained in that state. The reason why this value is computed as an average is that the rewards received in each NE state are not always the same, as well as the probability to converge to some NE states is higher/lower than to converge to others, except for some cases.

Since in all the realizations of the experiment the SCs reach a NE state, in each configuration the average throughput tends to reach always approximately the same value, regardless the value of the activity period, as it can be seen in the following table.

Activity Period (Time Steps)	K=4, no OP2	K=4, OP2 fixed	K=4, OP2 ITEL_BA T_2=1	K=4, OP2 ITEL_BA T_2=T_1
T_1=1	1	0,64652886	0,66646052	0,66646052
T_1=5	1	0,64726701	0,68264493	0,68985915
T_1=10	1	0,64800264	0,69161183	0,69891579
T_1=20	1	0,64909214	0,69782846	0,69995293
T_1=50	1	0,64983761	0,7026983	0,70228265
T_1=100	1	0,65006073	0,70526146	0,70059093

Table E: Values of the throughput in steady state

Looking at [Figure 5.10], it is possible to observe this behavior of the curves.

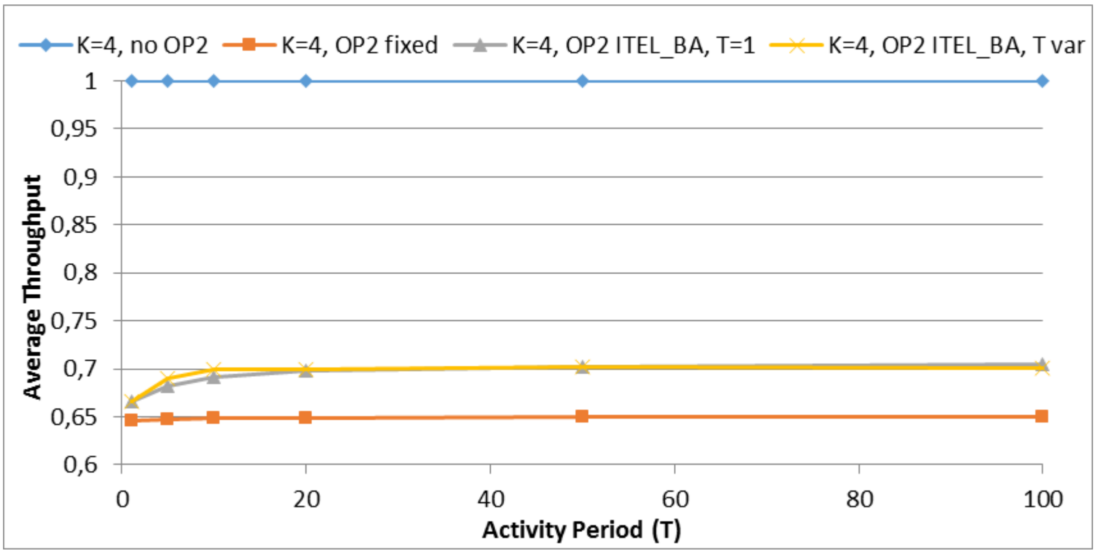


Figure 5.10: Average Throughput over Activity Period in steady case

In the case where OP2 is inactive, the average throughput is equal to 1 because in the scenario there are only four SCs (of the OP1) and four channels, so each SC does not have to share the channel with any other SC. Moreover, all the possible configurations of NE that exist in the scenario, which are only 24, are reached with equal probability (as shown in [Figure 5.11]) and in all of them the achievable normalized throughput is 1 [20].

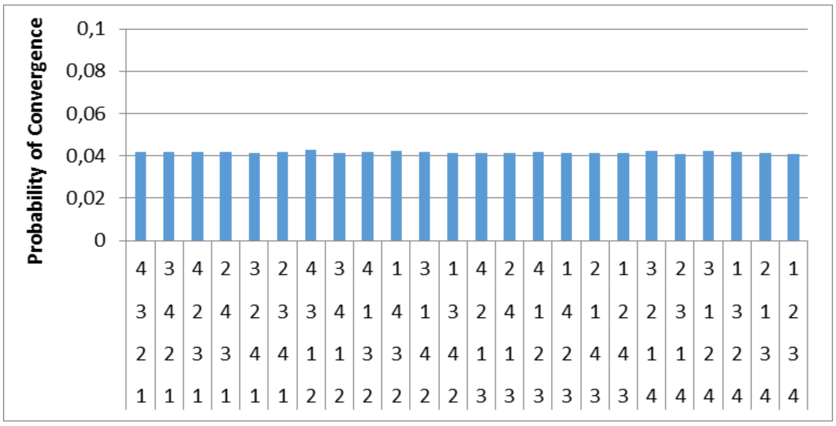


Figure 5.11: Probability of convergence to the different NEs

In the other three configurations, conversely, since the number of channel is lower than the number of SCs, the channels must be shared among the SCs. In these cases, not all NE correspond to the same throughput, as it will be dependent on the interference among the SCs of different operators. As it is explained in [20], the system tends to converge with higher probability to the NE corresponding to the higher throughput values. This behavior is shown in [Figure 5.12], where the results of one of the above mentioned configurations are reported as example.

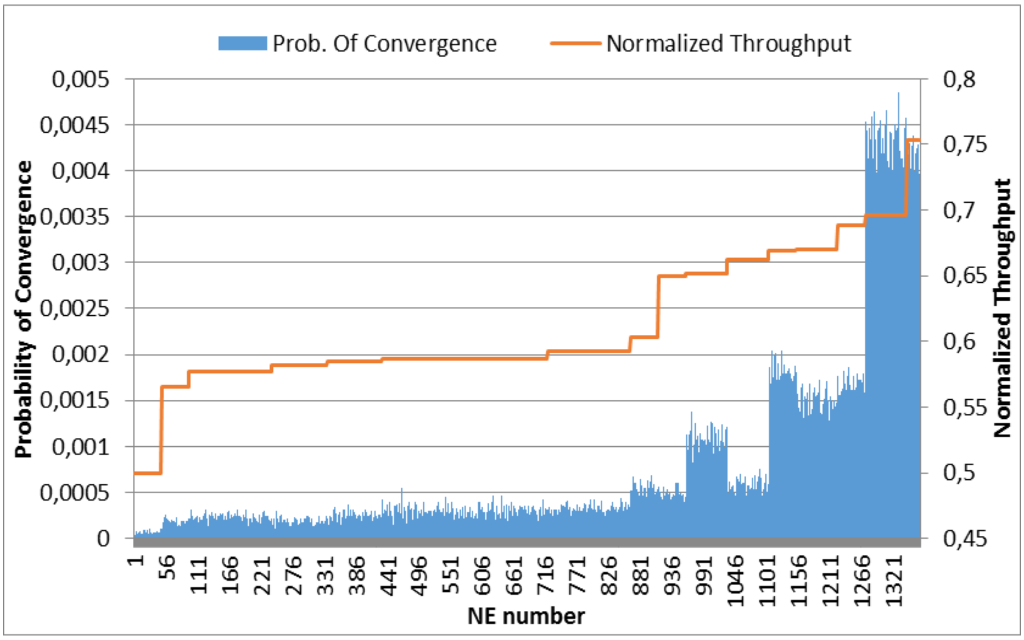


Figure 5.12: Probability of convergence to the different NEs and normalized throughput of each NE for the case K=4, ε=0,2 when the SCs of both OP1 and OP2 apply ITEL-BA with T_2=T_1=1

At last, going back to [Figure 5.10], the configuration where OP2 has a fixed channel allocation has lower values than the configurations where both operators apply the ITEL-BA algorithm; this may happen because in the second two configurations all the SCs compete each other so more NE states which provide higher throughput can be reached, contrarily of the first configuration where less NE states are available.

Achieved throughput along the whole simulation: in this analysis, the achieved throughput was evaluated like in the previous study of the exploration rate. Multiple experiments with a fixed duration for each simulation were made:

- 1000 experiments;
- Each one with a duration 10000 time steps.

The evaluation for this kind of throughput was made only two different configurations:

- SCs of OP2 with a fixed channel allocation;
- SCs of OP2 using ITEL-BA algorithm with an activity period equal to OP1 (T_2=T_1).

Here, the evaluations were made in order to observe the values of the achieved throughput in a first short period of activity of the system, considering the periods before and after converging.

Each value of the graph in [Figure 5.13] was obtained as the ratio between the values of two parameters obtained from the simulations:

- *stat_Rb_average*: average throughput achieved by all the SCs during all the experiments;
- *stat_Rb_optimum*: throughput in the optimum case.

For each configuration, this ratio was evaluated for all the values of activity period in study. In the following table these values are reported.

Activity Period (Time Steps)	K=4, OP2 fixed	K=4, OP2 ITEL_BA T_2=T_1
T_1=1	96,9662295	92,1602868
T_1=5	97,1493922	92,3717911
T_1=10	96,8520106	92,3717911
T_1=20	96,80415	92,292955
T_1=50	96,5712794	91,6091218
T_1=100	96,1679659	91,3048204

Table F: Values of the achieved throughput with respect to the optimum case

The graph in [Figure 5.13] shows the trend of the curve of the achieved throughput along the whole simulation, depending on the values of activity period.

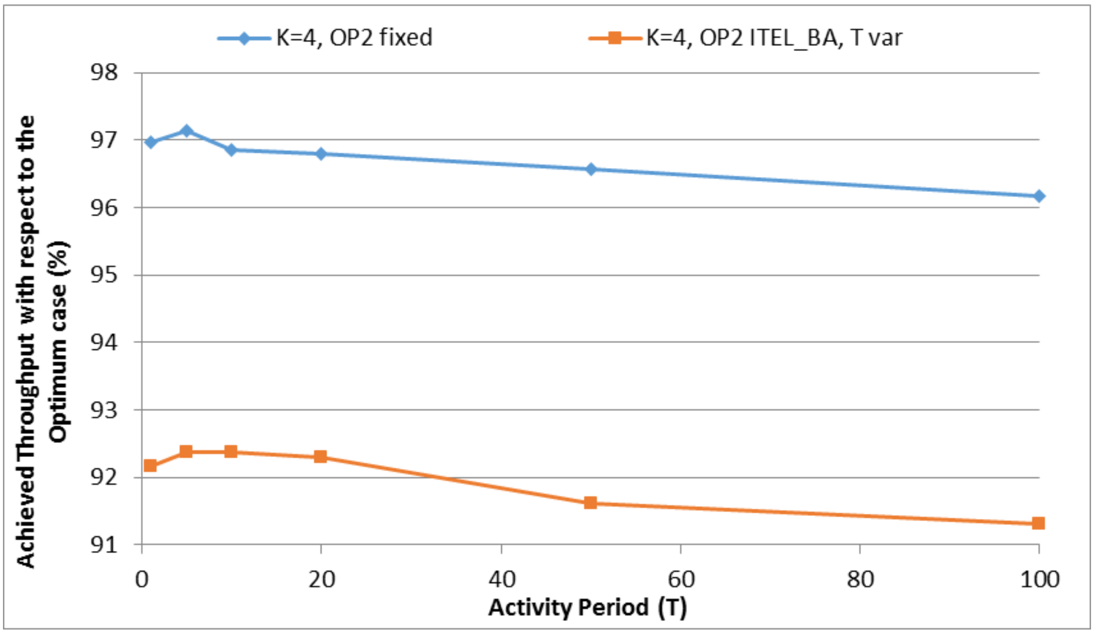


Figure 5.13: Achieved Throughput over Activity Period along the whole simulation

As it can be observed in [Figure 5.13], the curves representing the achieved throughput behave in a specular manner compared to the curves in [Figure 5.6] and [Figure 5.8] which represent the behavior of the convergence time. This observation has already been done in the study of the exploration rate, where the convergence time and the achieved throughput had specular trends increasing the value of ε. Also in this case, in fact, the values of the achieved throughput are higher for lower values of the activity period, which lead to lower values of convergence time, and they decrease with the increase of the values of T, which lead to higher values of convergence time.

Hence, it is possible to say that there is a correlation between the convergence time and the achieved throughput depending on the value of the activity period: if T leads to lower values of convergence time, then the achieved throughput will reach higher values, and conversely. Furthermore, another consideration that highlights this aspect, as well as in the study of the exploration rate, is that the configuration where both the operators use the ITEL-BA algorithm reaches lower values of throughput compared to the configuration where the SCs of OP2 have a fixed channel allocation. Nevertheless, this is the opposite of what happened in the steady case. In that case, the throughput was studied when the convergence had already been reached so it had higher values in the case of both operators applying the algorithm than in the case of fixed channel allocation, due to the higher number of NE which could be reached. Here, the throughput was evaluated while the SCs were applying the algorithm to reach the convergence; so in the case of OP2 with fixed channel allocation the system reached the convergence faster compared to the case where both operators apply the algorithm, leading to higher throughput.

In conclusion, generally, it is possible to summarize the results in this way:

- for all the configurations that were studied, increasing the value of the activity period, T, means that a SC takes more time to make a decision, which can be seen as a channel selection; in this way, the SCs in the whole scenario need more time to evaluate all the possible NE state configurations so that the convergence time needed to reach one of those becomes higher. Conversely, a lower value of activity period leads to a lower convergence time.

- Thanks to a faster activity of the SCs (lower value of T), the system, in the first short period of activity, can achieve higher values of throughput compared to the optimum case than in the case of slower activity; on the other hand, concerning to the steady case, the value of the activity period does not influence significantly the value of the average throughput, which tends to be constant, and its value depends on the configurations of the SCs.

5.4. Non-Stationary conditions analysis

Most of the scenarios in practical environments are non-stationary as their dynamic and their characteristics might change in an unknown or not predictable way. In the context of LTE-U, this also happens by means of the presence of SCs applying different channel selection strategies, the presence of other systems (as the Wi-Fi), the installation of new SCS, etc. These events lead to changings of the interference conditions observed in the wireless connections.

The repeated game strategy can be used in dynamic and non-stationary environments, but these random events force the learning method to relearn the selection policy whenever a changing in the scenario occurs. This may leads to a performance deterioration. Hence, the evaluation of the robustness and of the achievable performance of the system is based on how often changings occur and, in that case, how long the method takes to learn a new solution.

The analysis of the non-stationary conditions was made by means of the presence in the scenario of random events at different activity periods. More precisely, the SCs of OP1 applied the ITEL-BA algorithm, as usual, while the SCs of OP2, as a source of non-stationarity, carried out random channel selections, which introduced variability in the environment. As in [15], the time between two consecutive channel selections made by a SC of OP2 was modelled as a geometrical random variable with average Δ, which characterized the rate at which the environment changed from OP1's perspective.

In this analysis, the performance of the system was evaluated only in term of throughput. The convergence time could not be studied due to the changings of the environment which every time forced the method to relearn the selection policy. In order to study the behavior of the achieved throughput, multiple experiments for each simulation were made:

- 50 experiments;
- Each one with duration 1000000 time steps.

At last, the values of the activity period of the SCs of OP1 are T=[1;5;10;20;50;100], the value of the exploration rate is ε=0,2 and the considered values of the average rate with which the environment changes are Δ=[100;500;1000;5000;10000;50000].

In the analysis, considering the configurations with ε=0,2 and those values of activity period, the achieved throughput was studied for each value of Δ. The obtained values are reported in the following table.

Δ (time steps)	**T=1**	**T=5**	**T=10**	**T=20**	**T=50**	**T=100**
100	87,227813	86,355371	85,037215	83,439656	81,069974	79,399028
500	89,183922	89,037009	88,257708	87,231389	85,330193	83,669020
1000	89,798804	89,637695	89,121880	88,392756	86,904659	85,374550
5000	90,816564	90,431714	90,24232	89,970595	89,266802	88,566581
10000	91,148873	90,662147	90,398861	90,080027	89,779195	89,294104
50000	91,594424	90,898038	90,526904	90,272676	90,453416	90,148427

Table G: Values of the achieved throughput in non-stationary conditions with ε=0,2

The graph in [Figure 5.14] shows the trend of the achieved throughput along the whole simulation depending on the velocity of environment changings, for the configurations with different values of activity period.

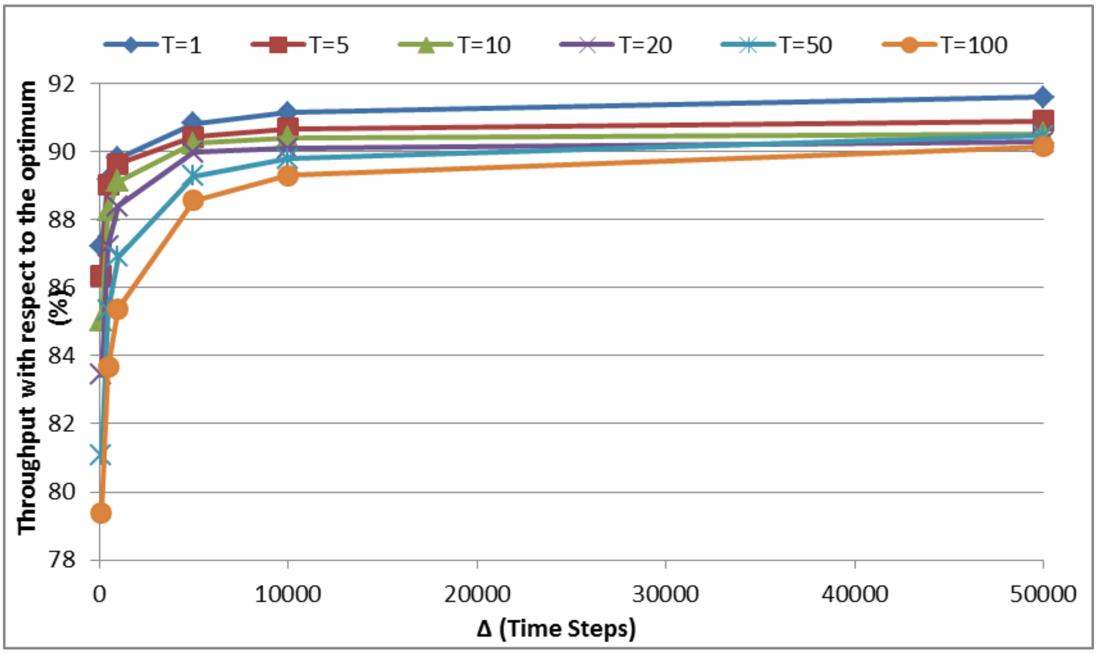


Figure 5.14: Achieved Throughput over Δ

As it can be observed in the graph and from the values in the table above, the curve representing the achieved throughput raises for higher values of Δ. More precisely, the achieved throughput increases rapidly for values of Δ between 100 and 5000, while it tends converge to a constant value (approximately 90-92%) for higher values of Δ.

When Δ has lower values, the SCs of OP2 change channel very often, leading to fast changings in the environment, while, in case of higher values of Δ, the environment changes more slowly. Consequently, also the SCs of OP1 have to relearn the selection policy every time they find a changing, as shown in [Figure 5.15]. For this reason, when Δ has lower values, because the time needed to learn a new solution might be higher than the velocity with which the environment changes, the values of throughput are respectively low. After a certain value of Δ, approximately 5000 time steps, environment changes occur slowly enough that the SCs have enough time to learn a new solution; this way doing, the achieved throughput reaches higher values.

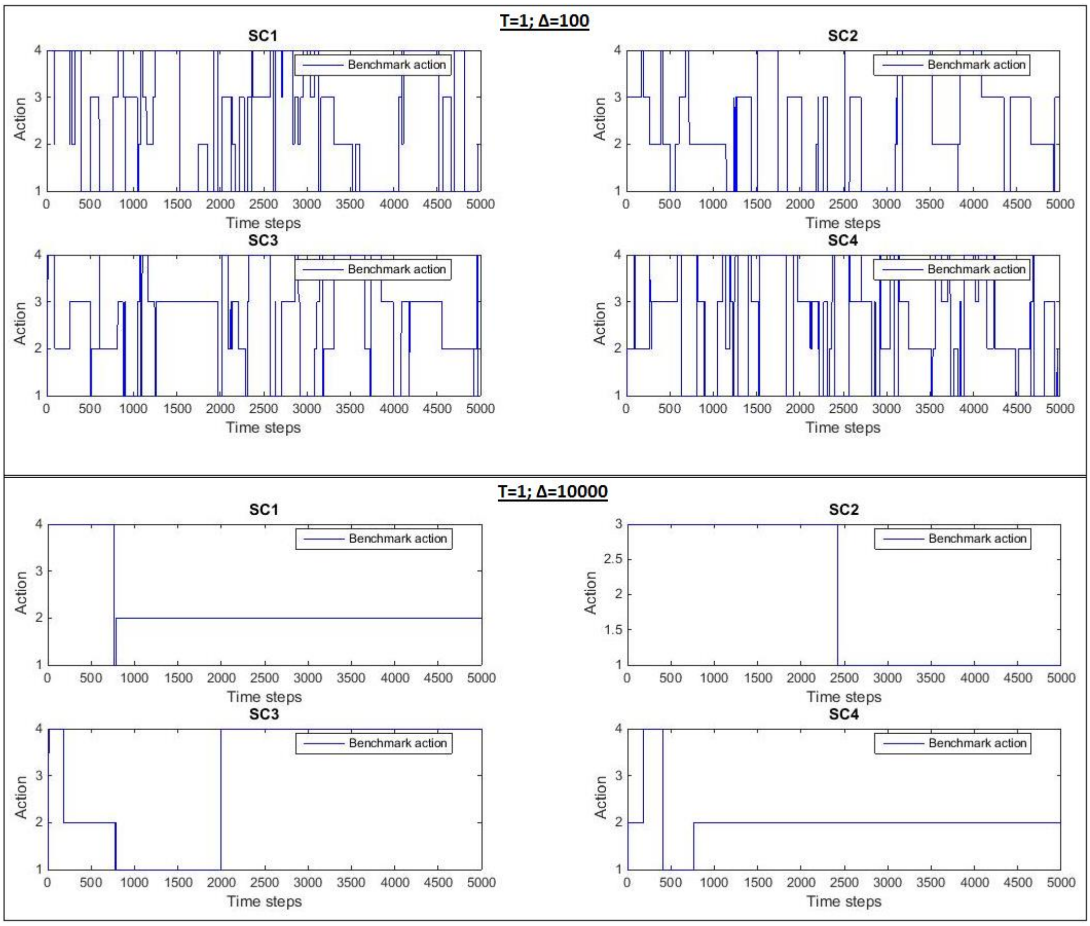


Figure 5.15: Time evolution of the benchmark actions depending on Δ

Furthermore, another observation can be made from the graph in [Figure 5.14]. It is possible to notice that each curve corresponding to a certain value of activity period is always above all the other curves corresponding to higher values of T. The lower the value of activity period, the higher the achieved throughput. As it was discussed in the previous chapter, in fact, lower values of activity period lead to lower value of convergence time, meaning that, in case of changings in the environment, the SCs might learn faster a new selection policy in order to find a new solution. In other words, with lower values of activity period, the system reacts faster to changings in the environment and the achieved throughput is greater.

Combining the results in a different way, it is possible to evaluate the value of the achieved throughput in comparison with the value of the ratio between Δ and the activity period T. This behavior is shown if [Figure 5.16].

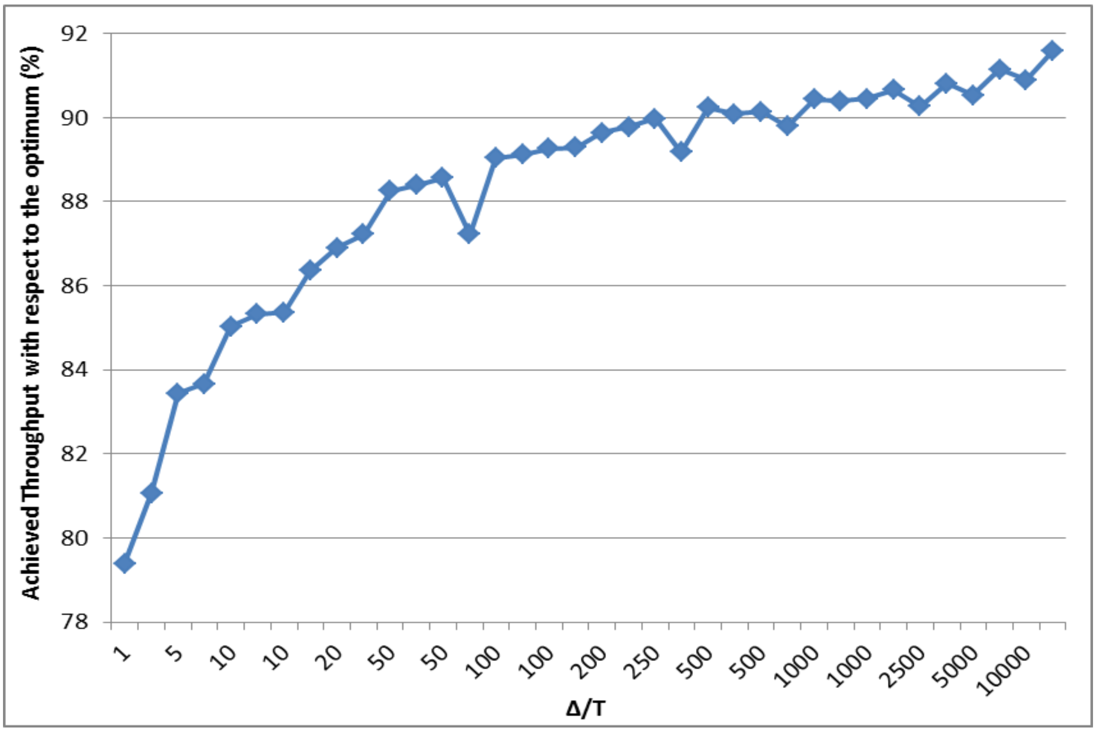


Figure 5.16: Achieved Throughput over Δ/T

The graph shows the trend of the curve of the throughput with respect to Δ/T. This parameter is given by the ratio between the amount of time that the environment remains stationary and the time needed for the learning process (considered proportional to T). As it can be observed, higher values of the ratio lead to higher values of throughput; this happens because when the time needed for the learning process is much smaller than the time that the environment remains constant, an optimal channel configuration can be found faster and this leads to higher values of throughput. Hence, in order to achieve good results in terms of throughput, the learning time of new solutions must be smaller than the time Δ that the environment remains stationary.

Summarizing the results it is possible to draw the following conclusions:

- the presence of external events bringing changings in the environment leads to a degradation of the performance in terms of throughput;
- higher values of Δ, as well as lower values of activity period of the SCs, lead to higher throughput;
- the time needed for the learning process related to the time that the environment remains stationary is a metric that affects the performance degradation. Consequently, it is possible to say that the ratio Δ/T is a metric to characterize the achieved throughput of the proposed strategy, since it compares the level of non-stationarity of the environment to the learning time of the method. The best performance is achieved for higher values of the ratio Δ/T.

6. Budget

The aim of this project was the performance evaluation of the game theory-based channel selection strategy for LTE-U. The tools utilized for this purpose were:

- The software which simulates the scenario where several SCs, players of the game, applied the method in order to find the best channel where to set up the LTE-U carrier;
- The PC of the workstation form where the work was carried forward;
- Two servers where the simulations were run.

The implementation and utilization of physical devices were not needed. For this reason the only cost that can be taken into account is in term of time spent for the simulations, for the elaboration of the results and for the writing of the final report. The set up for the simulations and the elaboration of the results were, surely, the most demanding and important parts. The time spent for them can be split into three main periods:

- Analysis of the exploration rate which took approximately three weeks;
- Analysis of the activity period which took more than one month;
- Analysis of the non-stationary conditions which took one month and a half.

Without considering the time needed for the simulations, which were continuously running in the servers, it was possible to estimate about 600/700 hours as the time that I needed for the understanding of the state of the art and of the analyzed method, for the familiarization with the software, for the elaboration of the results and for the writing of the finale report.

7. Conclusions and future development

This project has focused on the performance evaluation of a channel selection strategy for LTE-U realized to enable the coexistence of multiple operators using the same unlicensed band. The strategy is based on a fully distributed approach and the channel selection problem is modeled as a non-cooperative repeated game with the ITEL-BA as learning algorithm that drives the system towards a NE state. The performance of the system was studied in terms of convergence time and achieved throughput in relation to several parameters, such as the exploration rate, the activity period and the non-stationarity condition.

The performance was evaluated in an indoor scenario under different conditions regarding the number of players and the presence of external influence. Analyzing the results obtained from the tests, it has been possible to reach the following main conclusions:

- There is an inverse relation between the convergence time and the achieved throughput. Lower values of convergence time correspond to higher values of achieved throughput and vice versa. Consequently, optimal values of exploration rate and of activity period must be chosen, depending on the configuration, in order to reach the best performance. The range of values of ε between 0,1 and 0,3 leads to lower convergence time and higher throughput, while the lower the value of T, the better the performance of the system.
- The non-stationary condition of the environment might lead to a degradation of the performance. The achievable throughput depends on the velocity with which random changings occur in the environment and on the time needed for the learning process. The algorithm can achieve better performance when random changings occur less frequently; particularly, higher values of throughput can be reached for values of Δ greater than 10000, meaning that the learning process is fast enough compared to the non-stationarity of the environment.

As part of future work, several different studies can be made in order to analyze and enhance the performance of the method. The behavior of the ITEL-BA algorithm can be investigated in different scenarios: modifying the number and/or position of the SCs, modifying the number of the channels, evaluating the impact of the number of UEs, evaluating the impact of the parameters of the propagation model, etc. Moreover, variations of the technique can be analyzed, such as ITEL-BAWII, where the assumption of perfect interference estimation is removed.

Bibliography

[1] Anders Furuskar, Tomas Jonsson, and Magnus Lundevall, The LTE Radio Interface - Key Characteristics and Performance, Ericsson Research, Sweden, 2008.

[2] Erik Dahlman, Anders Furuskär, Ylva Jading, Magnus Lindström and Stefan Parkvall, Key features of the LTE radio interface, 2008.

[3] Magdalena Nohrborg, for 3GPP, "www.3gpp.org," [Online]. Available: http://www.3gpp.org/technologies/keywords-acronyms/98-lte.

[4] C. Gessner, A. Roessler, M. Kottkamp, LTE Technology Introduction, July, 2012.

[5] Freescale Semicondutor, Long Term Evolution Protocol Overview, 2008.

[6] Sravanthi Kanchi, Shubhrika Sandilya, Deesha Bhosale, Adwait Pitkar, Mayur Gondhalekar, Overview of LTE-A Technology, Vidyalankar Institute of Technology , Wadala, Mumbai.

[7] Jeanette Wannstrom, for 3GPP, "www.3gpp.org," June 2013. [Online]. Available: http://www.3gpp.org/technologies/keywords-acronyms/97-lte-advanced.

[8] Ran Zhang, Miao Wang, Lin X. Cai, Zhongming Zheng, Xuemin (Sherman) Shen, Liang-Liang Xie, LTE-Unlicensed: The Future of Spectrum Aggregation for Cellular Networks, June 2015.

[9] O. Sallent, J. Pérez-Romero, R. Ferrús, R. Agustí, "Learning-based Coexistence for LTE Operation in Unlicensed Bands," in IEEE International Conference on Communications (ICC2015) - Workshop on LTE in Unlicensed Bands (LTE-U), London, UK, June, 2015.

[10] Baoan Jia, Meixia Tao, A Channel Sensing Based Design for LTE in Unlicensed Bands, Shanghai Jiao Tong University, 2015.

[11] Jeongho Jeon, Huaning Niu, Qian (Clara) Liy, Apostolos Papathanassiou, Geng Wu, LTE with Listen-Before-Talk in Unlicensed Spectrum, Santa Clara, CA 95054, USA, 2015.

[12] 3GPP TR 36.889, "Feasibility Study on Licensed-Assisted Access to Unlicensed Spectrum," [Online]. Available: http://www.3gpp.org/DynaReport/36889.htm.

[13] R. Hellberg, "How different are LTE-U and LAA?," 5 November 2015. [Online]. Available: https://www.qualcomm.com/news/onq/2015/11/04/how-different-are-lte-u-and-laa.

[14] Qualcomm Research, LTE in Unlicensed Spectrum: Harmonious Coexistence with Wi-Fi, June 2014.

[15] J. Pérez-Romero, O. Sallent, R. Ferrús, R. Agustí, "A Robustness Analysis of Learning-based Coexistence Mechanisms for LTE-U Operation in Non-Stationary Conditions," in IEEE Vehicular Technology Conference Fall (VTC Fall 2015), Boston, USA, September, 2015.

[16] Theodore L. Turocy, Bernhard von Stengel, Game Theory, CDAM Research Report LSE-CDAM-2001-09, October 8, 2001.

[17] Giacomo Bacci, Marco Luise, Game Theory in Wireless Communications with an Application to Signal Synchronization, April, 2010.

[18] N. Garg, "[Proposal] Network Selection with LTE-Unlicensed and WiFi: A Game Theoretic View," [Online]. Available: gargnikhil.com/files/Garg_EE359Proposal.pdf.

[19] Wenlong Yin, Jinlong Wang, Small Cell Deployment in Licensed/Unlicensed Band: A Local Interaction Game Framework, Nanjing, China, 2015.

[20] J. Pérez-Romero, O. Sallent, H. Ahmadi, I. Macaluso, "On Modeling Channel Selection in LTE-U as a Repeated Game," in IEEE Wireless Communications and Networking Conference (WCNC 2016), Doha, Qatar, April, 2016.

[21] "www.mathworks.com," [Online]. Available: http://uk.mathworks.com/products/matlab/index.html.

[22] 3GPP TR 36.814 v9.0.0, "Further advancements for E-UTRA physical layer aspects," March, 2010.

[23] 3GPP TR 36.942 v12.0.0, "Radio Frequency (RF) system scenarios," September 2014.