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Cooperative Spectrum Sharing of Cellular LTE-Advanced and Broadcast DVB-T2 Systems

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Abstract

The allocation of parts of the Ultra High Frequency (UHF) band to International Mobile Telecommunications (IMT) technologies on a co-primary basis with terrestrial broadcasting technologies has been the major change in worldwide spectrum allocation in recent years. Nowadays, thanks to the Second Generation for Terrestrial Digital Video Broadcasting (DVB-T2) and the Long Term Evolution Advanced (LTE-A) technologies a new model of cooperation between cellular and broadcasting systems arises, where the cellular network can use of broadcast spectrum using time multiplexing. This paper proposes the cooperative spectrum sharing of DTT spectrum between DVB-T2 systems and LTE-A cellular networks by means of the use of DVB-T2 FEF for LTE-A analyzing the potential benefit.

Key words: Spectrum sharing, LTE-A, DVB-T2, FEF, Carrier aggregation

1. Introduction

Radio spectrum is a scarce resource that has a considerable economic and social importance. The total spectrum bandwidth requirements for mobile communication systems in the year 2020 are predicted to be 1280 MHz and 1720 MHz for low and high demand scenarios [1], respectively. However, the spectrum bandwidth allocated by International Telecommunication Union (ITU) for mobile technologies is much lower than these needs: 693 MHz in

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Region 1 (Europe, Middle East and Africa, and Russia), 723 MHz in Region 2 (Americas) and 749 MHz in Region 3 (Asia and Oceania).

Terrestrial broadcasting technologies use a significant part of the frequency spectrum, mainly in the Ultra High Frequency (UHF) (470-862 MHz) and Very High Frequency (VHF) (173-230 MHz) bands. For many decades, this spectrum was used by analogue television. However, the switchover from analogue to Digital Terrestrial TV (DTT) has released a significant amount of spectrum in UHF, which is known as digital dividend [2]. It was in the World Radiocommunications Conference 2007 (WRC-07) where the ITU decided to allocate the upper part of the UHF band from 790 to 862 MHz to International Mobile Telecommunications (IMT) technologies on a co-primary basis with terrestrial broadcasting technologies. In Region 2 and several countries of Region 3, the 698-790 MHz band was also identified for IMT. For the second digital dividend, in the WRC-15 the worldwide allocation of 698-862 MHz band to IMT technologies is to be discussed.

Cognitive Radio (CR) technology is an alternative to maximize the spectrum efficiency of cellular networks by performing spectrum sharing. Among all the mechanisms provided by CR, the opportunistic spectrum access is devised as a dynamic method to increase the overall spectrum efficiency by allowing non-licensed -cognitive or secondary- users to utilize unused licensed -primary- spectrum [3]. Currently, CR is being researched for secondary access on the DTT spectrum, also known as TV white space (TVWS) [4]. Hence, there is a clear opportunity to enhance the capacity of cellular systems by exploiting TVWS spectrum sharing schemes for the mobile broadband systems and DTT coexistence.

Nowadays, with the Second Generation for Terrestrial Digital Video Broadcasting (DVB-T2) [5] and the Long Term Evolution Advanced (LTE-A) [6] technologies a new model of cooperation between cellular and broadcasting systems arises, where the cellular network can use of broadcast spectrum using time multiplexing. Concerning the technological enablers, DVB-T2 includes the Future Extension Frames (FEFs) concept to time multiplex in the same frequency extensions of the standard, but it also allows other technologies to be transmitted. On the other hand, one of the main features of LTE-A issued in Release 10 is Carrier Aggregation (CA) [7], which allows aggregating multiple carriers such that a fragmented spectrum can be efficiently used. In addition, one of the CA enhancements currently studied for beyond Release 12, the new carrier type (NCT), aims to increase both spectrum flexibility and spectral efficiency [8]. These carriers can be activated

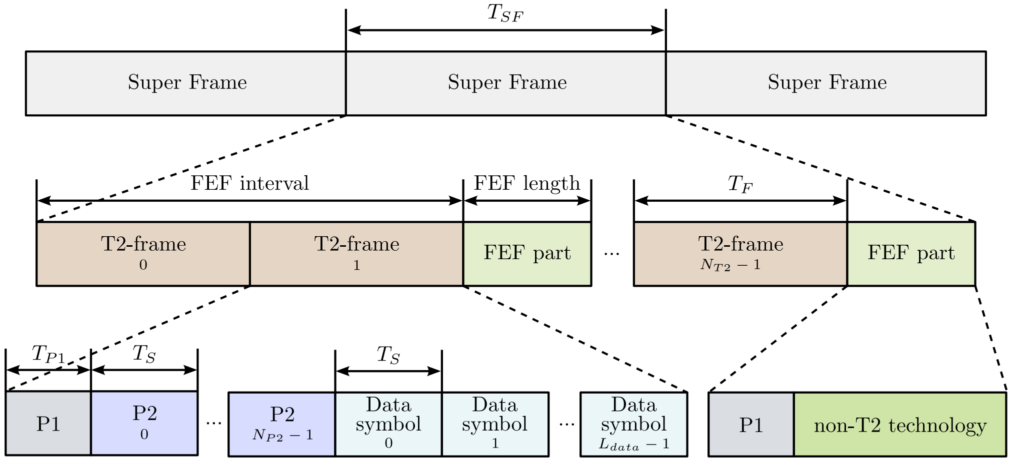

Figure 1: The DVB-T2 frame structure, showing the division into super-frames, T2-frames and FEF.

and deactivated on demand, which allows time-division service multiplexing like the one envisioned in DVB-T2.

This paper proposes the cooperative spectrum sharing of DTT spectrum between broadcast DVB-T2 systems and 4th Generation (4G) cellular networks LTE-A by means of the use of DVB-T2 FEF for LTE-A. The next section describes the frame structure and FEF characteristics of DVB-T2 followed by a section that review the CA concept in LTE-A and beyond Release 12 NCT features. Then, the configuration for DVB-T2 and LTE-A cooperation is proposed showing the potential benefit gained with spectrum sharing. The final section draws the main conclusions of the paper.

2. Physical Frame Structure and FEF in DVB-T2

The physical frame structure of DVB-T2 consists of super frames, frames, and Orthogonal Frequency Division Multiplexing (OFDM) symbols, as illustrated in Figure 1. Super frames comprise an integer number of frames that may be of two types: T2 frames and FEFs. Likewise, each frame is formed by an integer number of OFDM symbols, either preamble symbols, which carry control information, or data symbols.

P1 and P2 are the preambles that provide control information to DVB-T2 receivers. P1 is the first OFDM symbol of each T2 frame and FEF part, and consists of a 1K OFDM symbol used for fast synchronization. It also carries some basic transmission parameters, like the frame type (e.g., T2, mobile profile of T2 known as T2-Lite, or handheld evolution of T2 known as Next Generation Handheld (NGH)). In T2 frames, one or several P2 symbols - depending on the Fast Fourier Transform (FFT) size- are inserted after the P1 symbol. These preamble symbols have the same FFT size as data symbols and convey the rest of Layer 1 (L1) signaling information. This signaling enables the reception of subsequent data symbols that contain the actual DVB-T2 services.

L1 signaling configures the number of T2 frames and FEF parts carried by a super frame. The minimum and maximum numbers of T2 frames in a super frame are 2 and 255, respectively, being all of them of the same duration. The maximum length of a T2 frame, T_F, is 250 ms. The use of FEFs is optional, but if included in the transmission, super frames must start with a T2 frame and end with a FEF. The pattern insertion scheme of FEFs can be configured on a super frame basis. The maximum number of FEFs in a super frame is 255, that is, one FEF after every T2 frame. As an example, Figure 1 illustrates a frame structure in which there is one FEF every two T2 frames.

2.1. FEF in DVB-T2

FEFs allow combining in the same frequency legacy DVB-T2 transmissions with other technologies. They can be inserted between T2 frames to enable a flexible mix of services within a single multiplex in a time division manner. During FEFs, DVB-T2 receivers ignore the received signal in such a way that any service can be inserted in these temporary slots without affecting the DVB-T2 reception. The only attributes of FEFs defined in the standard are the following:

- They shall begin with a preamble P1 symbol.
- Their position and duration in the super frame are indicated in the L1 signaling within the T2 frames.

The maximum length of a FEF part is 250 ms for the T2-base profile, whereas for T2-Lite and DVB-NGH it has been extended up to 1 s [9]. The existing DVB-T2 receivers are not expected to decode FEFs. They simply must be able to detect and correctly handle FEF parts so that the reception of T2 frames is not disturbed.

Although FEFs were designed to enable future extensions of the DVB-T2 standard, other use cases are possible. As depicted in Figure 1, another technology can make use of the DVB-T2 spectrum taking advantage of the temporal multiplexing of services that enable the FEF concept. It is worth noting that the T2 system is always responsible for inserting the P1 symbol at the beginning of all FEF parts so that all T2 receivers can detect the FEFs parts correctly.

2.2. L1 Signaling related to FEF

The use of FEFs is signaled in the preamble P1 and P2 symbols. The P1 symbol has two signaling fields S1 and S2, with three and four signaling bits, respectively. The S1 field is used to distinguish the preamble format. The frame type that can be either T2 or a FEF used for T2-Lite, DVB-NGH or non-T2 applications, with S1 field equal to 010. This case can be used to time-multiplex other services like LTE-A.

For DVB-T2, T2-Lite, and DVB-NGH, the S2 field mainly indicates the FFT size, but it has one bit dedicated to the FEFs. This bit specifies whether the preambles are all of the same type or not, that is, if more than one type of frame exists in the super frame. This speeds up the scanning process.

L1 signaling data in the preamble P2 provides, among others, the guard interval, the number of T2 frames per super frame, N_{T2}, the number of data symbols, L_{DATA}, the type of the associated FEF part, FEF_TYPE, the length of the associated FEF part, FEF_LENGTH, and the number of T2-frames between two FEF parts, $FEF\_INTERVAL$. It should be pointed out that the FEF_LENGTH indicates the length of the FEF parts in elementary time periods[1] , T, from the start of the P1 symbol of the FEF part to the start of the P1 symbol of the next T2 frame.

Therefore, with N_{T2} and $FEF\_INTERVAL$ the receiver can compute the number of FEFs in a super frame, N_{FEF}, and subsequently the total super frame duration, T_{SF}.

3. CA in LTE-Advanced

IMT-Advanced requirements established a minimum support of 1 Gbps peak rate for low-mobility user. In order to fulfill these challenging requirements,

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[1] Samples in the receiver.

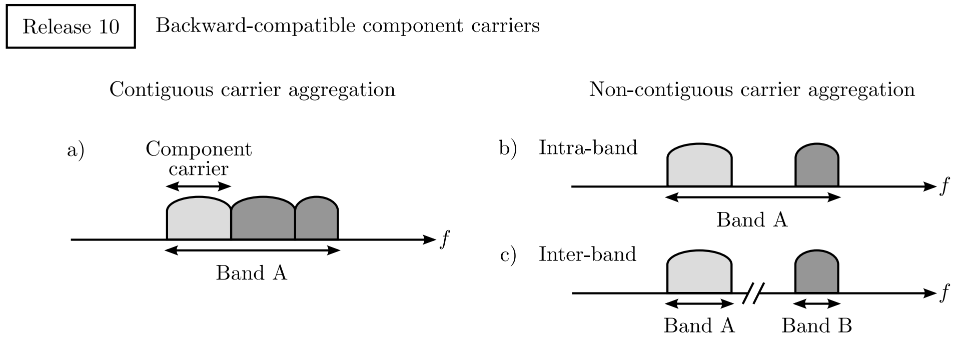

Figure 2: CA types in LTE-A Release 10: a) intra-band contiguous; b) intra-band non-contiguous; c) inter-band non-contiguous.

wider channel bandwidth than legacy systems had to be supported, up to 100 MHz. However, the available spectrum resources of mobile network operators vary considerably depending on the specific country, being spread out over different frequency bands and with different bandwidths. All IMT-Advanced technologies incorporate as one of their key features the aggregation of continuous or discontinuous spectrum in order to achieve wider bandwidth and consequently increase transmission capability. This concept is known as CA. The main features of the first version of CA included as part of 3GPP LTE-A Release 10 are described in [7]. In 2012, the 3GPP technical specification group dedicated to the Radio Access Network (TSG RAN) started discussing some CA enhancements to be included in future releases of the standard. This section describes CA and its current roadmap.

3.1. CA in Release 10

3.1.1. Component Carrier Types

The legacy LTE carriers, that is Release 8/9, have a maximum bandwidth of 20 MHz. In order to ensure backward compatibility, LTE-A supports the aggregation of up to five 20 MHz Component Carriers (CCs). CA is designed to support aggregation of a variety of different arrangements of CCs, including CCs of the same or different bandwidths, adjacent or non-adjacent CCs in the same frequency band, and CCs in different frequency bands. The deployment scenarios considered in the design of LTE-A, exemplified with two component carriers, can be seen in Figure 2. All CCs in LTE-A Release 10 are designed to be backward-compatible. This means that each

CC is fully accessible to legacy LTE User Equipments (UEs). Therefore, essential Release 8 channels and signals such as synchronization signals and system information are transmitted on each CC. Nevertheless, there are some mechanisms such as cell barring that can be used to avoid legacy LTE UEs to camp on a specific CC.

3.1.2. Primary and Secondary Serving Cells

Each CC appears as a separate cell with its own Cell ID. A UE that is configured for CA is connected to one Primary Serving Cell -PCell- and up to four Secondary Serving Cells -SCells-. Firstly, the UE establishes the radio access connection with a serving cell that becomes the PCell. This PCell plays an essential role with respect to security, mobility information and connection maintenance. SCells may be configured after connection establishment, just to provide additional radio resources. When adding a new SCell, dedicated signaling is used to send all the required system information for the new SCell.

3.1.3. SCell Activation and Deactivation

SCell activation/deactivation is a mechanism aiming to reduce UE power consumption in LTE-A CA [10]. If a UE is configured with one or more SCells, the eNodeB can activate and deactivate the configured SCells sending a medium access control (MAC) command. In addition, a UE maintains a timer per configured SCell and automatically deactivates the associated SCell upon its expiry. When a SCell is deactivated, the UE stops monitoring that CC.

Activation/deactivation is not applicable for the PCell that must remain active during the whole LTE-Active state. The activation/deactivation timing is carefully defined in order to ensure a perfect synchronization between the eNodeB and the UE. When a UE receives a MAC control element activating a SCell, the SCell has to be ready for operation after 8 frames (8 ms). At this moment, the SCell deactivation timer is started. Note that this timer can be set to infinity to avoid automatic deactivation.

3.1.4. Physical Layer Aspects

At the physical layer, each transport block is mapped into a single CC. Even if a UE is simultaneously scheduled on multiple CCs, hybrid automatic repeat request (HARQ), modulation, coding and resource allocation are performed independently on each CC. Each downlink CC carries the same control signaling region at the start of each subframe as in Release 8/9. The Physical Downlink Control Channel (PDCCH) allocates downlink resource to users at the same CC but it can also perform cross-carrier scheduling, which allows scheduling data transmissions on another CC.

3.2. CA Enhancements beyond Release 10

After the introduction of CA in Release 10, a 3GPP TSG RAN work item was set up to improve the operation of CA. This work item focused on several topics, namely, support of multiple uplink timing advance values, intra-band non-contiguous CA, support of inter-band CA for time division duplex (TDD) and the definition of additional carrier types [11]. Among these topics, one of the key components is the NCT, focused on non-backward compatible carrier types, which were already considered during Release 10 standardization but they were left for later releases. The NCT will be completed beyond Release 12.

The main motivation for the definition of the NCT is the use of carriers with minimized transmission of legacy control signaling and common reference signals (CRS), which would reduce interferences and signaling overhead [8]. Thus, NCT can increase spectrum flexibility and reduce network energy consumption by allowing base stations to switch off transmission circuitry based on cell load. As depicted in Figure 3, NCT support both non-standalone and standalone use cases. On the one hand, a non-standalone carrier must be aggregated to a legacy LTE carrier, where carrier segments and extension carriers are the main candidates. On the other hand, a standalone carrier could be used without a connection with a legacy LTE carrier. Anyway, as the NCT are non-backward compatible carriers, they are not accessible by legacy LTE UEs.

Carrier segments are defined as bandwidth extensions of a legacy LTE carrier and constitute a mechanism to expand bandwidth -process also known as band filling-. With carrier segments additional resource blocks are aggregated to the legacy carrier, while still keeping the backward compatibility of the original carrier. The advantage of carrier segments is that no additional PDCCH resources are required. Moreover, these segments can be smaller than legacy LTE bandwidths. Carrier segments are always adjacent and linked to a legacy carrier, thus, this legacy carrier is who provides synchronization and system information. They support the same HARQ process, PDCCH indication, and transmission mode as the legacy carrier.

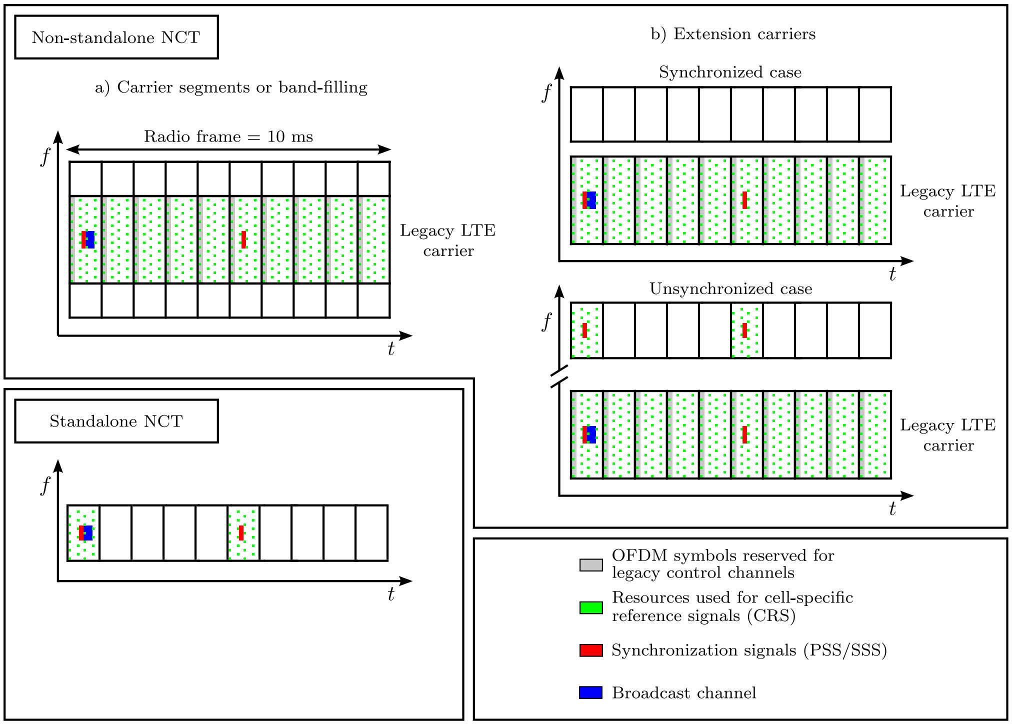

Figure 3: Non-backward compatible NCT.

An extension carrier must also be associated with a legacy LTE carrier because it has no control channels. Currently, two types of extension carriers are under discussion in 3GPP depending on the synchronization with the legacy carrier. An extension carrier may be considered synchronized with the legacy carrier only if they are co-located and the frequency separation is sufficiently small. In that case, synchronization signals and CRS do not need to be present on the synchronized extension carrier and the measurements for the extension carrier can also rely on the legacy carrier. Otherwise, the extension carrier needs to provide a proper synchronization signal for discovery and time/frequency tracking. For this purpose, a new reference signal is added, also named extended synchronization signal (eSS) [8], which is based on the CRS but only appears once every five subframes. The same solution may also be adopted for the standalone NCT.

Finally, due to the lack of many of the legacy LTE common signals, the system operation with NCT relies heavily on the LTE-A Multiple Input Multiple

Output (MIMO) functionality, that is, Transmission Mode 9 and 10 using demodulation reference signal (DM-RS) for data demodulation and channel state information reference signals (CSI-RS) for radio channel quality feedback. Another Release 11 feature, the enhanced PDCCH (E-PDCCH) [11], plays also a key role in the NCT since E-PDCCH, together with cross-carrier scheduling, allows removing the common downlink control channels from the NCT.

4. Cooperative Spectrum Sharing between DVB-T2 and LTE-A using DVB-T2 FEFs

Figure 4 shows the proposed spectrum sharing solution between DVB-T2 and LTE-A based on the CA capabilities of LTE-A and the NCT features currently under study in 3GPP. As it can be seen, two are the different use cases that LTE-A CA and NCT allows. In the former, the cooperative solution is based on that DVB-T2 transmitter is switched off during FEF and conventional eNodeBs activate a new carrier making use of the free spectrum. In the latter, the DVB-T2 transmitter stops DVB-T2 signal and starts transmitting LTE-A, hence creating a new cell.

Option a) is feasible with current CA schemes, since as the eNodeBs also transmit on a legacy carrier, a SCell could be activated occupying the FEF spectrum being deactivated with timers before the re-start of DVB-T2 transmission. Option a) could be also accomplished with extension carriers of NCT, which are even more flexible than legacy carriers and then could occupy perfectly the available spectrum. Concerning option b), this alternative is unfeasible with the current LTE-A standard, although it could be implemented in the future if the standalone NCT is included. The rest of the paper focuses the feasible option a).

4.1. DVB-T2 and LTE-Advanced Frame Configuration

The spectrum sharing between both systems should be transparent from the point of view of all DVB-T2 and LTE-A receivers. This implies that both systems must not transmit simultaneously on the same frequency. Therefore, a connection between the T2-Gateway and the LTE network should be maintained to guarantee perfect synchronization. Moreover, the configuration of both systems depends on whether spectrum sharing is performed in a static manner, where FEF intervals do not change, or dynamically, where the FEF intervals can be adapted according to the traffic load of the LTE-A network.

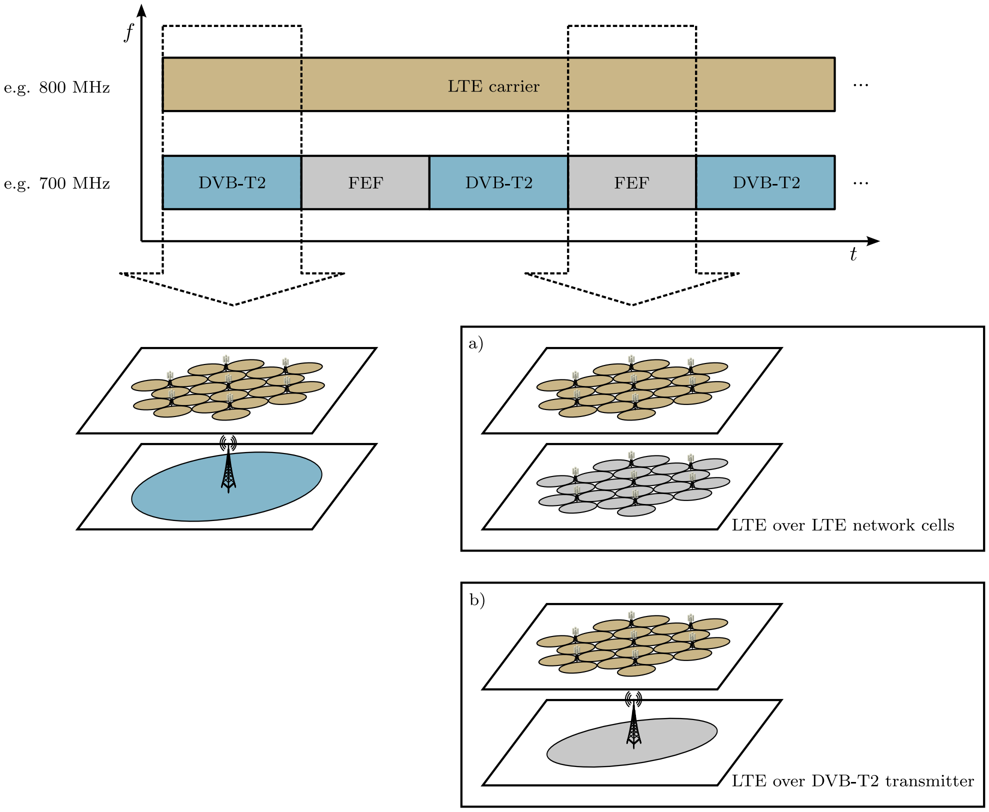

Figure 4: Use of DVB-T2 FEF and LTE-A for spectrum sharing.

The latter case would have implications on the number of TV channels provided by the DVB-T2 network, then, the connection maintained between both systems would be necessary to negotiate the applied configuration in each moment. Figure 5 shows the DVB-T2 and LTE-A frame configuration for spectrum sharing.

According to the DVB-T2 specification, the length of the FEF is an integer number of elementary time periods. The value of this elementary period depends on the channel bandwidth (e.g. 7/64 µs for 8 MHz bandwidth) and may differ from the time unit of LTE-A, which is the radio frame duration, T_F, of 10 ms. In general terms, the time available on the FEFs and the time used by LTE-A will not be exactly the same, as depicted in Figure 5. The configuration of both systems must take into account this issue in order to

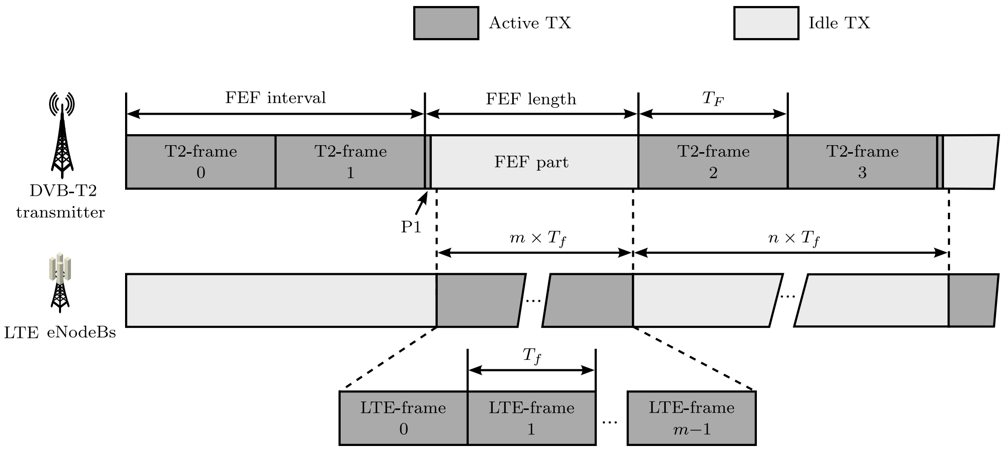

Figure 5: DVB-T2 and LTE-A frame configuration for spectrum sharing.

minimize the blank gaps required to avoid overlapping. Moreover, a problem that could appear as time passes is the synchronization loss between both networks due to their different time units. One solution could be that the T2-gateway adapts the superframe configuration. Anyway, the connection between T2-gateway and LTE network plays an essential role since it could be also used to keep perfect synchronization.

DVB-T2 receivers know the presence of a non-T2 service in the FEFs after processing the P1 symbol at the beginning of the FEF. Therefore, the remaining contents of the FEF part, which lasts *FEF_LENGTH*, should be ignored by the DVB-T2 receivers. Concerning LTE-A, m radio frames should fit into the FEF part. This number depends on the *FEF_LENGTH*. The cellular scheduler must announce the activation of the SCell to the LTE-A users 8 ms in advance and set the deactivation timers to fit m radio frames. After the activation phase, the SCell will be deactivated during n radio frames, being this value aligned with the *FEF_INTERVAL*. In case of using extension carriers of NCT, only a synchronized carrier could be used. In this case, during FEFs the scheduler could allocate resources to users in the extension carrier located in the DVB-T2 channel.

4.2. LTE-A Component Carrier Configuration

Two are the different options to configure the carrier that makes cooperative use of the DVB-T2 spectrum in LTE-A. The first option is based on Release

10 CA and the second one is based on beyond Release 12 NCT. Anyway, it must be avoided that legacy LTE UEs camp on the cooperative carriers. Cell barring could be a simple means to guarantee this since cell system information will indicate that camping is prohibited. Cell barring will also prevent this carrier from being used as a PCell by LTE-A UEs. This is necessary since PCells cannot be deactivated.

On the other hand, the extension carriers defined as NCT fit perfectly within FEFs.

4.3. Frequency Bands

This paper assumes that LTE-A will be the dominant 4G cellular technology worldwide in the coming years. Currently, the spectrum bands identified for LTE are 698-960 MHz, 1710-2025 MHz, 2110-2200 MHz, 2300-2400 MHz, 2500-2690 MHz and 3400-3600 MHz, although other operating bands are under consideration.

Although DVB standards -DVB-T and DVB-T2- are widely used around the world, other DTTs technologies exist. Advanced Television Systems Committee (ATSC) technology is also used in Region 2, Digital Terrestrial Multimedia Broadcast (DTMB) in Region 3, and Integrated Services Digital Broadcasting -Terrestrial (ISDB-T) in Regions 2 and 3. DTT technologies use part of the spectrum of the UHF band (470-790 MHz) and VHF band (173-230 MHz).

Consequently, the joint operation of LTE-A and DVB-T2 should happen in the overlapping band, that is, from 698 to 790 MHz.

4.4. System Bandwidths

Another aspect to be considered is the different bandwidths supported by each system. DVB-T2 supports 1.7, 5, 6, 7, 8 and 10 MHz bandwidth, being 8 MHz the typical bandwidth assigned to one DVB-T2 multiplex in Region 1. Legacy LTE carriers have the following bandwidths: 1.4, 3, 5, 10, 15 or 20 MHz. In the typical case of DVB-T2 multiplex of 8 MHz, a cooperative carrier will be only able to take advantage of 5 of the 8 available MHz. However, although initial LTE specifications only defined the above-mentioned set of supported system bandwidths, the standard also contemplates the possibility of considering other channel bandwidths in future releases. In fact, NCT are expected to be able to accommodate to the DVB-T2 typical bandwidth of 8 MHz.

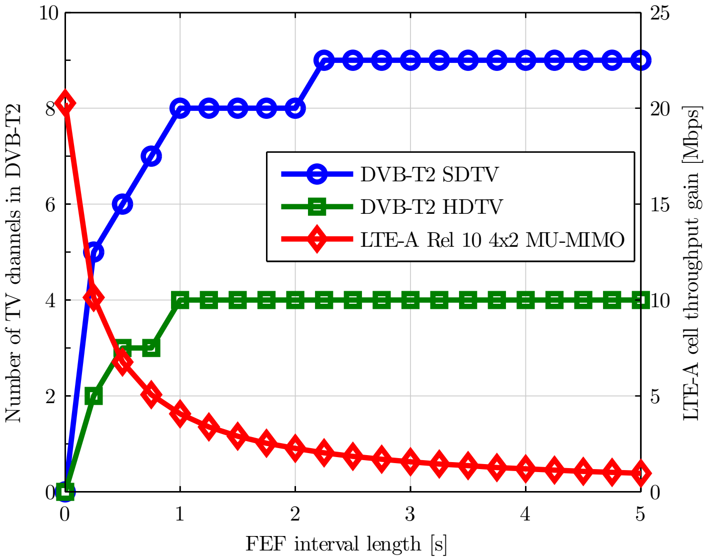

Figure 6: LTE-A potential gain depending on the FEF interval length with a FEF length of 250 ms.

4.5. Benefit Gained from the Spectrum Sharing

This section analyses the benefit of the joint operation of DVB-T2 and LTE-A. The DVB-T2 deployment in United Kingdom (UK) has been taken as a reference. In this UK deployment, an extended 32k FFT mode, a guard interval of 1/128, PP7 as scattered pilot pattern and a modulation and coding scheme of 256-QAM 2/3 are used. Then, the data rate that results from these configuration parameters is 40.2 Mbps in an 8 MHz bandwidth. In addition, it has been assumed that standard-definition TV (SDTV) and high-definition TV (HDTV) services require 4 Mbps and 8 Mbps, respectively with H.264/AVC video encoding. With these assumptions, DVB-T2 system could transmit 10 SDTV or 5 HDTV channels. The LTE-A results were obtained assuming a cell spectral efficiency of 2.533 bps/Hz for Release 10 4x2 multi-user MIMO (MU-MIMO) and cross-polar antennas as presented in [11].

Figure 6 compares the performance of DVB-T2 and LTE-A when sharing an 8 MHz channel as a function of the FEF interval length. It is worth noting that there are optimum configuration points. With a reduction of only two SDTV and one HDTV channels, LTE-A can gain almost 4 Mbps of capacity per cell, assuming 1 s of FEF interval length, which corresponds to the allocation of 20 % of time to LTE-A.

5. Conclusions

This article has proposed a new model for cooperation between cellular and broadcasting systems in which the cellular network can make use of broadcast spectrum using time multiplexing. This proposal can be accomplished thanks to the FEF concept defined in DVB-T2, which allows for this time multiplexing of other technologies, and the CA and NCT concepts defined in LTE-A, which allows aggregating multiple carriers to make an efficiently use of the fragmented spectrum.

In this paper, issues such as the use cases, DVB-T2 and LTE-A frame configuration, frequency bands and system bandwidths related to the cooperative spectrum access of LTE-Advanced using DVB-T2 FEFs have been discussed. The proposed solution requires some communication between the T2-Gateway and the LTE network to guarantee perfect synchronization and avoid simultaneous transmission on the same frequency. Finally, results have shown that the proposed cooperative spectrum sharing can make LTE-A cells gain almost 4 Mbps of capacity with a reduction of only two SDTV or one HDTV channels assuming that LTE-A occupies DVB-T2 channel 20 % of time.

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