LTE Uplink Extension in TV White Spaces

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***Abstract*—Dynamic Spectrum Access (DSA)/Cognitive Radio (CR) represents a promising and versatile concept to improve the efficiency of spectrum exploitation by allowing unlicensed users to opportunistically access underutilised licensed bands, provided that no harmful interference is caused to the legitimate (licensed) users of the spectrum. This revolutionary spectrum access paradigm can be exploited not only to deploy new radio systems and technologies in the already allocated spectrum, but also to increase the capacity of existing systems. A good example of this application is the extension of Long Term Evolution (LTE) cellular systems in TeleVision (TV) white spaces (i.e., TV channels not used in a certain region), which has received significant attention. Most of the existing studies, however, have focused on the extension of the LTE downlink component. By contrast, this work complements previous studies by considering the LTE uplink component in TV white spaces. By means of system-level simulations, this work analyses the conditions under which such coexistence is feasible and the underlying implications.**

I. INTRODUCTION

The Dynamic Spectrum Access (DSA) paradigm [1, 2], based on the Cognitive Radio (CR) concept [3, 4], has the potential to improve the spectrum use efficiency by permitting unlicensed (secondary) users to access, in an opportunistic and non-interfering manner, licensed spectrum bands during the inactivity periods of the licensed (primary) users. This revolutionary spectrum access approach, which has been motivated by the already demonstrated spectrum underutilisation (see [5] and references therein), allows the coexistence of several radio systems and technologies in the same portion of the spectrum, thus enabling a more efficient exploitation thereof.

The DSA/CR concept can be employed not only to deploy new radio systems and technologies in the already allocated spectrum, but also to increase the capacity of existing systems where the allocated spectrum is insufficient to satisfy the existing traffic demand. This situation is commonly observed in the spectrum bands allocated to cellular mobile communication systems, where the introduction of new high data-rate services during the last years has resulted in a severe congestion and overcrowding of the cellular bands [5]. As a matter of fact, the spectrum available for current mobile communication systems [6] is clearly insufficient according to predictions of the International Telecommunications Union (ITU) [7]. The offloading of traffic by means of opportunistic access to alternative bands has been considered as a means to solve this problem and increase the capacity of cellular mobile communication systems, which is particularly important for future mobile technologies such as Long Term Evolution (LTE). A candidate band that has received special attention for this purpose is the TeleVision (TV) band. First of all, not all the TV channels have always been used over the regulated geographical areas, thus leading to the existence of TV White Spaces (TVWS) (i.e., TV channels not used in a certain region). Moreover, as a result of the transition from the analogic to the digital television technology, which is more bandwidth-efficient, a significant amount of TV spectrum has been released for its use by other radio systems and technologies, which has lead to the existence of abundant TVWS. In addition to that, the relatively low frequencies of the TV bands make them attractive for radio communication systems. These observations highlight the convenience of reusing the free TVWS spectrum to solve the spectrum issues of LTE mobile communication systems.

The extension of LTE systems in TVWS has attracted the researchers' interest in the existing literature [8–13]. Most of the existing studies, however, have focused on the extension of the LTE downlink component, while little attention has been paid to the uplink component. While cellular mobile communication networks are subject to asymmetric traffic demands resulting in higher traffic loads in the downlink, the offloading of the uplink traffic constitutes an interesting strategy that can provide important benefits as well. First of all, TV bands operate at lower frequencies than traditional cellular bands. The path loss reduction due to a lower frequency of operation[1] results in an increased battery life for the mobile terminals and a coverage outage reduction since the uplink is more seriously power-limited than the downlink. The reuse of TVWS for uplink transmissions enables the LTE system to offload downlink traffic to part of the spectrum allocated to the uplink, thus leading not only to an increase in the overall system capacity (as it would be the case when directly offloading downlink traffic to TVWS) but also to an increased battery life and coverage extension. In this context, this work complements previous studies by analysing the extension of the LTE uplink component in TVWS. By means of system-level simulations, this work performs a detailed analysis on the conditions under which such coexistence is feasible as well as the underlying implications in terms of the protection of the primary TV system, the performance of the secondary LTE system, and the overall efficiency of spectrum utilisation.

The rest of this work is organised as follows. First, Section II describes the considered performance metrics. Section III then presents the simulation platform employed in this study.

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[1] The path loss reduction from the LTE band (2000 MHz) to the TV band (600 MHz) is around 18 dB according to the COST 231 Hata model and 10 dB according to the free space model (worst case).

The obtained simulation results are analysed and discussed in Section IV. Finally, Section V concludes the paper.

II. PERFORMANCE METRICS

Three main groups of performance metrics are considered, aimed at analysing and quantifying the protection of the primary TV system, the performance of the secondary LTE system, and the efficiency of spectrum utilisation.

The protection of the primary TV system can be analysed be means of the Carrier-to-Noise Ratio (CNR) and Desired-to-Undesired power Ratio (DUR), the latter following the same concept of the Carrier-to-Interference Ratio (CIR). While the CNR is independent of the secondary system and its interference, this parameter allows to determine the distance from the TV transmitter at which the minimum CNR is satisfied and thus the intended coverage area of the primary transmitter. Within this coverage area, the aggregated interference generated by the secondary system (quantified by means of the DUR) must be lower than the maximum tolerable level. Notice that an appropriate operation of the TV receivers requires not only a minimum CNR but also a minimum DUR to be met. As long as this protection criterion is met, the coexistence of the TV and LTE systems in the same spectrum is considered to be feasible.

The performance of the secondary LTE system is analysed mainly in terms of transmission rates such as the net data throughput (i.e., number of bits correctly transmitted per time unit). The employed simulation platform also provides other output metrics to quantify the performance of the secondary system in terms of error rates, such as the BLock Error Rate (BLER) and Bit-Error Rate (BER), and the experienced channel quality in terms of common metrics such as the Signal-to-Interference plus Noise Ratio (SINR) experienced by the users and the employed transmission powers. Although not presented here in detail due to the lack of sapce, all these metrics have been analysed as a part of the study.

The efficiency of spectrum utilisation is quantified based on two metrics, assuming that all the spectrum available in a TVWS is allocated and exploited by the LTE scheduler. The first metric is the *bandwidth utilisation*, defined as the quotient between the total data throughput in a sector/cell and the maximum achievable bit-rate at the highest modulation and coding rate. The main interest of this parameter lies in its ability to quantify the real efficiency of the spectrum utilisation in a single parameter by capturing the impact of many relevant aspects such as the overhead resulting from collisions, signalling messages, packet headers, back-off timer delays and any other network control data. The second metric quantifies the spectrum efficiency in terms of the classical concept of data rate per bandwidth unit (bit/s/Hz).

III. SIMULATION PLATFORM

The considered simulation scenario comprises a TV broadcast link as the primary system and a LTE cellular network as the secondary system (see Figure 1). As it can be appreciated in Figure 1, the TV station broadcasts a TV signal for the TV receivers (incumbent users) within a certain coverage area. However, this signal is also captured by the receivers of the LTE system (i.e., base stations or eNodeBs), thus leading to some interference levels on the cellular network. Similarly, the signal of LTE transmitters (mobile terminals) leads to some undesired interference over the primary/incumbent receivers. These interference interactions could be estimated by means of radio propagation models and their corresponding mathematical equations. However, while such type of study may be adequate for a downlink scenario, a simulation-based approach results more convenient in this case. In terms of interference interactions, computing the effective aggregated interference generated by a reduced number of static base stations could be relatively simple based on radio propagation equations while it would result more complicated for a high number of randomly deployed mobile terminals. Moreover, system-level simulations allow for a simple analysis of other aspects such as the performance of the secondary LTE system and the efficiency of spectrum utilisation, which could not be easily explored by means of analytical studies. Therefore, this study relies on the use of a sophisticated LTE simulation platform, which has been developed at the Centre for Communication Systems Research (CCSR) of the University of Surrey.

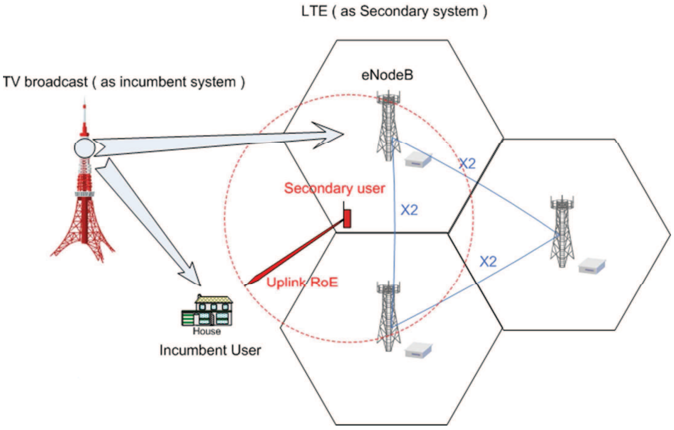

Fig. 1. Considered simulation scenario.

The simulated scenario is composed of a complete LTE cellular network where a primary TV transmitter is present at a certain distance from the geometrical centre of the cellular network. The simulation platform is divided into three modules: a) a main module integrating general aspects such as the cell deployment, mobility and traffic models, path loss models, shadow (slow) fading models, multipath (fast) fading models, antenna radiation patterns, etc.; b) a downlink module integrating aspects related to the downlink of the LTE system (scheduler, link adaptation, handover and other radio resource management methods for the downlink); and c) an uplink module integrating the same aspects for the uplink.

Table I summarises the main simulation parameters. The platform considers an LTE cellular system composed of 19 trisectorial cells arranged in 2 tiers. Three different load levels (low, medium and high) as a function of the amount of

TABLE I
CONFIGURATION OF THE SIMULATION PLATFORM

Parameter	Value	Unit
Common parameters		
Carrier frequency	600	MHz
LTE bandwidth	1.4 / 5 / 20	MHz
Cellular layout		
No. of eNodeB	19	–
No. of sectors per eNodeB	3	–
No. of eNodeB rings/tiers	2	–
Inter-eNodeB distance	500	m
User speed	5	km/h
No. of users per sector	See Table II	–
LTE mobile terminal parameters		
Antenna height	1.5	m
Antenna gain	0	dB
Max. transmission power	24	dBm
Modulation	QPSK and 16-QAM	–
LTE eNodeB parameters		
Antenna height	30	m
Antenna gain	14	dB
Noise figure	5	dB
BLER target	0.1	–
TV transmitter parameters		
Antenna height	100	m
Antenna gain	10	dB
Transmission power	1000	W
TV receiver parameters		
Antenna height	10	m
Antenna gain	7	dB
Noise figure	7	dB
Required CNR	21	dB
Required DUR	21	dB
Pathloss models		
TV TX to TV RX (signal)	Hata COST 231 macrocell	–
TV TX to eNodeB (interf.)	Egli	–
User to eNodeB (signal)	Hata COST 231 macrocell	–
User to TV RX (interf.)	Hata COST 231 microcell	–
Shadow (slow) fading		
Fading type	Space-correlated maps [14, 15]	–
Map resolution	5 meters/pixel	–
Mean	0	dB
Standard deviation	5.5	dB
Inter-site fading correlation	0.5	–
Multipath (fast) fading		
Power Delay Profile (PDP)	Pedestrian	–
Trace length	3	s

TABLE II
SIMULATED LOAD LEVELS

		No. of users per sector		
LTE BW	**No. of RBs**	**Low load**	**Medium load**	**High load**
1.4 MHz	6	1	3	6
5 MHz	25	5	12	25
20 MHz	100	20	50	100

available resources, in terms of Resource Blocks (RBs), are considered (see Table II). The minimum CNR required for a proper operation of TV receivers is set at 21 dB as indicated in Table 1 of [16] for fixed receivers. Several organisations [17–19] have provided requirements for the DUR and its details. In spite of different standards, the requirement is quite similar for the different broadcast formats, which is generally the same as the required minimum CNR, on the assumption that the interferer has a noise-like characteristic. Following this assumption, the DUR is set equal to the CNR. For path loss calculations, several empirical radio propagation models can be applied depending on the propagation environment. Examples of such models are the Okumura-Hata model [20, 21] and the COST 231 extensions [22], the ITU-R P.1546 model [23] and the flat-terrain model. The path loss models employed in this study have been selected based on their range of applicability in terms of the environment, frequency range and distance. As shown in Table I, the Hata COST 231 models are employed in most of the rays between transmitters and receivers. These models were envisaged for cellular mobile communication systems but are still valid in terms of operating frequency and distance for the TV signals. However, for the interference computation from the TV transmitter to the secondary receivers (i.e., eNodeBs), the distances observed in practice were higher than 20 km, beyond which the Hata COST 231 model is not applicable. In such a case, a simple but optimistic alternative would be to make use of the free space model. A more accurate but complex alternative would be the ITU-R P.1546 model [23]. In this study, the Egli model [24] has been employed, which constitutes an intermediate alternative between both extreme points in terms of complexity and accuracy. Typically used for outdoor line-of-sight point-to-point links, this terrain model provides the path loss as a function of the transmitter and receiver heights, distance and frequency. The model does not account for travel through some vegetative obstruction or other factors accounted for by the ITU-R P.1546 model, thus providing a presumably less accurate estimation of the path loss. However, the model was derived from real-world data on UHF and VHF TV transmissions in several large cities and is applicable to scenarios where the transmission has to go over an irregular terrain, thus providing a much more accurate estimation than the free space model. Besides path loss models, shadow (slow) fading and multi-path (fast) fading models are considered as well (see Table I). Shadow fading is modelled as a log-normal process with 0-dB mean and 5.5-dB standard deviation [23]. Fast fading is assumed to be constant during one Transmission Time Interval (TTI), but independent between consecutive TTIs. A pre-recorded fast fading trace of 3 seconds (3000 TTIs) is employed and repeated periodically for longer simulations.

IV. SIMULATION RESULTS

This section presents and analyses the obtained results, based on the three main aspects discussed in Section II.

A. *Protection of the primary TV system*

Table III shows the minimum distance required between the LTE mobile users and the border of the TV coverage area (determined by the required CNR) in order to guarantee an adequate protection of the primary TV receivers in terms of the minimum required DUR. The results are shown as a function of the LTE BandWidth (BW) and supported load.

As observed in Table III, the minimum separation distance required between the TV and LTE systems depends on the supported load and the amount of TVWS (bandwidth) reused. In particular, the required distance increases with the supported load and the selected bandwidth. This can be explained by the fact that a higher number of users results in a higher aggregated interference level at the primary TV receivers. Therefore, as the load increases, the LTE system needs to operate further away from the TV system in order to keep the aggregated interference below the maximum tolerable level and meet the required minimum DUR. As a wider block of TV spectrum is reused, a higher amount of radio resources is available to the LTE system and therefore a higher maximum number of users can be supported, which requires a larger operation distance of the LTE users to meet the DUR limit.

Note that the minimum required distance between the TV and LTE systems is determined by the maximum tolerable aggregated interference (minimum DUR), which depends on the actual number of supported users rather than the operation bandwidth itself. In fact, an LTE bandwidth of 5 MHz (20 MHz) at low loads results in a similar protection distance as an LTE bandwidth of 1.4 MHz (5 MHz) at high loads (respectively), since in both cases the number of UEs is similar (see Table II). As a result, the volume of LTE uplink traffic that can be offloaded to TVWS, and also the amount of bandwidth (TVWS) that can be reused by the LTE system, depend on the distance to the edge of the TV coverage area. This means that an LTE system would need to be aware of the location of the different TV transmitters and, based on this information, determine which users can access the TVWS depending on their distances to the edge of the coverage areas and their resulting aggregated interference.

While the previous appreciation may apparently seem to be intuitive, there is, however, an important aspect that needs to be carefully taken into account when offloading LTE uplink traffic to TVWS, which is specific to the uplink component. The actual DUR boundary (i.e., the distance at which the minimum DUR is guaranteed) is not constant but shows certain variation around an average value, within certain maximum and minimum values, thus leading to the existence of a *DUR strip*. The existence of such DUR strip is mainly the result of the mobility of the users but it also depends on several radio resource management aspects such as the user admission criterion and the scheduling sequence (i.e., how many and which users are allowed to transmit at every time instant), the power control method (i.e., the interference power from every active user), etc. Since all these aspects determine the exact location of the DUR boundary and they vary with time, the DUR boundary varies with time as well. The behaviour of the DUR boundary can be characterised in a simple way by means of the minimum and maximum values within which it is confined. Figure 2 shows the width of the DUR strip as a function of the distance between the TV and LTE systems for an LTE bandwidth of 1.4 MHz (similar trends were observed for other bandwidths). As it can be observed, the width of the DUR strip increases as the separation between the systems increases and is higher for low loads. This is therefore an important aspect to be accounted for when offloading LTE uplink traffic to TVWS, since it may play an important role in determining which TVWS can actually be used by the LTE system and how much uplink traffic can be offloaded.

TABLE III
PROTECTION DISTANCES FROM THE BORDER OF THE TV COVERAGE AREA

		Load		
		Low	**Medium**	**High**
LTE BW	**1.4 MHz**	9.82 km	14.82 km	19.83 km
	5 MHz	19.83 km	22.41 km	24.82 km
	20 MHz	24.81 km	29.81 km	34.79 km

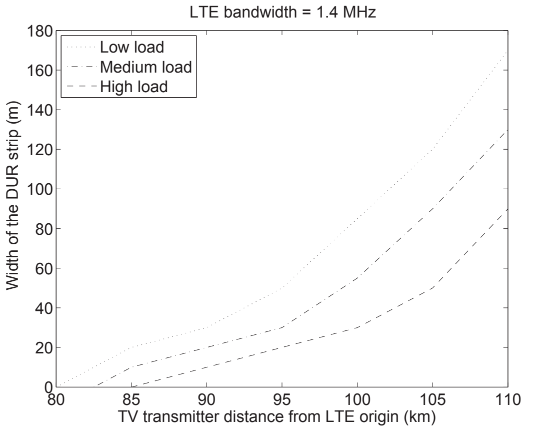

Fig. 2. Width of the DUR strip for an LTE bandwidth of 1.4 MHz.

These results indicate that the benefits of offloading uplink traffic instead of downlink traffic to TVWS (i.e., longer battery life and improved coverage) come at the expense of more complicated procedures and algorithms in the LTE system in order to guarantee the protection of the primary TV system, as a result of the mobility of the transmitters in the uplink.

B. *Performance of the secondary LTE system*

1) Impact of the distance between the TV and LTE systems: While the protection of the TV system is highly dependent on the TV-LTE distance, the performance of the LTE system, however, is observed to be rather unaffected by the distance between both systems. This is illustrated in Figures 3 and 4 in terms of the user and sector throughputs (i.e., the average throughput experienced per user and the average throughput aggregated over all the users within the same sector, respectively). The results are shown for an LTE bandwidth of 20 MHz (similar trends were observed for other LTE bandwidths).

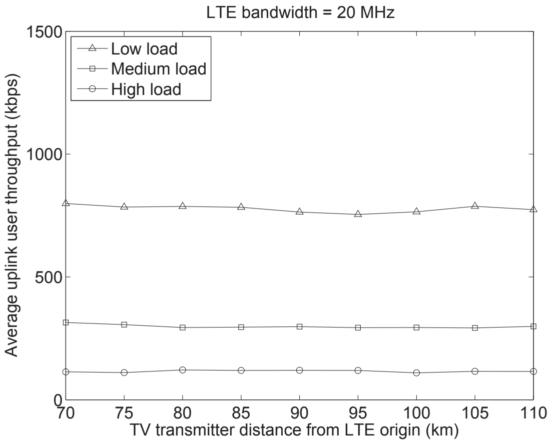

Fig. 3. Average uplink user throughput for an LTE bandwidth of 20 MHz.

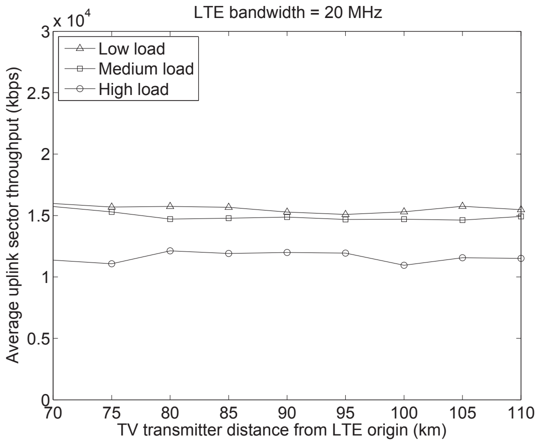

Fig. 4. Average uplink sector throughput for an LTE bandwidth of 20 MHz.

As it can be appreciated, the LTE system performance is not noticeably affected by the operation distance with respect to the TV system. This can be explained by the fact that the protection of the primary system requires a minimum separation distance that results in low interference levels from the TV system, thus leading to similar performance results at various TV-LTE distances. As it can be noted in Figure 1, the most relevant interference from the LTE system to the TV system occurs from LTE users close to the border of the LTE coverage area to TV receivers close to the border of the TV coverage area. Therefore, the LTE-to-TV interference occurs at the minimum separation distance between both systems, which explains the high impact of such distance on the protection of the primary system. On the other hand, the interference from the TV system to the LTE system occurs from the TV transmitter, which is far from the border of the TV coverage area, to the LTE receivers (i.e., the eNodeBs), which are far from the LTE cell border as well. Therefore, the TV-to-LTE interference occurs at much larger distances than the LTE-to-TV interference, which explains the negligible impact of such distance on the observed LTE performance.

This is an important observation since it implies that the design and operation of the LTE system and its associated radio resource management algorithms and methods do not need to change when switching from cellular bands to TVWS, since the experienced quality of service and performance of the LTE users should not be degraded (as a result of the interference from the TV system) when switching between both bands. Therefore, under typical operation parameters, the protection of the primary system should also result in the protection of the performance of the LTE users.

2) Impact of the selected bandwidth and supported load: While the operation distance between the TV and LTE system cannot be considered as a crucial aspect in the uplink LTE performance, the selected bandwidth and supported load have a more relevant impact as illustrated in Tables IV and V. The obtained results can be explained as follows. For a constant operation bandwidth, higher loads result in a lower amount of available resources per user and therefore in a lower user throughput as expected. While in principle the overall sector throughput should remain constant for different load levels, in practice higher loads also result in lower sector throughputs since the higher number of users leads to higher levels of interference in the system. In any case, the supported load level has a higher impact on the user throughput than in the sector throughput. On the other hand, increasing the selected bandwidth means increasing the amount of available resources for the LTE system and therefore in an appreciable increase of the overall sector throughput and the overall uplink capacity. For a similar ratio of users per available bandwidth (i.e., load level), the user throughput should be similar for different bandwidths. However, higher operation bandwidths lead to a higher number of supported users thus leading to higher interference levels in the system, which explains the user throughput degradation as the selected bandwidth increases. In summary, Tables IV and V provide an indication on how the LTE system performance can be expected to vary depending on the amount of TVWS reused and uplink traffic offloaded.

TABLE IV
AVERAGE LTE UPLINK USER THROUGHPUT

		Load		
		Low	**Medium**	**High**
LTE BW	**1.4 MHz**	941.67 kbps	318.74 kbps	132.32 kbps
	5 MHz	781.79 kbps	312.86 kbps	121.76 kbps
	20 MHz	777.68 kbps	298.44 kbps	116.02 kbps

TABLE V
AVERAGE LTE UPLINK SECTOR THROUGHPUT

		Load		
		Low	**Medium**	**High**
LTE BW	**1.4 MHz**	0.97 Mbps	0.94 Mbps	0.79 Mbps
	5 MHz	3.91 Mbps	3.82 Mbps	3.04 Mbps
	20 MHz	15.5 Mbps	14.92 Mbps	11.60 Mbps

C. *Efficiency of spectrum utilisation*

Tables VI and VII show the results obtained for the *bandwidth utilisation* and *spectral efficiency* parameters defined in Section II. Similarly to the LTE system performance analysed in Section IV-B, the efficiency of spectrum utilisation does not show a relevant difference for the considered operation distance between the TV and LTE systems, but shows certain variations depending on the operation bandwidth and supported user load. In general, it is observed that when the number of simultaneous users increases (i.e., for higher loads and/or operation bandwidths) the overall efficiency decreases, for both metrics, as a result of the resulting increased interference levels. Notice that the convenient choice in terms of spectral efficiency would be the selection of narrower operation bandwidths. However, this would not be a feasible alternative when the LTE traffic demands require large bandwidths.

TABLE VI
EFFICIENCY OF SPECTRUM UTILISATION (BANDWIDTH UTILISATION)

		Load		
		Low	**Medium**	**High**
LTE BW	**1.4 MHz**	0.87	0.85	0.77
	5 MHz	0.86	0.84	0.76
	20 MHz	0.78	0.77	0.69

TABLE VII
EFFICIENCY OF SPECTRUM UTILISATION (SPECTRAL EFFICIENCY)

		Load		
		Low	**Medium**	**High**
LTE BW	**1.4 MHz**	0.78 bit/s/Hz	0.76 bit/s/Hz	0.61 bit/s/Hz
	5 MHz	0.77 bit/s/Hz	0.75 bit/s/Hz	0.58 bit/s/Hz
	20 MHz	0.69 bit/s/Hz	0.67 bit/s/Hz	0.57 bit/s/Hz

V. CONCLUSIONS

The extension of LTE in TVWS, based on the DSA/CR paradigm, represents a convenient option to solve the problem of spectrum shortage faced by the future LTE systems and increase their effective capacity. Most of the existing studies, however, have focused on the extension of the LTE downlink component, while the extension of the uplink component, which can provide important benefits such as longer battery life and extended coverage, has received less attention. This work has explored the extension of the LTE uplink component in TVWS. By means of system-level simulations, this work has analysed this coexistence scenario and the underlying implications in terms of the protection of the primary TV system, the performance of the secondary LTE system, and the efficiency of spectrum utilisation. Several conclusions, with practical implications, have been derived in this study.

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