TV White Spaces as part of the future Spectrum Landscape for Wireless Communications

Protection techniques of the incumbent service and implementations

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Abstract—The evolution of future wireless communication systems imposes a strong requirement on the efficiency of spectrum usage, which is expected to be leveraged by interacting and cooperating cognitive radio systems (CRS). It is very difficult to find unused radio spectrum resources to allocate future wireless communication systems. However, sharing the same spectrum allocations for specific purposes can be achieved to release additional spectrum resources. As a result of the transition from analogue to digital TV transmission in UHF frequency band, certain parts of the spectrum are no longer used for TV transmission. In Europe for example, the 790 to 862 MHz sub-band has been reserved for mobile services. Moreover, bands used for TV transmissions are geographically interleaved to avoid causing interference to co-channel or adjacent channel digital TV transmitters - forming the so called TV white spaces (TVWS). These frequencies are available in the 470 to 790 MHz for a wireless communication application at a given time in a geographical area on a non-interfering/non-protected basis with regard to incumbent services and other services with higher priority. This article presents the protection techniques of the incumbent service and implementations and new use cases in TVWS are introduced.

I. INTRODUCTION

The popularity of wireless devices such as smartphones, dongles and tablets as well as other connected devices such as video games, embedded appliances, sensors and Machine-to-Machine (M2M) has extraordinarily increased as they have become more affordable. Several reports [1][2][3] predict tremendous worldwide growth in the market size of mobile broadband services. According to the report [1], the growth ranges from 1 billion users in 2012 up to 2.5 billion in 2015 or from 3 billion users in 2012 up to 8 billion in 2015 assuming a conservative or an aggressive growth scenario, respectively. In this regard, the launch of mobile data and value-added services brings considerable benefits to consumers, enterprises as well as governments.

On the other hand, radio spectrum is a limited resource. If different users can share the same spectrum resources for their specific purposes, we can take advantage of wireless innovation to achieve additional spectrum capacity [4]. White Spaces provide an opportunity for the spectrum resources sharing with the incumbent service using the cognitive radio systems (CRS) technology. Recently, the operational requirement for CRS in TV White Spaces (TVWS) in order to ensure the protection of the incumbent service is being discussed in European Conference of Postal and Telecommunications Administrations (CEPT). The protection of the incumbent service is very important to share the same spectrum resources in White Spaces. There are some cognitive techniques such as sensing, geo-location database (GLDB), beacon, etc., in order to ensure the protection of the incumbent service [5].

This article introduces the recent White Spaces activities in the regulatory framework and standardisation. The next section presents the incumbent protection techniques using advanced geo-location engine approach and out-of-band emission suppression with advanced pre-coding. The following section gives the use cases and key applications of TVWS. The final section concludes the article.

II. REGULATORY FRAMEWORK AND STANDARDISATION ACTIVITIES FOR TVWS

A. Regulatory framework in US


FCC defines two types of “unlicensed TV band devices”: fixed devices and personal/portable devices. There are three modes in Personal/Portable device, Mode1 (Client), Mode2 (Independent), and Sensing-only. EIRP of devices depend on types and modes. Fixed and Mode2 devices require accessing GLDB for operation in TVWS. Sensing-only devices with FCC certification are allowed to operate in TVWS as well.

B. Regulatory framework in Europe

European Commission (EC) issued a mandate to CEPT on technical considerations regarding harmonisation options for the digital dividend [10] in 2007. CEPT studied the possibility of harmonising a sub-band for fixed/mobile communication applications and the practicability of implementation of new/future applications within the white space spectrum in the
band 470 – 862 MHz and the reports [11][12][13] were prepared in response to the EC mandate.

CEPT SE43 started to study the requirements within the European environment for the use of cognitive techniques for the protection of the incumbent service. As the result of this study [5], the use of a GLDB to avoid possible interference to Digital Terrestrial Television (DTT) receivers appears to be the most feasible option in TVWS. EIRP of devices is determined by the location specific, and the master device requires accessing a GLDB for operation in TVWS. Sensing-only devices are prohibited to operate in TVWS.

C. Standardisation Activities

1) The Institute of Electrical and Electronics Engineers, Inc. (IEEE)

IEEE 802 Standards Committee has several TVWS activities. IEEE 802.22 [14] standard specifies the air interface, including the medium access control (MAC) layer and physical (PHY) layer, of the fixed and portable point-to-multipoint wireless regional area networks (WRAN) operating in spectrum allocated to the Television Broadcasting Service in the frequency range 54 MHz to 862 MHz. IEEE 802.11af Error! Reference source not found. is developing IEEE 802.11 wireless local area networks (WLAN) standards amendment for operation in TVWS. IEEE 802.15.4m Error! Reference source not found. is developing IEEE 802.15.4 low-rate wireless personal area networks (WPAN) standards amendment for operation in TVWS. IEEE 802.19.1 [17] is developing TVWS network coexistence system.

IEEE DySPAN Standards Committee [18] (former SCC41) has some white spaces activities. IEEE 1900.4a [19] standard specifies architecture and interfaces for dynamic spectrum access networks in white space frequency bands amendment to architectural building blocks enabling network-device distributed decision making for optimized radio resource usage in heterogeneous wireless access networks. IEEE 1900.7 is developing for radio interface for white space dynamic spectrum access radio systems supporting fixed and mobile operation.

2) Ecma International (ECMA)

Standard ECMA-392 [20] specifies a MAC sub-layer and a PHY layer for personal/portable cognitive wireless networks operating in TV bands. This Standard also specifies a MUX sub-layer for higher layer protocols and a number of incumbent protection mechanisms which may be used to meet regulatory requirements, which themselves are outside of the scope of this standard. Conforming devices implement the MUX sub-layer, MAC sub-layer and the PHY layer as specified herein and support at least one of the device types (master, peer, or slave) and at least one of bandwidths (6 MHz, 7 MHz, 8 MHz), and may support multiple antenna modes.

3) European Telecommunications Standards Institute (ETSI)

ETSI Technical Committee (TC) Reconfigurable Radio Systems (RRS) is responsible for standardisation activities related to Reconfigurable Radio Systems encompassing system solutions related to Software Defined Radio (SDR) and Cognitive Radio (CR). TC RRS has several work items related to white space activities. The technical report of use cases for operation in white space [21] was issued in October 2011. TC RRS is developing two technical reports [22][23] and two technical standards for the system requirements for operation in TVWS [24] and coexistence architecture for cognitive radio networks in TVWS [25].

ETSI TC Broadband Radio Access Networks (BRAN) is developing a candidate harmonised standard for wireless access systems in the TV broadcast White Spaces Devices (WSD) [26].

III. INCUMBENT PROTECTION TECHNIQUES AND IMPLEMENTATIONS

A. Advanced geo-location engine

The basic calculation method for location specific maximum EIRP level of WSD in GLDB operation, where master-slave WSD network operation is assumed, is shown in ECC Report 159 [5]. In draft ECC Report 186 [27], a calculation method to account for interference aggregation from multiple WSDs has also been addressed. Therefore CEPT SE43 has considered determining the Interference Margin (IM) value as follows:

a) Fixed/Predetermined IM value setting based on the potential maximum number of interferes in each operational frequency in a given area at the same time.

b) Flexible IM value setting based on the maximum number of active/actual interferes in each operational frequency in a given area at the same time.

c) Minimized IM value setting based on the intrinsic feature of each active interferer in each operational frequency of master WSD in a given area at the same time.
There will be several possible deployment scenarios for the IM calculation engine of location specific output power level allowing for the number of active master WSDs. For example, the calculation engine may be a part of GLDB controlled by National Regulatory Authority (NRA), or a separate engine (namely advanced geo-location/IM-calculation engine) from the GLDB managed by NRA as shown in Figure 1. In a case where it is a separate engine, a third party should take a responsibility to protect the incumbent service receivers from an aggregated interference problems, and the operation should be kept under surveillance by NRA. The merit will be to enable the processing load of the GLDB managed by NRA to offload to the third party engine. Such third party engines may also provide other services, such as coexistence services which will be standardized in specifications such as ETSI TS 102 908 [25] or IEEE 802.19.1 [17] to the WSDs operating in the same area.

The results have shown that the consideration of the number of active master WSDs of each available channel in the IM calculation engine will bring us the highest communication opportunity of master WSDs, according to the performance differences among fixed, flexible and minimized IM calculation methods. In addition, the minimized IM calculation method can show the highest performance in three methods, because there will be some redundancy in calculating output power level of master WSDs in cases where the fixed and flexible margin based IM calculation methods are adopted. This may be due to the fact that the fixed and flexible margin based calculation methods cannot differentiate between the path loss conditions of a target master WSD from one of the other potential interferers in calculating output power level of a target master WSD.

Table 1. Comparison of different calculation methods

<table>
<thead>
<tr>
<th>Method</th>
<th>WSD network capacity</th>
<th>System overhead</th>
<th>Calculation overhead</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed IM</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Flexible IM</td>
<td>Moderate</td>
<td>High</td>
<td>Moderate</td>
</tr>
<tr>
<td>Minimized IM</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>

Table 1 shows the comparison of different calculation methods from the viewpoints of the master WSD network capacity, the system overhead and the calculation overhead. One can see that the system overhead will increase due to the consideration of the number of active master WSDs in each available channel, because the number of interaction between the IM calculation engine and its connected master WSDs will be significantly increased due to the consideration of new-entry/deactivation of master WSD(s) in actual network operation. Subsequently, the calculation overhead in the calculation engine will be much higher than a case where fixed margin based calculation method is adopted. However, the calculation engine will have much higher computation power via many core processors configuration. Therefore there may be a small impact in comparison on the increase of the system overhead via the proposed method.

B. Interference monitoring integrated with advanced geo-location engine

Several GLDB deployments are foreseen by regulators and ETSI [22] for incumbent user protection. One of them can be set-up with an advanced incumbent protection technique. Interference monitoring technique, among others, can be categorised as part of the advanced function of the GLDB and will be combined with spectrum sensing. The spectrum sensing basically detects incumbent signals to determine if incumbent transmitters are operating around WSD. On the other hand, GLDB approach can utilize the incumbent system information. It estimates interference level from WSD to incumbent receivers by using propagation model [5]. However, propagation models inevitably include estimation error of path loss in actual radio environments, which results in estimation error of carrier to interference ratio (CIR) of the incumbent receivers. Due to this error, considerable margin in allowable transmit power has to be set for incumbent protection. To improve the accuracy of CIR estimation, interference monitoring is applied to reduce the margin [28]. It enables estimating CIR by combining measurements around the incumbent receiver and propagation estimation.

The concept of interference monitoring is shown in figure 2. The advanced geo-location engine calculates the allowable transmit power of WSD based on the propagation estimation and provides the information to the WSD. The power is limited by including both the margin for propagation estimation error and that for multiple interferences so that CIR of the incumbent Rx can be kept at the required level. When the WSD starts transmission at power not exceeding the provided one, the interference monitoring is performed as follows: both the interference power from the WSD and the incumbent signal power are actually measured at spectrum sensors which are located near the incumbent receiver at the edge of incumbent service area. Using the measurement results, the CIR of the incumbent receiver estimated by the propagation model is compensated. In this way, the actual measurements are effectively used to improve the CIR estimation accuracy. Thus the advanced geo-location engine can utilize the resultant CIR estimate to reduce margin in the allowable transmit power. The advanced geo-location engine recalculates allowable transmit
power and notify it to WSD. Thus interference monitoring can protect the incumbent system from harmful interference while expanding white space opportunities.

C. Incumbent protection by Out-of-band emission suppression

To minimize any interference to the incumbent TV transmission on adjacent channels and channels beyond the adjacent channel, the FCC rules [8] provide limits on out-of-band (OOB) emissions which impact the spectral mask of TV band devices (TVBDs). Table 2 shows the FCC limits on 1st adjacent channel. The UK Office of Communications (Ofcom) is considering to use FCC rules to define the limitation on OOB emissions of TVBDs. The strict OOB emission requirement is challenging the traditional emission suppression technique. On the other hand, an advanced OOB emission suppression technique could make potential more TVWS availability.

![Table 2. FCC limit on 1st adjacent channel](image)

New conceptual approaches for OOB emission suppression have recently been described in [22][29][30]. In particular, several ways to apply linear pre-coding prior to the OFDM FFT-modulation have been proposed in [22]. Traditionally, multi-carrier systems control their OOB emissions as illustrated in the top of Figure 3. A low-pass filter is applied right after the base-band OFDM modulator. The bottom of Figure 3 presents the advanced linear pre-coding technique.

![Figure 3. Traditional, post-FFT, low-pass filtering (top) and advanced pre-coding (bottom)](image)

One class of spectral pre-coders in the literature, projection pre-coders, relevant for the TVBD systems is described briefly here. More details can be found in [22]. The projection pre-coders are linear operations represented by \( \mathbf{d} = \mathbf{G}_p \mathbf{d} \), where \( \mathbf{d} \) is the column vector of \( K \) data symbols, \( \mathbf{d} \) is the column vector of \( K \) pre-coded data symbols, and \( \mathbf{G}_p \) is the \( K \times K \) pre-coder matrix. Instead of feeding the transmitter FFT with the modulation symbols \( \mathbf{d} \), it is fed the pre-coded symbols \( \mathbf{d} \). The key characteristic of projection pre-coders in this class is that the precoder the matrix \( \mathbf{G}_p \) is a projection matrix that orthogonally projects the vector \( \mathbf{d} \) onto a linear subspace defined by a \( M \times K \) matrix \( \mathbf{A} \) in which all vectors have the same spectrum with suppressed out-of-band emission. The matrix \( \mathbf{A} \) represents a set of \( M \) linear requirements on the transmitted symbols vector \( \mathbf{d} \) that uniquely specifies the spectrum characteristics. According to above pre-coding process, the OOB emission at TVBD transmitter will be suppressed largely. Figure 4 illustrates the OOB emission suppression results by pre-coding technique when considering both linear and non-linear PA applied in the evaluation. The suppression is more than 70 dB in any of the protected TV channels.

![Figure 4. OOB emission suppression by pre-coding technique](image)

The main advantages of the pre-coding over the traditional means (filtering and/or windowing) are:

1. Flexibility: Traditional out-of-band power reduction techniques (filtering) are not suitable. Filters would be designed as notching filters and changing these filters in an agile manner may be difficult. It appears that the swift and transient-free adaptation of a pre-coder can be implemented much more convenient.

2. Spectral suppression performance: For secondary transmitters that exhibit high degree of frequency-isolation (low OOB emission) more white space will be available. It is therefore in the immediate interest of the secondary to assure low out-of-band power emissions. The extent to which the pre-coder reduces the out-of-band emission is likely to be better than that of their traditional filtering/windowing counterparts.

3. Performance in dispersive channels: Performance in dispersive channels improves. While a low-pass filter inevitably increases the channel delay spread as it is perceived by the receiver (the receiver cannot distinguish between dispersion caused by the radio channel and that caused by the transmitter), a pre-coder does not. Hence, a system with a pre-coder can handle larger channel delay spreads.

The main challenges of the pre-coding over the traditional means (filtering and/or windowing) are:
1. From Figure 4, it can be seen that the non-linear RF components will discount the OOB emission suppression effect brought by the pre-coding technique.

2. In many contemporary standards the particular way to satisfy spectral requirements is not specified – means of power reduction are left to the vendor to design, and are only subject to a maximum error vector magnitude (EVM) budget. If standardizing the pre-coding technique, EVM is freed for other transmitter operations. If not, how can good pre-coders be designed within the limits of this budget.

IV. KEY APPLICATIONS OF TVWS

The use of TVWS opens up new opportunities for both existing Mobile Network Operators (MNOs), and new entrants. Several interesting use cases, like Wi-Fi/Cellular access augmentation and M2M communications can benefit from the use of TVWS.

A. Wi-Fi access augmentation

A key use case for TVWS is Wi-Fi Access augmentation. Wi-Fi currently operates in the unlicensed bands 2.4 and 5.0 GHz. Enabling Wi-Fi operation in TVWS can benefit residential, enterprise, hotspot, and metropolitan deployments in many ways:

   a) Increased capacity: Wi-Fi bands are often congested, particularly in high traffic public areas. Using shared spectrum increases the number of available frequency channels, contributing to user and network capacity.

   b) Increased reliability and robustness through channel management and aggregation: Unlicensed bands are typically harsh environments with various devices contending for a limited number of channels. The ability to select from more channels, assess channel quality, and choose the best among available alternatives is a clear advantage. Moreover, the ability to aggregate and switch between non-contiguous channels provides another measure of flexibility for finding and utilizing the maximum amount of available spectrum, avoiding interference, and co-existing with other users.

   c) Longer range operation and improved indoor penetration: Using TVWS bands can increase range by up to 3x compared to operation in the ISM bands, with less attenuation from walls and other building materials, better propagation around obstructions, and greater tolerance of non-line of sight conditions. These features are desirable for metropolitan and indoor-to-outdoor deployments, and are of particular interest to fixed/non-cellular operators, cable providers and new entrants.

B. Cellular access augmentation

Using TVWS as offload or capacity relief is a very interesting use case for established operators that may already be using, or considering the use of, unlicensed bands for Wi-Fi offload. Adapting LTE to operate in shared spectrum can be very beneficial as LTE is already a more efficient and reliable technology than Wi-Fi, and intrinsically supports non-contiguous carrier aggregation. Established operators can leverage existing infrastructure to integrate and aggregate TVWS with currently licensed LTE spectrum.

This use case also aligns with the current trend towards deployment of small cells (femto, pico, relay, etc.), where LTE in TVWS can be the small cell air interface technology. The access link and/or the wireless backhaul link can use the spectrum resources available in TVWS. This can alleviate the concern about small cells needing some portion of an operator’s licensed spectrum, or small cells operating in the same licensed spectrum as the macro overlay where the resulting interference can reduce the potential network capacity improvements.

Another example is the provision of Multimedia Broadcast Multicast Service (MBMS) in LTE/LTE-A systems. Currently MBMS shares the same spectrum with the unicast services in a MBMS Single Frequency Network (MBSFN) area consisting of a group of eNBs, thus the establishment of the MBMS may be refused if there are not sufficient radio resources in one of the eNBs in the MBSFN area. If the MBMS can be provisioned on the TVWS spectrum band, this provides great flexibility to coordinate the MBMS and unicast transmission for various services to users.

C. M2M communications

The use of TVWS for M2M communications seems to be a natural fit, given the anticipated explosion of M2M devices. Some devices will require low latency and guaranteed connectivity, but many will be non-real time and compatible with opportunistic access protocols. Using shared spectrum, along with the channel management, can provide the robust and reliable radio connections required by M2M systems without tapping capacity from already congested licensed bands.

V. CONCLUSIONS

To foster the development of wireless communication, it is necessary to continuously improve the opportunities for harmonised spectrum access in both licence-exempt bands and licensed spectrum and to establish new tools for more shared use of the available radio spectrum resources in a regulatory framework. There are some cognitive techniques to access the shared spectrum resources and to protect the incumbent service. A suitable cognitive technique in TVWS for the protection of the broadcasting service is GLDB. If harmonised spectrum access such as Licensed Shared Access is extended to other frequency bands, NRA may provide the protection requirements and methods for the incumbent service and information on issues and requirements that need to be addressed when setting up a GLDB and/or the management of independent database providers with third party engines. Additionally, NRA may provide a master set of the overall requirements for communication and interaction between a WSD and GLDB. Harmonised standards for GLDB will be needed to enable the development of WSDs based on regulatory requirements for the next step in standardisation.
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