Protection of Incumbent Services and Its Impact on Coverage of TV Band Device Networks in TV White Space

Kyu-Min Kang, Jae Cheol Park, Sang-In Cho, and Seungkeun Park

This paper presents a set of candidate regulatory requirements for TV band devices (TVBDs) in the Rep. of Korea. To guarantee the protection of incumbent services, especially digital TV (DTV) and wireless microphones, in TV frequency bands, we suggest minimum separation distances of TVBDs from the noise-limited contour according to incumbent users and TVBD types. This paper also deals with multiple sets of separation distances of a co-channel TVBD network from a DTV protected contour on the basis of the radio propagation characteristics of different geographic areas to make good use of TV white space (TVWS) and safely protect the DTV service. We present a low-power transmission mode of TVBDs and the relevant separation distances for small-cell deployment. The service coverage reduction ratio of a TVBD network is investigated in the presence of DTV interference in four geographic areas. The TVWS field verification results, conducted on the island of Jeju (Rep. of Korea), show that incumbent services operate well without harmful interference from neighboring TVBDs with the proposed separation distances.

Keywords: TV white space, TV band device, separation distance, digital TV, service coverage.

Manuscript received Nov. 11, 2014; revised Oct. 22, 2015; accepted Nov. 11, 2015.

This work was supported by Institute for Information & communications Technology Promotion (IITP) grant funded by the Korea government (MSIP) (No. B0101-15-222, Development of core technologies to improve spectral efficiency for mobile big-bang).

Kyu-Min Kang (corresponding author, kmkang@etri.re.kr), Jae Cheol Park (jchpark@etri.re.kr), Sang-In Cho (sicho@etri.re.kr), and Seungkeun Park (seungkp@etri.re.kr) are with the Broadcasting & Telecommunications Media Research Laboratory, ETRI, Daejeon, Rep. of Korea.

I. Introduction

As the use of mobile and Wi-Fi devices becomes an important part of our everyday lives, the demand for mobile broadband and wireless data capacity is rapidly increasing [1]–[4]. The 2.4 GHz industrial, scientific, and medical band is currently occupied by short-range and low power applications, including Wi-Fi, cordless phones, and Bluetooth. As a result, 802.11ac equipment only works in the 5 GHz band. Since the full benefits of Wi-Fi can only be realized with additional spectra in 5 GHz, the Federal Office of Communications (OFCOM) recently considered the extension of 5 GHz to provide sufficient spectrum for the use of Wi-Fi devices [5]. Additional spectra in various frequency bands are definitely required to support future growth in indoor/outdoor wireless connections, mobile broadband use, and so on. Given the limited frequency resources, spectrum sharing will play an important role in expanding the supply of spectra for mobile broadband and wireless emerging services, such as the Internet of things. The Federal Communications Commission (FCC) has recently considered the 3.5 GHz band as a shared spectrum with a three-tier authorization model to address wireless coverage and capacity issues [6]. OFCOM also has a plan to utilize the 2.3 GHz band and a range of other bands between 3.4 GHz and 4.2 GHz for mobile broadband use with a licensed shared access approach [5].

Most of all, TV white space (TVWS) is expected to be used in the near future for a wide range of wireless applications [7]–[10]. TVWS refers to TV bands that are not being used by any licensed services at a particular time in a particular geographic

http://dx.doi.org/10.4218/etrij.16.0114.1303

area. TVWS is recognized as having suitable frequency bands for cognitive radio (CR) because this spectrum is rarely congested compared to the 2.4 GHz and 5 GHz bands [11]–[15]. When wireless networks are deployed in the TVWS, TV band devices (TVBDs) should not cause any harmful interference to licensed services, such as digital TV (DTV) and wireless microphones (WMs). To this end, the FCC has released a third memorandum opinion and order for the unlicensed operation of TVBDs in TVWS [16]. The European Union released Electronic Communications Committee Report 159 to provide technical and operational requirements for the possible operation of CR systems in TVWS, and complementary works are ongoing [17]. Since OFCOM proposed the unlicensed use of TVWS in 2007, regulatory requirements for white-space devices in the ultra-high frequency TV band have been announced [18]. The Korea Communications Commission announced its proposed regulations on TVBDs in September 2012 [19]. Moreover, spectrum sharing policy and regulatory requirements for TVWS has recently been developed in many other countries to efficiently activate TV bands that are not being used by licensed services [20]–[22]. As such, a TVBD can work on available channels in TVWS at its current position within the regulatory requirements.

The minimum separation distance from the noise-limited contour, which is called the keep-out distance, should be well established to guarantee the incumbent services in TV frequency bands and to achieve as many available TV channels as possible [10]. The FCC recently amended the separation distances between fixed TVBDs and the DTV noise-limited contour (grade B contour) of co-channel and adjacent-channel TV stations for antenna height above average terrain (HAAT) values ranging from less than 3 m to a maximum of 250 m. This paper suggests separation distances of TVBDs, suitable for the topography of the Rep. of Korea, from the noise-limited contour for different ranges of TVBD transmitter antenna height above ground level (AGL) based on measurements. Note that the antenna AGL is the distance from the antenna's center of radiation above the ground to the actual ground directly below the antenna. The antenna HAAT is the difference between the antenna height above mean sea level and the average elevation of the surrounding terrain [16]. The proposed separation distances and relevant parameters have been verified in indoor and outdoor environments with interested parties.

When TVBDs operate in accordance with only one set of separation distances regardless of radio propagation characteristics in a specific geographic area, a DTV service can be provided without harmful interference from TVBD networks. However, available TV channels cannot be sufficiently obtained due to the excessive separation distance in some areas, such as urban areas. Thus, it is necessary to make multiple sets of separation distances based on the radio propagation characteristics of various geographic areas to efficiently secure available TV channels. Available TV channels can be further obtained, especially for small-cell network deployment, if regulatory requirements, including a low-power TVBD transmission mode of less than 100 mW equivalent isotropically radiated power (EIRP), and relevant separation distances are prepared. In the deployment scenario of TVBD networks in TVWS, a DTV service may interfere with TVBDs, despite the fact that the TVBDs themselves do not cause harmful interference to the DTV service. This phenomenon will be very important in network coverage planning and spectrum sharing in upcoming TVWS. To make good use of TVWS, this paper investigates the effects of the coverage reduction ratio of a TVBD network (due to a neighboring DTV service) according to the TVBD's transmit power level or the required minimum separation distance between the DTV protected contour and the TVBD network.

This paper aims to provide both a perspective on how to protect incumbent users in the TVWS and good information on available TV channels for fixed and portable TVBDs with different antenna heights. The remainder of this paper is organized as follows. The next section presents a set of candidate regulatory requirements of TVBDs in the Rep. of Korea both to safely protect incumbent services from interference by TVBDs and to utilize TVWS well. In Section III, we discuss the minimum separation distance from a noise-limited contour of an incumbent service in TV frequency bands for the protection of the incumbent service, especially in the cases of DTV and licensed WMs. The impacts of TVBD transmit power and separation distance on the coverage of TVBD networks are investigated in Section IV. The TVWS field test results are presented in Section V, and a summary and conclusions are given in Section VI.

II. Planning of Regulatory Requirements of TVBDs

In the Rep. of Korea, two kinds of TVBDs — fixed and portable — are taken into account to be operated on available channels in frequency bands ranging from 470 MHz to 698 MHz (TV channels 14 to 51). Table 1 summarizes the candidate regulatory requirements of permissible transmit power level and power spectral density (PSD) for fixed and portable TVBDs. TVBDs that comply with the regulatory requirements can be deployed in available TV channels, which are acquired using a geo-location and database access mechanism.

Fixed TVBDs are allowed to operate with a maximum EIRP of 4 W (maximum transmit power of 1 W and antenna

Table 1. Transmit power and emission limits for fixed and portable TVBDs.

TVBD type	Fixed	Portable	
Operation mode	Co-channel/adjacent channel with separation distance	Co-channel/adjacent channel with separation distance	Adjacent channel without separation distance
Maximum power [1)]	1 W	100 mW	40 mW
Maximum EIRP [1)] (including antenna gain)	4 W (36 dBm)	100 mW (20 dBm)	40 mW (16 dBm)
In-band PSD [2)]	12.2 dBm	2.2 dBm	–1.8 dBm
Out-of-band PSD [2)]	–42.8 dBm	–52.8 dBm	–56.8 dBm

1) Measurements of maximum transmit power and maximum transmit EIRP shall be performed using a resolution bandwidth of 6 MHz.
2) Measurements of in-band PSD and out-of-band PSD shall be performed using a resolution bandwidth of 100 kHz.

gain of 6 dBi) per 6 MHz of bandwidth on which the devices operate. For portable TVBDs, co-channel or adjacent-channel operation with a maximum EIRP of 100 mW is permitted with a required separation distance, whereas a maximum EIRP of 40 mW is only permitted for adjacent-channel operations that do not meet the required separation distance. The out-of-band (adjacent channel) PSD in fixed TVBDs is limited to a maximum of –42.8 dBm. Out-of-band PSD should be measured in the frequency ranges ranging from ± 3 MHz to ± 9 MHz at a specified center frequency using a resolution bandwidth of 100 kHz. Out-of-band emissions measured with a 100 kHz resolution bandwidth shall be at least 72.8 dB below the highest average power measured with a 6 MHz resolution bandwidth in the operating TV channel.

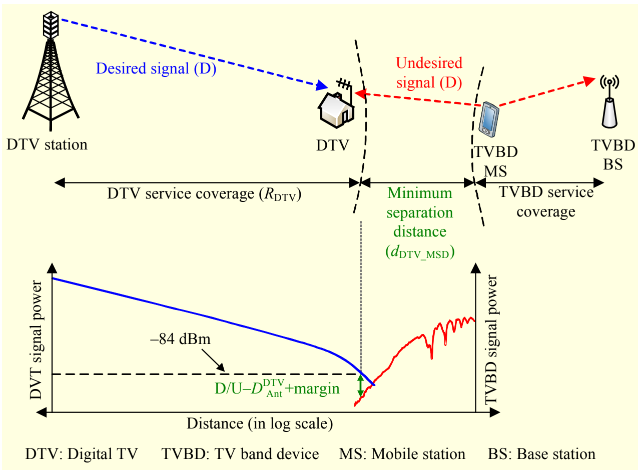


Fig. 1. Minimum separation distance of TVBD MS from edge of DTV service coverage (grade B contour).

III. Incumbent Service Protection

1. Measurement Setup

When a set of candidate regulatory requirements for the utilization of fixed and portable TVBDs in TVWS is prepared, it would be better if the maximum permissible power and emission levels of the TVBDs were to reflect global harmonization in the TVBDs. However, available channels and interference protection requirements, such as the separation distances of TVBDs from the noise-limited contour of an incumbent service and the TVBD transmitting antenna height, should be determined on the basis of the radio and geographic environments. An experimental model for determining the required minimum separation distance of a TVBD mobile station (MS) from the edge of DTV service coverage (grade B contour) is illustrated in Fig. 1.

The radio propagation environment is classified into several geographic areas and local shapes to investigate the characteristics of any radio propagation (in the Rep. of Korea). Then, the radio propagation characteristics are measured and analyzed to determine an appropriate separation distance from the noise-limited contour of an incumbent service in TV frequency bands. To obtain a reference propagation model of a TVBD signal in TVWS, the propagation attenuation over flat terrain is measured by using a measurement van to move the receive point from the TVBD transmitting point to a distance ranging from 10 m to

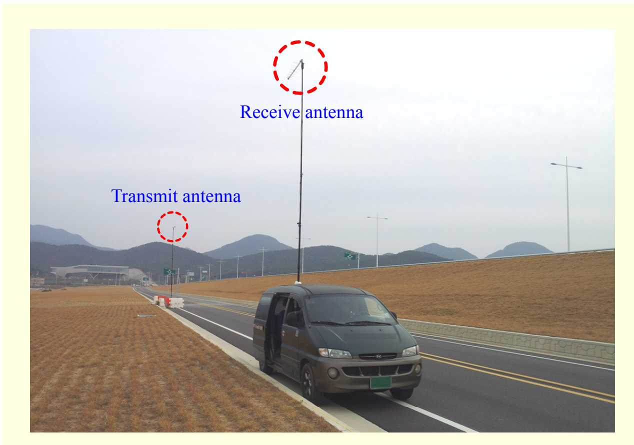


Fig. 2. Field strength measurement van.

http://dx.doi.org/10.4218/etrij.16.0114.1303

10 km at the Saemangeum seawall, which is located on the southwest coast of the Rep. of Korea. A measurement van used to investigate the interference protection requirements in TVWS is shown in Fig. 2. Note that many experimental measurements have also been conducted on the island of Jeju (Rep. of Korea), where the radio environment of TV bands is relatively good compared to other areas in the Rep. of Korea.

2. Minimum Separation Distance for Protection of DTV

Figure 3 shows a block diagram of the equipment setup used to measure threshold of visibility (TOV) and the desired-to-undesired signal (D/U) ratio for the Advanced Television Systems Committee (ATSC) DTV receiver. The purpose of this measurement is to adequately determine the co-channel and adjacent-channel separation distances from the well-known DTV noise-limited contour (grade B contour) to secure available channels under the constraint of DTV service protection. In normal transmit power mode, TVBDs must be deployed outside the DTV protected contour with a proper separation distance (see Table 1).

The TOV (in dBm) for three different kinds of ATSC DTV receivers operating on TV channel 15 is summarized in Table 2. A visible DTV image is displayed when the received DTV signal level is above –85.3 dBm for DTV #1, –84.7 dBm for DTV #2, and –85.1 dBm for DTV #3 for the case in which the DTV signals come from the DTV signal generator. However, changes in the TOV levels range between –80 dBm and –84 dBm when real ATSC broadcast signals are used for the source signals. The measurements showed that the DTV receivers had a noise-limited performance when the input signal level was about –84 dBm (grade B level). We choose –84 dBm as the TOV for the DTV receiver [23].

We observed that the co-channel D/U ratio ranged from 15 dB to 16 dB at a high signal-to-interference-plus-noise ratio (SINR), whereas the required co-channel D/U ratio ranges from 20 dB to 23 dB at a low SINR around the grade B contour. Thus, the co-channel D/U ratio should be 23 dB around the edge of the grade B contour, where SINR is 16 dB or less [24]. The D/U ratios at the grade B contour to protect the DTV service from co-channel and adjacent-channel TVBD interference are depicted in detail in Figs. 4(a) and 4(b). We determined the D/U ratio for adjacent channel protection to be –32 dB based on our measurements and analysis.

Now, a theoretical maximum allowable TVBD power level at the DTV receive antenna input is given by

$$P_{\mathrm{DTV\_Rx}}^{\mathrm{TVBD}} = P_{\mathrm{TOV}}^{\mathrm{DTV}} - P_{\mathrm{D/U}}^{\mathrm{DTV}} + D_{\mathrm{Ant}}^{\mathrm{DTV}} - G_{\mathrm{Ant}}^{\mathrm{DTV}} + L_{\mathrm{Line}}^{\mathrm{DTV}}, \quad (1)$$

where $P_{\mathrm{TOV}}^{\mathrm{DTV}}$ is the TOV of –84 dBm at the DTV receiver. $P_{\mathrm{D/U}}^{\mathrm{DTV}}$ denotes the D/U ratio; 23 dB for the co-channel case and –32 dB for the adjacent channel case. The off-axis antenna discrimination between the DTV receiving antenna and the TVBD transmitting antenna is denoted by $D_{\mathrm{Ant}}^{\mathrm{DTV}}$; and 14 dB off-axis antenna discrimination is employed. The receiving antenna gain and down-lead line loss from the antenna to the ATSC DTV receiver are denoted by $G_{\mathrm{Ant}}^{\mathrm{DTV}}$ and $L_{\mathrm{Line}}^{\mathrm{DTV}}$, respectively, which are assumed to be 10 dB and 4 dB, respectively [23]. Thus, the maximum allowable power of the co-channel and adjacent-channel TVBDs at the DTV receiving antenna input is calculated as –99 dBm and –44 dBm, respectively.

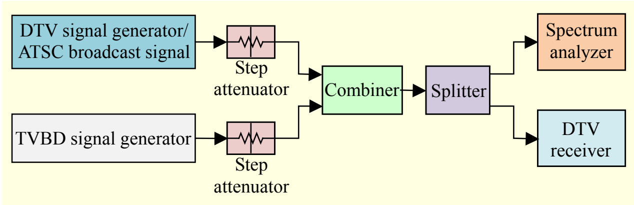


Fig. 3. Equipment setup to measure TOV and D/U for DTV service.

Table 2. TOV (in dBm) of three DTV receivers.

ATSC signal source	DTV #1	DTV #2	DTV #3
DTV signal generator	–85.3 dBm	–84.7 dBm	–85.1 dBm
ATSC broadcast signal	–80 dBm ~ –84 dBm		

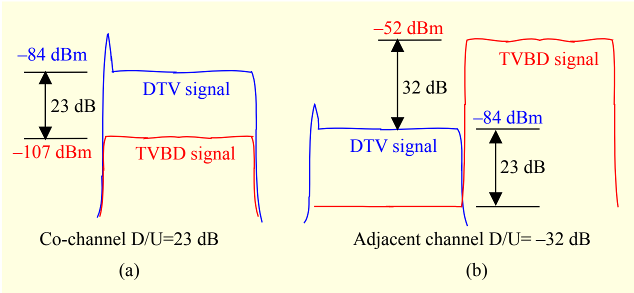


Fig. 4. (a) D/U ratio at grade B contour to protect DTV service from co-channel TVBD interference and (b) D/U ratio at grade B contour to protect DTV service from adjacent-channel TVBD interference.

The minimum separation distance is conceptually obtained by

$$P_{\mathrm{DTV\_Rx}}^{\mathrm{TVBD}} - P_{\mathrm{DTV,m}} = P_{\mathrm{TVBD\_Tx}}^{\mathrm{EIRP}} \cdot L(d_{\mathrm{DTV\_MSD}}, f, h_{\mathrm{Tx}}, h_{\mathrm{Rx}}), \quad (2)$$

where $P_{\mathrm{DTV,m}}$ is marginal power, $P_{\mathrm{TVBD\_Tx}}^{\mathrm{EIRP}}$ is the transmit EIRP at the TVBD transmitter, $L(\cdot)$ is propagation loss, which is generally a function of the separation distance ($d_{\mathrm{DTV\_MSD}}$) between the TVBD transmit and the DTV receive antennas, f is the operating frequency, h_{Tx} is the transmit antenna height,

Table 3. Required minimum separation distance of TVBDs from DTV protected contour (grade B contour).

TVBD type	Antenna height	Separation distance	
		Co-channel	Adjacent channel
Fixed	Less than 3 m	4 km	350 m
	3 m–10 m	8.5 km	
	10 m–30 m	15.3 km	
Portable	Typically 1.5 m	1.5 km	

and h_{Rx} is the receive antenna height. Thus, the minimum separation distance, d_{DTV_MSD}, is determined from (2). Because radio propagation characteristics vary by geographic area, a set of separation distances of TVBDs from the DTV protected contour for different ranges of TVBD transmit antenna heights has been determined based on many measurements of TV frequency bands and simulation results using the Okumura propagation model, the International Telecommunication Union Radiocommunication Sector (ITU-R) P.1546-4 propagation model, ITU-R P.1411-6 propagation model, and the FCC propagation curve [25]–[28].

Table 3 shows the co-channel and adjacent-channel separation distances of fixed and portable TVBDs from the DTV protected contour (grade B contour). These kinds of separation distances can be utilized in the TVWS database to obtain available channels in TVWS for the Rep. of Korea. Because portable TVBD is typically used at a height of 1.5 m, a separation distance of 1.5 km is sufficient to guarantee a neighboring DTV service. In constrast, in the interference protection requirements of the FCC, portable TVBDs should comply with the minimum co-channel separation distance of 4 km [16]. By considering the median bound of the ITU-R 1411-6 line-of-sight (LOS) propagation model, we suggest that the adjacent-channel separation distance between TVBDs and the DTV protected contour should be 350 m [27], [29]. Spectrum sharing issues to increase the overall network capacity of small cells have recently been investigated [4]–[6], [30]. We believe that a portable TVBD is quite suitable for the deployment of small cells in TVWS because a portable TVBD operates with a relatively low transmit power. To enlarge available channels in TVWS, different kinds of separation distances have been suggested for portable and fixed TVBDs, respectively.

3. Minimum Separation Distance for Protection of Licensed WMs

Figure 5 shows the connection for the laboratory

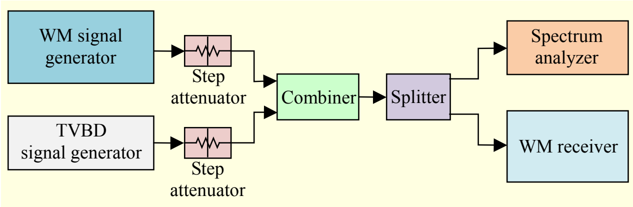


Fig. 5. Equipment setup to measure TOA and D/U for WM service.

Fig. 6. Interference measurements from TVBD into WM receiver in front of Jeju Art Center in Korea.

measurements for the WM interference parameter values, such as threshold of audibility (TOA) and D/U ratio. In the laboratory test, WM signals are first captured with a transmit antenna located very close to a receive antenna, and saved to a WM signal generator to accurately observe TOA and the D/U ratio. For the different kinds of WMs tested, audible WM sounds are heard when corresponding received WM signal levels fall within the range –91 dBm/250 kHz to –96 dBm/250 kHz in the laboratory tests. Note that the TOA level sightly increases in the outdoor measurements. The interference measurements from the TVBD into the WM receiver in front of the Jeju Art Center in Korea, are shown in Fig. 6. From the observations and analysis, we choose –95 dBm as the TOA for the WM receiver [17]. From the laboratory tests, we also observed that the co-channel D/U ratio ranges from 13 dB to 18 dB depending on the type of WMs around the noise-limited contour of the WM service. By considering the effects of the radio wave fluctuations in a real environment, the D/U ratio was determined to be 20 dB at the noise-limited contour.

Thus, a maximum allowable TVBD power level at the WM receiver is calculated by

$$P_{\mathrm{WM\_Rx}}^{\mathrm{TVBD}} = P_{\mathrm{TOA}}^{\mathrm{WM}} - P_{\mathrm{D/U}}^{\mathrm{WM}} + D_{\mathrm{Ant}}^{\mathrm{WM}} - G_{\mathrm{Ant}}^{\mathrm{WM}} + L_{\mathrm{Line}}^{\mathrm{WM}}, \quad (3)$$

where $P_{\mathrm{TOA}}^{\mathrm{WM}}$ is the TOA of –95 dBm at the WM receiver, $P_{\mathrm{D/U}}^{\mathrm{WM}}$ denotes a D/U ratio of 20 dB, and $D_{\mathrm{Ant}}^{\mathrm{WM}}$ is the antenna

Table 4. Maximum allowable TVBD power and related parameter values at noise-limited contour of incumbent service (DTV and WM).

Incumbent user	DTV	WM
Channel bandwidth	6 MHz	250 kHz
TOV/TOA	–84 dBm	–95 dBm
Co-channel D/U	23 dB	20 dB
Allowable co-channel TVBD power at a DTV receiver	–107 dBm	–115 dBm
Adjacent channel D/U	–32 dB	N/A
Antenna discrimination	14 dB	0 dB
Antenna gain	10 dBi	10 dBi
Down-lead line loss	4 dB	4 dB
Allowable co-channel TVBD power at receive antenna input	–99 dBm	–121 dBm

discrimination between the WM receiving antenna and the TVBD transmitting antenna. We take into account the antenna discrimination to be 0 dB in the WM deployment scenarios; $G_{\text{Ant}}^{\text{WM}}$ and $L_{\text{Line}}^{\text{WM}}$ denote the receiving antenna gain and the down-lead line loss from the antenna to the WM receiver, respectively. The bandwidth of the WM is assumed to be 250 kHz. The maximum allowable power of the TVBD at the WM receiver becomes –115 dBm/250 kHz. Table 4 summarizes the maximum allowable TVBD power levels at both the DTV and the WM receive antenna input, and the derived parameter values at the noise-limited contour of both the DTV and the WM.

Similar to the DTV case, the minimum separation distance of the TVBDs from the WM protected contour is obtained by

$$P_{\text{WM\_Rx}}^{\text{TVBD}} - P_{\text{WM,m}} = P_{\text{TVBD\_Tx}}^{\text{EIRP}} \cdot L(d_{\text{WM\_MSD}}, f, h_{\text{Tx}}, h_{\text{Rx}}), \quad (4)$$

where $P_{\text{WM,m}}$ is marginal power. The required minimum separation distance, $d_{\text{WM\_MSD}}$, is determined from (4). We have also observed that the radio propagation attenuation at the indoor locations of venues such as theaters, broadcasting studios, and concert halls is more than 20 dB larger than that at the outdoor locations. To reflect this phenomenon, we present two sets of separation distances for the licensed WM service. Figure 7 presents the co-channel separation distance of the TVBDs from the noise-limited contour for both the indoor WM service and the outdoor WM service. Meanwhile, the FCC permits the operation of fixed and portable TVBDs in TVWS with separation distances of 1 km and 400 m from the WM protected contour, respectively. In this case, some of the WM services may receive interference from TVBDs based on our measurements and analysis.

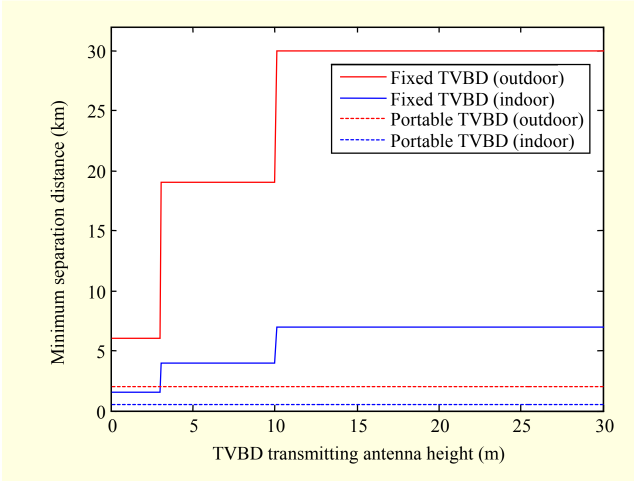


Fig. 7. Co-channel separation distance of TVBDs from noise-limited contour for both indoor and outdoor WM service.

IV. Impact on Coverage of TVBD Networks

1. Simulation Setup

When separation distances are established with a unified set of values regardless of the radio propagation characteristics, available TV channels generally decrease because separation distances should be determined to guarantee the protection of all the incumbent services in both good and bad propagation environments. To compensate for this, a multiple separation distance scheme can be considered; a short separation distance is employed in a bad propagation environment, whereas a long separation distance is adopted in a good one; the radio propagation environment is classified into urban, suburban, quasi-open, and open areas on the basis of the geographical characteristics [25]. Note that quasi-open is defined as midway between the open and suburban areas. Figure 8 shows the co-channel separation distances of fixed TVBDs from the DTV protected contour for different ranges of TVBD transmit antenna heights in four geographic areas, and the co-channel separation distances recommended by the FCC. The separation distances in the four geographic areas are determined by averaging the estimated separation distances in both a large city and a medium city using the Okumura propagation model [25]. We also suggest a low-power transmission mode of TVBDs less than 100 mW, and the relevant separation distances. Table 5 compares the required co-channel separation distances of fixed TVBDs from the DTV protected contour in a suburban area with three TVBD transmit power levels.

Table 6 summarizes the simulation parameters used to investigate the effects of both the TVBD's transmit power level and the required minimum separation distance on the coverage reduction ratio of the TVBD networks. When the service

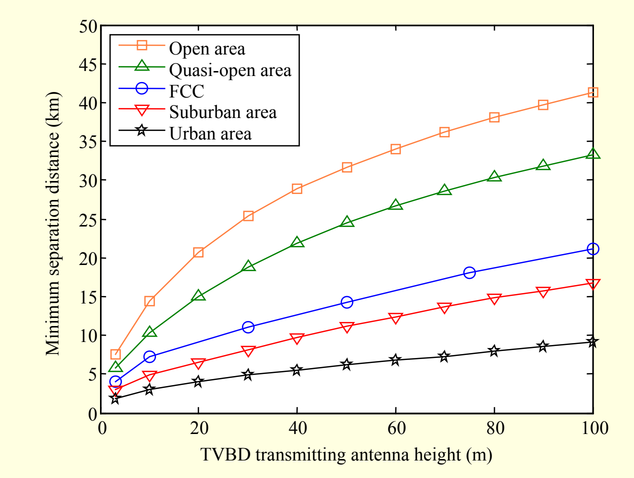


Fig. 8. Co-channel separation distances of 4 W fixed TVBDs from DTV protected contour for different ranges of TVBD transmit antenna heights in four geographic areas.

Table 5. Required co-channel separation distances in kilometers of fixed TVBDs with different transmit power levels from DTV protected contour in suburban area.

		TVBD transmitting antenna height					
		3 m	10 m	20 m	30 m	50 m	100 m
TVBD transmit power	4 W	3.03	4.87	6.59	8.04	11.1	16.71
	0.1 W	1.21	1.85	2.48	2.93	3.68	5.34
	0.01 W	0.83	1.05	1.30	1.47	1.86	2.58

Table 6. Simulation parameters.

Parameter	Value
Center frequency of DTV transmitter	617 MHz (Ch. 38)
DTV effective radiated power	2.5 kW
DTV transmitting antenna height	500 m
DTV receiving antenna height	10 m
Channel spacing of TVBD	5 MHz
TVBD BS EIRP	100 mW/10 mW
TVBD MS EIRP	100 mW/10 mW
TVBD BS antenna height	3, 10, 20, … , 90, 100 m
TVBD MS antenna height	1.5 m
TVBD Rx minimum sensitivity	–88 dBm

coverage of a TVBD network is estimated, the received signal power from the TVBD base station (BS) is calculated by using the ITU-R P.1411-6 propagation model assuming the upper bound in an LOS environment, and the interference power from the DTV station is calculated with the ITU-R P.1546-4 propagation model, respectively [26], [27].

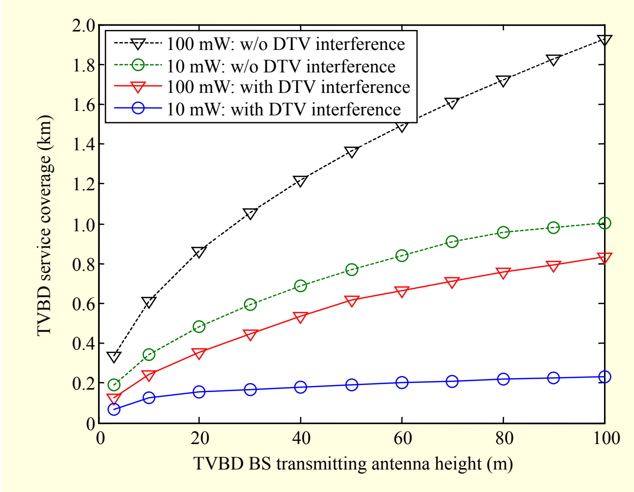


Fig. 9. Comparison of coverage reduction of TVBD network due to DTV interference with two different TVBD transmit power levels.

2. Effect of TVBD Transmit Power

Figure 9 compares the coverage reduction of the TVBD network due to DTV interference with two TVBD transmit power levels of 10 mW EIRP and 100 mW EIRP. The separation distance for the suburban area shown in Fig. 8 is used in the simulation. The transmit power level of a fixed TVBD BS is assumed to be 100 mW (10 mW) EIRP instead of 4 W (100 mW) EIRP to avoid downlink–uplink coverage imbalance with the portable TVBD MS of 100 mW (10 mW). With 10 mW transmit power, the service coverage of a TVBD network in the presence of DTV stations is reduced by 77% when compared with that in the absence of DTV interference for the TVBD BS antenna height of 100 m, whereas the service coverage is reduced by 57% with 100 mW transmit power. For relatively low antenna height scenarios, the coverage reduction ratio is similar in the two cases, whereas the coverage reduction ratio increases in the case of 10 mW transmit power as the antenna height of a TVBD BS increases. Although this phenomenon seems to be negative in the sense that the service coverage of a secondary user (TVBD) is reduced due to a nearby primary user (DTV service), it is expected to obtain available TVWS additionally for small cells if a low-power TVBD transmitting mode and the relevant separation distances are reflected in the regulatory requirements.

3. Effect of Separation Distance

Figure 10 compares the coverage of TVBD networks with different separation distances in the presence of DTV

http://dx.doi.org/10.4218/etrij.16.0114.1303

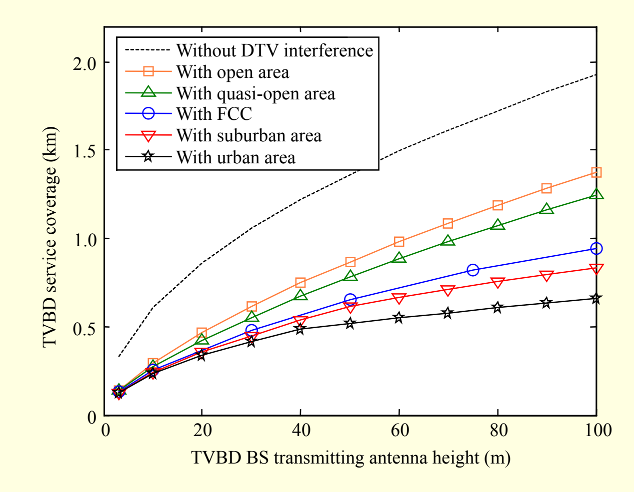


Fig. 10. Comparison of coverage reduction of TVBD network due to DTV interference with five different separation distances.

interference. The service coverage of a TVBD network in the presence of DTV interference is reduced by 66% when compared with that in the absence of DTV interference for the TVBD BS antenna height of 100 m with the separation distance for an urban area, whereas the service coverage is reduced by 29% for an open area. In the urban area, the coverage reduction ratio of about 60% is similar for all ranges of the TVBD BS transmitting antenna height, but the coverage reduction ratio decreases from 58% to 29% in the open area as the antenna height of the TVBD BS increases. From the results, it was found that the TVWS in a dense urban area is suitable for use in small cells because the service coverage of a TVBD network in an urban area is much smaller than it is in a rural area. Meanwhile, macrocell deployment strategies are adequate in rural areas.

V. TVWS Field Test

This section provides TVWS field verification, conducted on the island of Jeju (Rep. of Korea), for the proposed separation distances in Section III to protect incumbent services. We configure the fixed and portable TVBDs (TVBD prototype and/or signal generator) with the transmit power and emission requirements in Table 1. Refer to [31] for more details on the TVBD prototype. A TVBD is located outside the noise-limited contour by the separation distance. Note that the separation distance is determined by considering the TVBD type, TVBD antenna height, incumbent service type to be protected, and so on, as given in Tables 3 and 4. Then, we investigate whether harmful interference occurs from the secondary user (TVBD) to the neighboring primary users (DTV service).

Figure 11 shows the field-test location for the co-channel

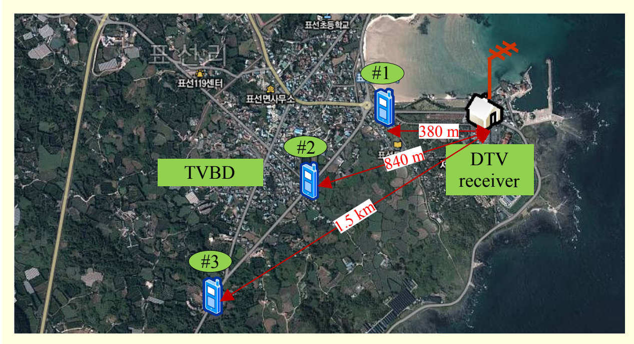


Fig. 11. Field test for required separation distance verification of 100 mW portable TVBDs in rural area near beach.

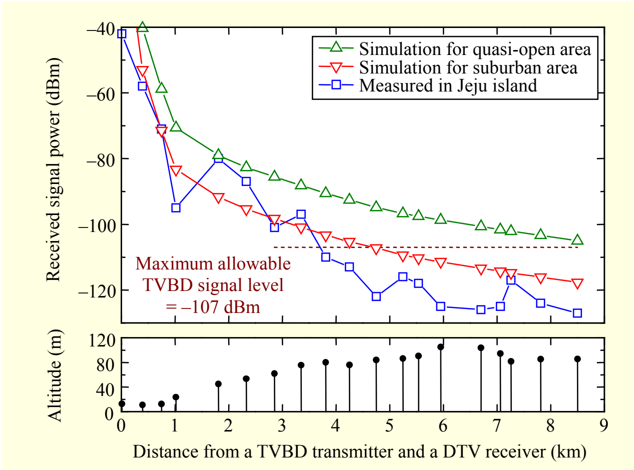


Fig. 12. Received interference signal power at ATSC DTV receiver with antenna height of 10 m; interference signal is transmitted from signal generator with transmitting antenna height of 10 m, which is located at distance ranging from 10 m to 8.5 km from DTV receiver.

separation distance verification of 100 mW portable TVBDs with an antenna height of 1.5 m in an outdoor environment. Both the DTV and TVBD are operated on TV channel 20. As shown in the figure, the measuring points are in a rural area near the beach, where the radio waves are transmitted at a comparatively long distance. Nevertheless, the DTV service is protected without interference from the portable TVBD when the TVBD is located more than 700 m away from the DTV receiving antenna. We also conducted additional measurements with the signal generator to observe the received interference power level at the ATSC DTV receiver. The TVBD signals with the transmit power level of 20 dBm, generated from the signal generator at points #1, #2, and #3, have been measured at the DTV receiver to be –75 dBm, –110 dBm, and –120 dBm, respectively. Note that the points #1, #2, and #3 are located 380 m, 840 m, and 1.5 km, respectively, away from the DTV receiving antenna. From these observations, a separation distance of 1.5 km for the portable TVBD is sufficient to protect the DTV service.

To check the feasibility of the co-channel separation distance for the fixed TVBD with an antenna height ranging from 3 m to 10 m, the DTV receiver is located at a fixed point (see Fig. 11), while the locations (not shown in Fig. 11) of the signal generator are changed in the experiments. We used the continuous waveform (CW) of 36 dBm rather than the modulated waveform, using the signal generator to measure the low-level interference signal power in detail at the spectrum analyzer on the receiving point. Figure 12 shows the measurement results of the received interference signal (CW in the measurements) power at a DTV receiver with an antenna height of 10 m. The received interference signal power from a TVBD transmitter with an antenna height of 10 m to a DTV receiver with an antenna height of 10 m was also estimated by simulation using the Okumura propagation model for both a suburban area and a quasi-open area; in the simulation, the altitudes of TVBD transmitting points and the receiving point were assumed to be 0. From the simulation, the received TVBD interference signal power in the quasi-open area is nearly the same as the maximum allowable TVBD signal level of 107 dBm at the DTV receiver located 8.5 km away from the TVBD transmitter. In the field test, the interference signal is transmitted from the signal generator with the transmitting antenna height of 10 m. The signal generator is located from 10 m to 8.5 km away from the DTV receiver. In this field test, the DTV service is protected from the 4 W fixed TVBD with a transmitting antenna height ranging from 3 m to 10 m when the TVBD is located more than 3.7 km away from the DTV receiving point. Furthermore, because the altitude of the DTV receiving point is much lower than that of any of the TVBD transmitting points, the separation distance of 8.5 km for the TVBD with a transmitting antenna height ranging from 3 m to 10 m is sufficient to protect the DTV service in a normal deployment scenario. From Fig. 12, the DTV service is guaranteed without interference from the TVBDs when the TVBDs are located at distances of around half that of the proposed separation distances, or less, away from the DTV receiving antenna.

VI. Conclusion

In this paper, we presented a set of candidate regulatory requirements for fixed and portable TVBDs. We proposed separation distances, suitable for the topography of the Rep. of Korea, by considering the realistic deployment scenarios of co-channel and adjacent-channel TVBDs in TVWS to protect DTV and licensed WM services. The service coverage reduction of a TVBD network in the presence of DTV interference was also investigated with five sets of separation distances. We performed many measurements and experiments throughout the country to guarantee incumbent services within the protected contour. During the TVWS field tests, we observed that the TVBDs did not cause harmful interference to either the DTV or the WM services when the TVBDs were deployed outside the protected contour by the proposed separation distance; during the field tests on the island of Jeju, even at distances of half that of the proposed separation distances, or less, incumbent services were protected from harmful interference caused by TVBDs. Our contribution will be helpful for improving the planning of regulatory requirements, spectrum sharing for unlicensed bands, and so on. It is also expected that our findings will enable service providers to obtain practical information for the deployment of TVBD networks.

References

[1] PCAST Final Report, *Traditional Practice of Clearing Government-Held Spectrum of Federal Users and Auctioning it for Commercial Use is not Sustainable*, PCAST, July 2012.

[2] J. Xiao et al., “Expanding LTE Network Spectrum with Cognitive Radios: From Concept to Implementation,” *IEEE Wireless Commun.*, vol. 20, no. 2, Apr. 2013, pp. 12–19.

[3] W. Ni and I.B. Collings, “A New Adaptive Small-Cell Architecture,” *IEEE J. Sel. Areas Commun.*, vol. 31, no. 5, May 2013, pp. 829–839.

[4] H. Elsawy, E. Hossain, and D.I. Kim, “HetNets with Cognitive Small Cells: User Offloading and Distributed Channel Access Techniques,” *IEEE Commun., Mag.*, vol. 51, no. 6, June 2013, pp. 28–36.

[5] OFCOM Statement, *The Future Role of Spectrum Sharing for Mobile and Wireless Data Services: Licensed Sharing, Wi-Fi, and Dynamic Spectrum Access*, OFCOM, Apr. 2014.

[6] FCC 14-49, *Further Notice of Proposed Rulemaking*, FCC, Apr. 2014.

[7] K.G. Shin et al., “Cognitive Radios for Dynamic Spectrum Access: From Concept to Reality,” *IEEE Wireless Commun.*, vol. 17, no. 6, Dec. 2010, pp. 64–74.

[8] OFCOM Statement, *Digital Dividend: Cognitive Access, Statement on License-Exempting Cognitive Devices Using Interleaved Spectrum*, OFCOM, July 2009.

[9] J. van de Beek et al., “TV White Space in Europe,” *IEEE Trans. Mobile Comput.*, vol. 11, no. 2, Feb. 2012, pp. 178–188.

[10] K.-M. Kang et al., “Deployment and Coverage of Cognitive Radio Networks in TV White Space,” *IEEE Commun. Mag.*, vol. 50, no. 12, Dec. 2012, pp. 88–94.

[11] M. Song et al., “Dynamic Spectrum Access: From Cognitive Radio to Network Radio,” *IEEE Wireless Commun.*, vol. 19, no.

1, Feb. 2012, pp. 23–29.

[12] D. Makris, G. Gardikis, and A. Kourtis, “Quantifying TV White Space Capacity: Qualifying TV White Space Capacity,” *IEEE Commun.*, *Mag.*, vol. 50, no. 9, Sept. 2012, pp. 145–152.

[13] H.N. Vu and H.Y. Kong, “Optimal Throughput of Secondary Users over Two Primary Channels in Cooperative Cognitive Radio Networks,” *J. Electromagn. Eng. Sci.*, vol. 12, no. 1, Mar. 2012, pp. 1–7.

[14] J. Zuo et al., “Energy-Efficiency Power Allocation for Cognitive Radio MIMO-OFDM Systems,” *ETRI J.*, vol. 36, no. 4, Aug. 2014, pp. 686–689.

[15] G.P. Villardi, G.T.F. de Abreu, and H. Harada, “TV White Space Technology: Interference in Portable Cognitive Emergency Network,” *IEEE Veh. Technol. Mag.*, vol. 7, no. 2, June 2012, pp. 47–53.

[16] FCC 12-36, *Third Memorandum Opinion and Order*, *In the Matter of Unlicensed Operation in the TV Broadcast Bands*, *Additional Spectrum for Unlicensed Devices Below 900 MHz and in the 3 GHz Band*, FCC, Apr. 2012.

[17] ECC Report 159, *Technology and Operational Requirements for the Possible Operation of Cognitive Radio Systems in the ‘White Spaces’ of the Frequency Band 470–790 MHz*, ECC, Jan. 2011.

[18] OFCOM Regulatory Requirements, *Regulatory Requirements for White Space Devices in the UHF TV Band*, OFCOM, July 2012.

[19] KCC Notification no. 2012-113, *Notice of Draft Revised Rules on Radio Equipment*, KCC, Sept. 2012.

[20] C.S. Sum et al., “Cognitive Communication in TV White Spaces: An Overview of Regulations, Standards, and Technology,” *IEEE Commun. Mag.*, vol. 51, no. 7, July 2013, pp. 138–145.

[21] M. Nekovee, T. Irnich, and J. Karlsson, “Worldwide Trends in Regulation of Secondary Access to White Spaces Using Cognitive Radio,” *IEEE Wireless Commun.*, vol. 19, no. 4, Aug. 2012, pp. 32–40.

[22] H.B. Yilmaz et al., “Radio Environment Map as Enabler for Practical Cognitive Radio Networks,” *IEEE Commun. Mag.*, vol. 51, no. 12, Dec. 2013, pp. 162–169.

[23] FCC OET Bull. 69, *Longley-Rice Methodology for Evaluating TV Coverage and Interference*, FCC, Feb. 2004.

[24] ATSC Doc. A/74, *ATSC Recommended Practice: Receiver Performance Guidelines*, Advanced Television Systems Committee, June 2004.

[25] Y. Okumura et al., “Field Strength and its Variability in VHF and UHF Land Mobile Radio Service,” *Rev. Elect. Commun. Laboratory*, vol. 16, no. 9–10, Sept.–Oct. 1968, pp. 825–873.

[26] ITU-R Recommendation P.1546-4, *Method for Point-to-Area Predictions for Terrestrial Services in the Frequency Range 30 MHz to 3000 MHz*, *Tech. Rep.*, *the ITU Radiocommunication Assembly*, 2009.

[27] ITU-R Recommendation P.1411-6, *Propagation Data and Prediction Methods for the Planning of Short-Range Outdoor Radiocommunication Systems and Radio Local Area Networks in the Freq. Range 300 MHz to 100 GHz*, *Tech. Rep.*, *the ITU Radiocommunication Assembly*, 2012.

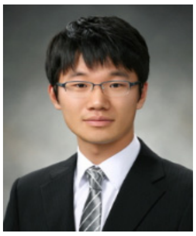
[28] FCC. Accessed Oct. 1, 2014. https://www.fcc.gov/media/radio/fm-and-tv-propagation-curves

[29] K.-M. Kang, “Minimum Separation Distance of Adjacent Channel TV Band Devices from DTV Protected Contour in TV White Space,” *Electron. Lett.*, vol. 50, no. 14, July 2014, pp. 1024–1025.

[30] T. Nakamura el al., “Trends in Small Cell Enhancements in LTE Advanced,” *IEEE Commun. Mag.*, vol. 51, no. 2, Feb. 2013, pp. 98–105.

[31] K.-M. Kang and J.C. Park, “A New Scheme for Compliance with TV White Space Regulations Using Wi-Fi Modules in a Cognitive Radio System,” *IEEE Trans. Consum. Electron.*, vol. 60, no. 4, Nov. 2014, pp. 567–573.

Kyu-Min Kang received his BS, MS, and PhD degrees in electronic and electrical engineering from Pohang University of Science and Technology, Rep. of Korea, in 1997, 1999, and 2003, respectively. Since 2003, he has been with ETRI. His current research interests include cognitive radio networks, spectrum engineering, digital signal processing, and high-speed digital transmission systems.



Jae Cheol Park received his BS degree in electronics engineering and MS degree in electronics and radio engineering from Kyung Hee University, Yongin, Rep. of Korea, in 2009 and 2011, respectively. He is currently a member of the engineering staff with the Radio Technology Research Department, ETRI. His research interests include cognitive radio and cooperative networks; mobile communications; and MIMO systems.

Sang-In Cho received his BS and MS degrees in information and telecommunication engineering from Chonbuk National University, Jeonju, Rep. of Korea, in 1997 and 1999, respectively. Since 1999, he has been with ETRI. His current research interests include VLSI digital signal processing and digital communications with applications to wireless transmission systems.

Seungkeun Park received his BS and MS degrees in applied statistics from Korea University, Seoul, Rep. of Korea, in 1991 and 1993, respectively. He received his PhD degree in information communication engineering from the University of Chungbuk, Cheongju, Rep. of Korea, in 2004. He is currently a principal member at ETRI. His current research interests include statistical communication and electromagnetic theories.