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Research Article

Channel-Allocation Plan for National and Local T-DAB Services in VHF Band III

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The digital audio broadcasting (DAB) system is mainly designed for large-area coverage and is suited for a single-frequency network (SFN) operating in Very High Frequency (VHF) Band III. To operate successfully, the SFN requires a different network-planning approach for multiple-frequency networks and should avoid self-interference. This paper focuses on nationwide SFN planning and DAB channel-allocation planning to replace all frequency-modulation (FM) services with terrestrial DAB services in VHF Band III. In South Korea, VHF Band III has been used for terrestrial digital multimedia broadcasting (T-DMB) services; thus, available frequencies should be investigated for T-DAB services and the nationwide SFN. An approach for broadcasting channel-interference analysis is proposed herein. For the interference analysis, the geographical features and the information for stations of legacy FM radio broadcasting and T-DMB, such as transmission parameters, are considered. The ratio of the interference area to the coverage is calculated via the channel-interference analysis. Areas affected by the self-interference in the nationwide SFN are investigated. The results of this paper provide insights regarding channel-allocation planning for T-DAB services and an approach for nationwide SFN planning.

1. Introduction

Digital-radio broadcasting technology was first developed by Europe in 1980s [1], and the conventional analog frequency-modulation (FM) radio is currently being replaced by digital radios throughout the world. Popular digital-radio broadcasting systems include digital audio broadcasting (DAB) [2], digital-radio mondiale plus (DRM+) [3], high-definition (HD) radio [4], and integrated services digital broadcasting–terrestrial digital sound broadcasting [5]. Compared with analog FM radio, these systems can provide increased robustness, reduced transmission power, increased coverage, and high-quality audio similar to that of a compact disc, as well as value-added services. In addition, the single-frequency network (SFN) can be supported for the digital-radio broadcasting system.

The current FM radio system operated by a multiple-frequency network (MFN) faces the issue of broadcasting-frequency scarcity in South Korea; thus, it is difficult to insert new radio channels or stations. The SFN—a network of transmitters operating on the same frequency and carrying the same data simultaneously—can be an efficient solution for this. The received signal is a superposition of signals transmitted from several transmitters; thus, diversity gain can be obtained [6–8]. The SFN also allows a high spectrum efficiency; thus, the required number of channels for a broadcasting coverage area can be significantly reduced compared with the MFN. However, because the same frequency is allocated to all transmitters in a given coverage area in an SFN, the SFN requires a different network-planning approach from the MFN, in which different frequencies are allocated to each transmitter for avoiding undue interference between adjacent transmitters. To successfully operate an SFN, the guard-interval (GI) condition must be guaranteed. Received signals outside the GI can cause self-interference in the SFN. Therefore, in an SFN, the separation distance between adjacent transmitters is limited by the GI. This is a key consideration for SFN planning.

In South Korea, the adoption of digital-radio broadcasting systems has been discussed since 1997. From the initial stage of the technological research, various digital systems—such as in-band on-channel, HD radio, in-band adjacent channel, DRM+, and DAB [2–4]—were considered as candidates for a new digital-radio service. During the DAB standardization process, a digital multimedia broadcasting (DMB) system based on a DAB system was designed [9–11]. The Korean domestic standard for DMB was announced in 2004, and the European Telecommunications Standards Institute and the International Telecommunication Union Radio communication Sector accepted the standards in 2005 and 2007, respectively [12, 13]. T-DMB is currently employed in Very High Frequency (VHF) Band III. A field test of major digital-radio technologies—DAB, DAB+, HD radio, and DRM+—was performed for two years from 2009 to 2010 [14–18]. Presently, a revised DAB+ system employing unified speech and audio coding is being developed [19–22]. Considering the field-test results and other factors, including the above, the Korea digital-radio committee which consists of the government, broadcasters, receiver manufacturers, research institutes, and universities has been discussing and debating the appropriate digital-radio standard for South Korea, led by the government.

In addition to the aforementioned research, for the successful adoption of a new broadcasting system, frequency planning to minimize the interference effect is required. In South Korea, as T-DAB services have been considered for application in VHF Band III with legacy T-DMB services, our research group has been investigating various T-DAB channel-allocation plans to minimize the interference between new T-DAB and legacy T-DMB channels [23, 24]. These were investigated in an environment where legacy T-DMB channels are reallocated to maximize the available channels for T-DAB services [23] and the current T-DMB channel-allocation status in VHF Band III [24], respectively.

Recently, the channel interference under the coexistence of new system with the legacy system [25, 26] and the planning SFNs [27] has been investigated. In [25], system protection ratios were proposed for the cochannel and the adjacent channel between the second generation of the digital terrestrial television (DTT) and the IEEE 802.22 Wireless Regional Area Network. The protection ratios for the adjacent channel between the DTT and 4G Long-Term Evolution networks were investigated under laboratory conditions in [26]. However, these works only offer values for the reference parameter, i.e., protection ratios, used for the analysis of the cochannel interference (CCI) or the adjacent-channel interference (ACI). Channel-interference analysis for broadcasting service areas is required for optimal frequency planning for new communication systems. In [27], the maximum size and minimum frequency reuse distance were investigated to avoid the CCI between multiple SFNs of a DTT system. The analysis was performed using theoretical hexagonal networks, which is not the focus of the present paper.

This study investigates a T-DAB channel-allocation plan with nationwide SFN for national and local broadcasting services in VHF Band III. An in-depth network-planning approach is needed for implementation of the nationwide SFN; thus, the nationwide SFN is planned via self-interference analysis between adjacent transmitters. The analysis approach for CCI and ACI is investigated between allocated DAB channels (DAB ↔ DAB) and between existing DMB channels and inserted DAB channels in the T-DMB frequency band (DAB ↔ DMB). The practical geographical features and information for broadcasting stations are considered for all interference analyses, and the ratio of the interference area to the coverage area is investigated via CCI or ACI analysis.

The paper is organized as follows. In Section 2, the available channels in VHF Band III for local T-DAB services and nationwide SFN are investigated. The number of DAB channels needed to cover all the offered FM radio broadcasting services in each of the local broadcasting areas is investigated. Section 3 describes the T-DAB channel-allocation plan, which is based on the nationwide SFN and the results presented in Section 2, and various interference cases and interference deployment scenarios are investigated. In Section 4, the analysis approach and results are presented for each interference deployment scenario. Section 5 concludes the paper.

2. Frequency Investigation for T-DAB Services in VHF Band III

2.1. T-DAB/DMB Channel Feature in South Korea. The DAB system uses coded orthogonal frequency-division multiplexing, which is capable of operating successfully in a multipath and fading environment, and MPEG-1/-2 Layer II is used for high-quality audio. The DAB system supports four transmission modes called modes I, II, III, and IV, each having a particular set of parameters. They are used for different transmission network configurations and operating frequencies. Most countries provide a DAB service with transmission mode I in VHF Band III. DAB transmission mode I is designed for large-area coverage and suited for an SFN operating at frequencies including VHF Bands I, II, and III [2].

In South Korea, T-DMB based on DAB transmission mode I uses a 42-MHz bandwidth in VHF Band III (174–216 MHz), as shown in Figure 1. The 42-MHz bandwidth is divided into seven 6-MHz-bandwidth channels (CH 7 to CH 13). Each channel is divided into three ensembles designated by the letters A, B, and C, along with the VHF channel number. Each ensemble has a bandwidth of 1,536 MHz. The guard band between adjacent ensembles is 192 kHz, and the lower guard band and upper guard band are 512 and 496 kHz, respectively. Because of the sufficient guard band between different channels, the channel interference is not considered between different channels. The ensemble is the DAB transmission signal, comprising a set of regularly and closely spaced orthogonal carriers. It is arranged into the transmission frame to be comprised of consecutive 76 orthogonal frequency-division multiplex (OFDM) symbols. Each OFDM symbol has a 1-ms data part and a 246-μs GI part. In the case of the DAB ensemble with the convolutional code rate of 1/2, an effective data rate is 1.152 Mbps [28]. Services—such as video programs, audio programs, or data services—can be multiplexed into an ensemble. In this study,

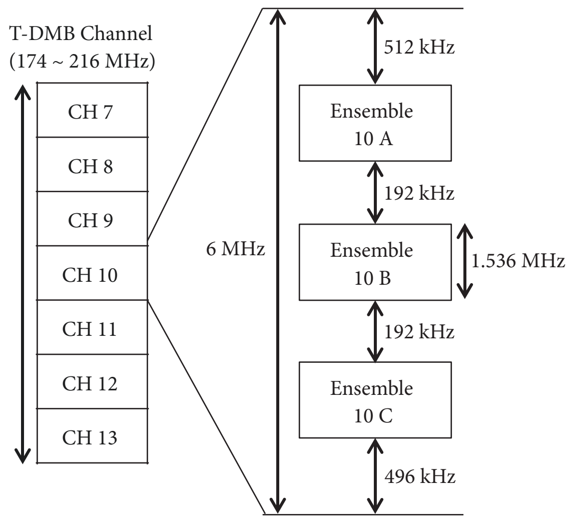


Figure 1: Ensemble arrangement for T-DAB/DMB in South Korea.

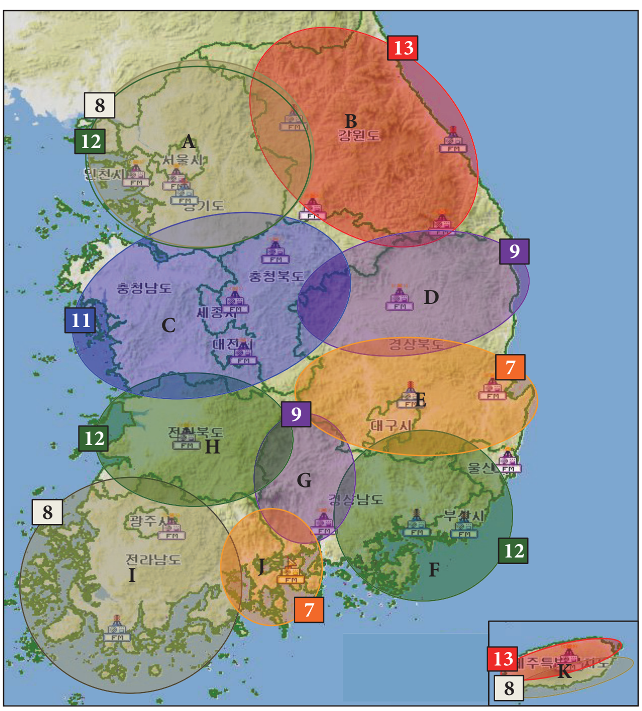


Figure 2: Channel-allocation status for T-DMB services in VHF Band III.

transmission of 9 T-DAB services with a 128-kbps data rate in an ensemble is assumed.

2.2. Channels Investigation for T-DAB Services Considering Nationwide SFN. The available channels for local T-DAB services and the nationwide SFN in VHF Band III are investigated. The channel-allocation status for T-DMB services in VHF Band III is shown in Figure 2. The numbers in the boxes represent the allocated channels for T-DMB services, and

Table 1: Channel investigation for T-DMB areas.

DMB Area	Using Channels	Available Channels
A	8, 12	7, 9, **10**
B	13	7, **10**
C	11	**10**
D	9	8, **10**, 12
E	7	8, **10**, 13
F	12	8, **10**, 11
G	9	**10**, 11, 13
H	12	**10**, 13
I	8	**10**, 11
J	7	**10**, 11
K	8, 13	9, **10**, 11, 12

each circle represents the coverage area of a T-DMB channel. The T-DMB areas are designated by the letters from A to K. One or two channels are allocated in each of the local T-DMB areas. CH 8 and CH 12 are allocated for T-DMB services for area A, and CH 13 and CH 11 are allocated for areas B and C, respectively. Therefore, if CH 11 or CH 13 is allocated for T-DAB services in area A, CCI is caused by the T-DMB channel of area B or C. Therefore, as shown in Figure 2, CH 7, CH 9, and CH 10 can be used as channels for T-DAB services in area A. For area B, because CH 8, CH 9, CH 11, and CH 12 are allocated for contiguous areas, CH 7 and CH 10 are available. In the same manner, available channels can be investigated for all the T-DMB areas. Table 1 shows the channels used for T-DMB services and the available channels in each T-DMB area [24]. The channel investigation reveals that CH 10 is available for all areas in VHF Band III. It can be used for T-DAB services in the nationwide SFN.

Next, we investigate the number of DAB ensembles needed to cover all the offered local services for each of the local radio broadcasting areas, which are shown in Table 2. The second column in Table 2 presents the name of the divided local radio broadcasting areas in each T-DMB area. There are 22 local radio broadcasting areas in South Korea. For notational convenience, each local area is designated by a letter and a number, e.g., the three local areas A1, A2, and A3 in the T-DMB area A. The third column shows the number of offered FM radio broadcasting services. Areas A1 and A2 have 23 and two local FM radio broadcasting services, respectively. The last column shows the number of DAB ensembles needed to cover all local radio broadcasting services in each area. For area A1, as 23 local broadcasting services are offered, three ensembles are required. For local T-DAB services in the other areas, the number of required ensembles is determined in the same manner. One ensemble is also required to the nationwide SFN in all areas. Figure 3 depicts 22 local radio broadcasting areas and the site of kilowatt-class transmitters providing the local radio broadcasting services for each area. In the case of area A1, there are two transmitters: Tx.1-1 and Tx.1-2. The self-interference deployment scenarios for the nationwide SFN are investigated according to the separation distance between the kilowatt-class transmitters of adjacent local broadcasting areas in Section 3.

Table 2: Number of FM broadcasting services and required DAB ensembles for each local radio broadcasting area.

DMB Area	Local Radio Broadcasting Area (Area Name)	# of FM Broadcasting Services	# of Required Ensembles for Local T-DAB
A	A1 (Seoul)	23	3
	A2 (Incheon)	2	1
	A3 (Gyeonggi)	3	1
B	B4 (Chuncheon)	11	2
	B5 (Gangneung)	13	2
	B6 (Wonju)	7	1
	B7 (Samcheok)	7	1
C	C8 (Daejeon)	13	2
	C9 (Cheongju)	9	1
	C10 (Chungju)	7	1
D	D11 (Andong)	10	2
E	E12 (Daegu)	15	2
	E13 (Pohang)	12	2
F	F14 (Ulsan)	11	2
	F15 (Busan)	16	2
	F16 (Changwon)	10	2
G	G17 (Jinju)	7	1
H	H18 (Joenju)	11	2
I	I19 (Gwangju)	17	2
	I20 (Mokpo)	7	1
J	J21 (Yeosu)	10	2
K	K22 (Jeju)	12	2

3. T-DAB Channel-Allocation Plan and Interference Deployment Scenarios

The T-DAB channel-allocation plan for national and local T-DAB services is investigated in accordance with the investigated available channels, as shown in Table 1, and the number of required ensembles, as shown in Table 2, for each local radio broadcasting area. The ensembles with the lowest channel-interference impact are allocated according to the channel-interference analysis. The channel-interference analysis is performed for two interference cases, as follows:

(1) CCI and ACI between the allocated DAB ensembles for national and local services (DAB ↔ DAB)

(2) CCI and ACI between the allocated DAB ensemble for local services and the existing DMB ensemble (DAB ↔ DMB)

Self-interference analysis is performed to check the implementation feasibility of the nationwide SFN.

Table 3 shows the proposed DAB channel-allocation plan for national and local T-DAB services. Because the same channel is required for all areas for the nationwide SFN, we designate an ensemble 10A of CH 10 as an available channel for the nationwide SFN. Following the allocation of ensemble 10A for all areas, three local broadcasting areas—C8, C9, and C10—may face spectrum scarcity because the three ensembles of CH 10 are the only available channels and the number of required ensembles is four for all local broadcasting services of these areas. For areas C9 and C10, which each require one ensemble, ensembles 10B and 10C are allocated, respectively. For the 13 local broadcasting services of area C8, two available ensembles should be investigated in the other channels. In the T-DMB frequency band from CH 7 to CH 13, CH 8 and CH 12 are not available in area C8, because of the strong CCI between areas A, H, and C8. Additionally, CH 7 and CH 9 cannot be allocated, because of the strong CCI between area C8 and areas D, E, and G, to which these channels are allocated. Because the separation distance between areas B and C8 is longer than the others and area B is mountainous, CH 13 of area B has the smallest CCI effect for area C8 among all the channels investigated. Therefore, ensembles 13A and 13B are allocated for the T-DAB services of area C8. The CCI analysis result between areas B and C8 is presented in Section 4. Next, the channel allocation is performed for three local broadcasting areas: A1, A2, and A3. For area A, CH 7, CH 9, and CH 10 are investigated as available channels, as shown in Table 1. Because three ensembles are required for the 23 local broadcasting services of area A1, as shown in Table 2, ensembles 9A, 9B, and 9C are allocated for area A1. Ensembles of CH 7 and CH 10 can be allocated for areas A2 and A3, and ensembles of CH 7 are not affected by the CCI or ACI between adjacent areas.

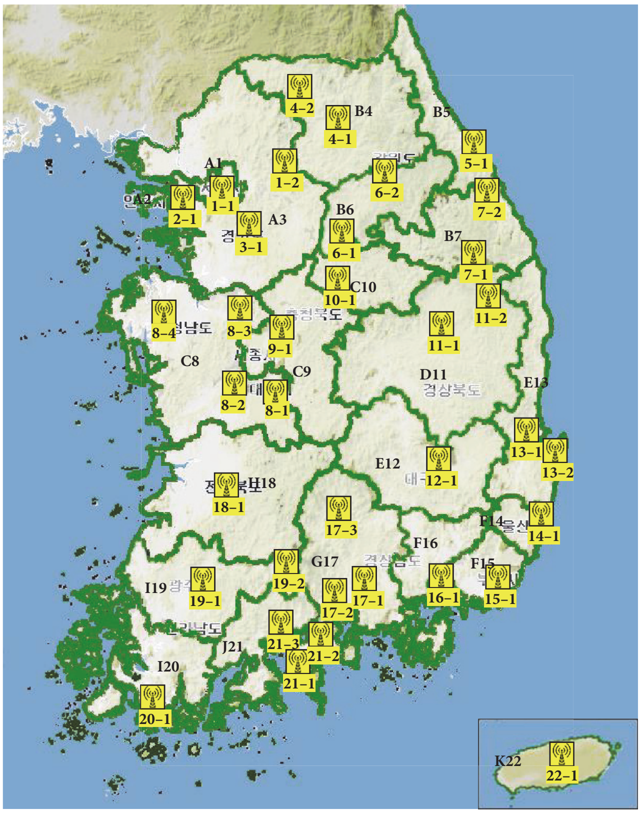


Figure 3: Local radio broadcasting areas and the distribution of kilowatt-class transmitters in each area.

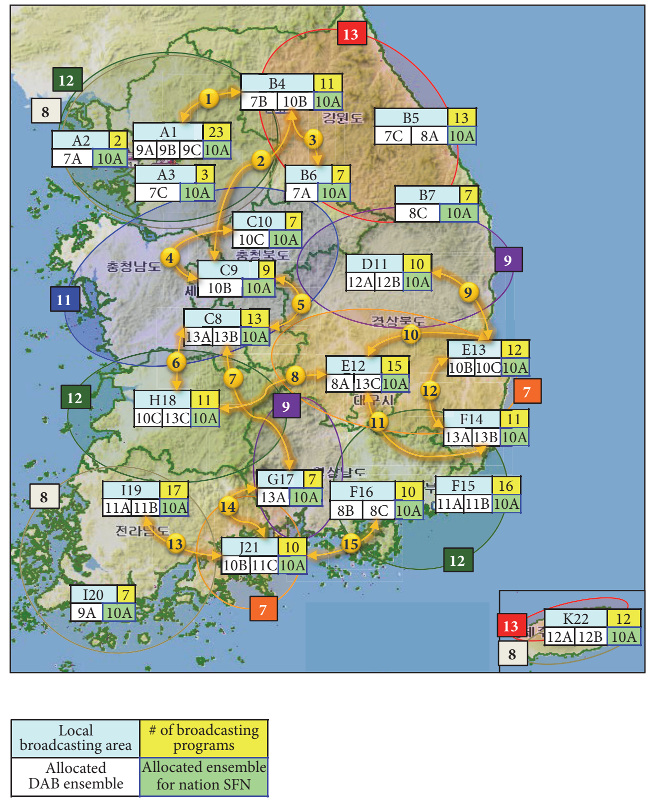


Figure 4: Considered CCI and ACI deployment scenarios between allocated DAB ensembles (DAB ↔ DAB).

According to the required number of ensembles, ensembles 7A and 7C are allocated for areas A2 and A3, respectively. Because areas A2 and A3 are contiguous, ensemble 7B is not allocated, to avoid ACI. The channel allocation is considered for local broadcasting areas B4, B5, B6, and B7 of area B. As shown in Table 1, area B has two available channels: CH 7 and CH 10. Between CH 7 and CH 10, ensembles 7C and 10C cannot be allocated for areas B4 and B6, because of the CCI caused by the adjacent areas A3 and C10. Ensembles 7A, 7B, and 10B can be allocated. Area B4 requires two ensembles for 11 local broadcasting services, and ensembles 7B and 10B are allocated for area B4. Ensemble 7A is allocated for seven local broadcasting services of area B6. Three ensembles are required for areas B5 and B7, but the remaining available channel has only one ensemble, 7C. In this study, we consider the used ensembles 8A and 8C for T-DMB services in area A, which is far from areas B5 and B7. In particular, area B5 is surrounded by a range of mountains; thus, it can avoid the channel interference. Therefore, ensembles 7C and 8A are allocated for local T-DAB services in area B5, and ensemble 8C is allocated in area B7. Similarly, ensembles for local T-DAB services are allocated for the remaining local areas considering the investigated conditions, as shown in Tables 1 and 2. Next, two channel-interference cases and the self-interference case are investigated for the allocated DAB ensembles, as shown in Table 3, and the interference areas are investigated via interference analysis.

3.1. CCI and ACI Cases between Allocated DAB Ensembles for National and Local Services (DAB ↔ DAB).

Figure 4 depicts all the CCI and ACI deployment scenarios between allocated ensembles for T-DAB services (DAB ↔ DAB). According to the local broadcasting areas, the number of radio broadcasting services and allocated DAB ensembles are expressed in the figure. First, because ensemble 10A is allocated for all areas for the nationwide SFN, ACI analysis is required for both areas to which ensemble 10B is allocated, as well as adjacent areas. The analysis of ACI by the nationwide SFN channel is performed between area B4 and two areas A1 and B6; between area E13 and three areas D11, E12, and E14; and between area J21 and three areas F16, G17, and I19. Although area B4 is far from area C9, cochannel 10B is allocated for these two areas. Therefore, CCI analysis is performed between areas B4 and C9. As shown in Figure 4, areas for which CCI or ACI is considered are connected by the arrow, and the number in the middle of each of arrow indicates the deployment scenario number for CCI or ACI. The analysis for CCI and ACI should be performed for 15 cases, as follows.

- CCI and ACI deployment scenarios for DAB ↔ DAB -

(1) area A1 (10A) ↔ area B4 (10B)
(2) area B4 (10B) ↔ area C9 (10B)
(3) area B4 (10B) ↔ area B6 (10A)

Table 3: Channel-allocation plan for national and local T-DAB services.

DMB Area	Local Radio Broadcasting Area (Area Name)	Allocated DAB Ensembles
A	A1 (Seoul)	9A, 9B, 9C, **10A**
	A2 (Incheon)	7A, **10A**
	A3 (Gyeonggi)	7C, **10A**
B	B4 (Chuncheon)	7B, 10B, **10A**
	B5 (Gangneung)	7C, 8A, **10A**
	B6 (Wonju)	7A, **10A**
	B7 (Samcheok)	8C, **10A**
C	C8 (Daejeon)	13A, 13B, **10A**
	C9 (Cheongju)	10B, **10A**
	C10 (Chungju)	10C, **10A**
D	D11 (Andong)	12A, 12B, **10A**
E	E12 (Daegu)	8A, 13C, **10A**
	E13 (Pohang)	10B, 10C, **10A**
F	F14 (Ulsan)	13A, 13B, **10A**
	F15 (Busan)	11A, 11B, **10A**
	F16 (Changwon)	8B, 8C, **10A**
G	G17 (Jinju)	13A, **10A**
H	H18 (Joenju)	10C, 13C, **10A**
I	I19 (Gwangju)	11A, 11B, **10A**
	I20 (Mokpo)	9A, **10A**
J	J21 (Yeosu)	10B, 11C, **10A**
K	K22 (Jeju)	12A, 12B, **10A**

(4) area C9 (10B) ↔ area C10 (10A, 10C)
(5) area C8 (10A) ↔ area C9 (10B)
(6) area C8 (13B) ↔ area H18 (13C)
(7) area C8 (13A) ↔ area G17 (13A)
(8) area E12 (13C) ↔ area H18 (13C)
(9) area D11 (10A) ↔ area E13 (10B)
(10) area E12 (10A) ↔ area E13 (10B)
(11) area E12 (13C) ↔ area F14 (13B)
(12) area E13 (10B) ↔ area F14 (10A)
(13) area I19 (10A, 11B) ↔ area J21 (10B, 11C)
(14) area G17 (10A) ↔ area J21 (10B)
(15) area F16 (10A) ↔ area J21 (10B)

3.2. CCI and ACI Cases between Allocated DAB Ensembles for Local Services and Existing DMB Ensembles (DAB ↔ DMB). Next, the considered CCI and ACI between the allocated DAB ensemble and the existing DMB ensemble must be analyzed. Figure 5 shows all the CCI and ACI deployment scenarios between the allocated DAB ensemble and the existing DMB ensemble (DAB ↔ DMB). In all cases, both CCI analysis and ACI analysis should be performed, because three ensembles of one VHF channel are in use for T-DMB services in each of the DMB areas. First, CCI and ACI analysis is performed between DAB ensemble 12A of area D11 and DMB ensembles 12A and 12B of area A and between DAB ensemble 12B of area D11 and DMB ensembles 12A, 12B, and 12C of area A. In this study, the CCI for ensemble 12B and the ACI for ensembles 12A and 12B are investigated for every CCI and ACI deployment case between areas A and D11. For areas A and B7, the CCI for ensemble 8C and the ACI for ensembles 8B and 8C are also investigated. The analysis of the CCI and ACI should be performed for the following seven cases.

- CCI and ACI deployment scenarios for DAB ↔ DMB -

(1) area D11 (12A, 12B) ↔ area A (CH12)
(2) area C8 (13A, 13B) ↔ area B (CH13)
(3) area B7 (8C) ↔ area A (8B, 8C of CH8)
(4) area B6 (7A) ↔ area E (7A, 7B of CH7)
(5) area I19 (11A, 11B) ↔ area C (CH11)
(6) area I20 (9A) ↔ area G (9A, 9B of CH9)
(7) area F16 (8B, 8C) ↔ area I (CH8)

3.3. Self-Interference Cases for Nationwide SFN (10A). Generally, for signals to be received without self-interference in the SFN, the time difference of received signals must be less than the GI. The GI of a DAB system in transmission mode I is 246 μs [2]. This means that signals can be received without self-interference when the separation distance between adjacent transmitters is up to 73.8 km. Therefore, in the case where the distance between adjacent transmitters is significantly

Table 4: Considered self-interference deployment scenarios in nationwide SFN.

No.	Adjacent Transmitters in which the self-interference analysis is needed		Separation Distance
1	Tx.2-1 of A2	Tx.8-4 of C8	83.80 km
2	Tx.2-1 of A2	Tx.8-3 of C8	88.37 km
3	Tx.8-1 of C8	Tx.12-1 of E12	113.63 km
4	Tx.8-1 of C8	Tx.17-3 of G17	87.91 km
5	Tx.9-1 of C9	Tx.11-1 of D11	99.20 km
6	Tx.10-1 of C10	Tx.11-1 of D11	87.75 km
7	Tx.11-2 of D11	Tx.13-1 of E13	83.83 km
8	Tx.12-1 of E12	Tx.14-1 of F14	79.15 km
9	Tx.12-1 of E12	Tx.17-3 of G17	83.66 km
10	Tx.20-1 of I20	Tx.21-1 of J21	104.75km
11	Tx.20-1 of I20	Tx.21-3 of J21	94.98 km
12	Tx.20-1 of I20	Tx.22-1 of K22	114.74 km

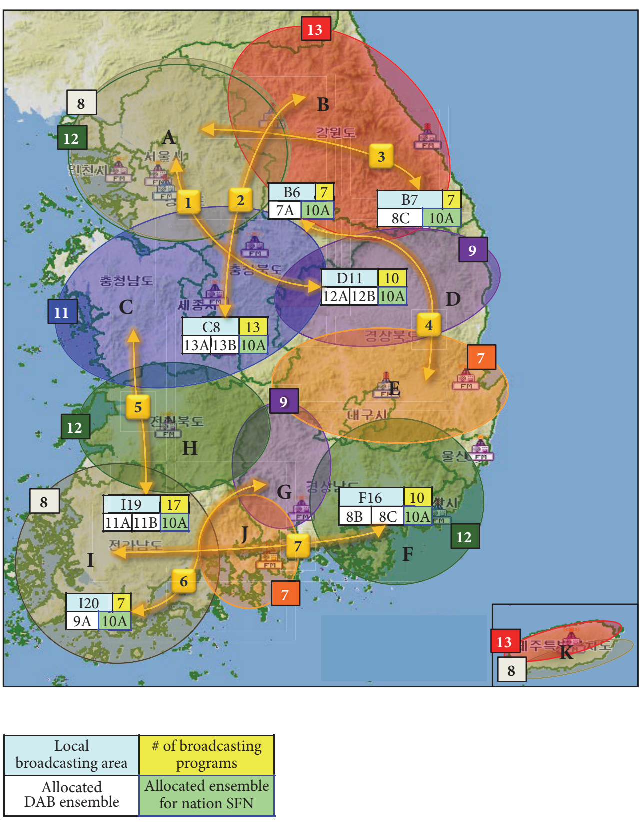


Figure 5: Considered CCI and ACI deployment scenarios between the allocated DAB ensemble and the existing DMB ensemble (DAB ↔ DMB).

greater than 73.8 km, the self-interference analysis should be performed.

To check the self-interference in the nationwide SFN for ensemble 10A, the separation distance for all kilowatt-class transmitters is investigated, as shown in Figure 3. Because existing T-DMB services are provided by a local SFN for each of the DMB areas, an SFN between local radio broadcasting areas in each of the DMB areas is possible. Therefore, the separation distance between the local areas of different DMB areas is investigated. There are one transmitter and four transmitters in areas A2 and C8, respectively, and the separation distance between Tx.8-4 of area C8 and Tx.2-1 of area A2 is 83.8 km. Because this exceeds the standard for SFN operation, the self-interference analysis should be performed. As the separation distance between Tx.8-1 of area C8 and Tx.12-1 of area E12 is 113.63 km, two transmitters are required for the self-interference analysis. Table 4 shows all the deployment scenarios in which the self-interference is considered. The results indicate that the self-interference analysis should be performed for 12 cases.

4. Total Interference Analysis Approach and Results

The interference analysis is performed in two parts, as mentioned in Section 3. First, the analysis of the CCI and ACI between allocated DAB ensembles for national and local services or between the allocated DAB for the local services ensemble and the existing DMB ensemble is performed. Second, the area affected by the self-interference in the nationwide SFN is investigated. The interference analysis results are derived via individual analysis procedures for each part.

4.1. Analysis for CCI and ACI

4.1.1. Detailed Interference Analysis Procedure. The channel-interference analysis is performed for the considered CCI or ACI deployment scenarios between allocated DAB ensembles or between an allocated DAB ensemble and an existing DMB ensemble. The ratio of the interference area to the coverage area is calculated via this analysis.

The spectrum management intelligence system (SMIs) is employed for the channel-interference analysis of the considered channel-interference deployment scenarios, as shown in Figures 4 and 5. This system is supported by the Korea National Radio Research Agency of the Ministry of Science, ICT, and Future Planning. The SMIs is a tool for

Table 5: Simulation parameters.

Parameter	Value	
Frequency	Center frequency of each ensemble	
Minimum Field Strength	45 dBμV/m	
Reception antenna height	2 m	
% of time and location	50% (both)	
Protection ratio	Co-channel	Adjacent
	10 dB	-37 dB

In addition to this, the information and parameters for the transmitters of each broadcasting area—such as the transmitter height, antenna gain, radiation pattern, and propagation loss—are applied.

broadcast network design and analysis for various terrestrial broadcasting methods, such as digital television, amplitude-modulation radio, FM radio, and T-DMB. The propagation analysis can be performed using methods for radio-propagation prediction, such as ITU-R P.1546 [29]. For the CCI and ACI analysis, this study complies with the following procedure.

(1) Select one case among the considered CCI or ACI deployment scenarios, as shown in Figure 4 or 5.

(2) Set up the desired and undesired areas for two areas of the selected case.

(3) Apply the simulation parameters and the transmitter information for each area, as shown in Table 5. The parameter values given in Table 5 are recommended by the Korean domestic standard and ITU-R Rec. [30].

(4) Compute the coverage area according to the transmission power of the transmitters of the desired area, in which the field strength of the reception area meets the minimum-field strength standard of 45 dBμV/m.

(5) Compute the reception-power ratio (RPR) of the signal from the desired area to the signal from the undesired area at an interval of the district of 200 m × 200 m for the computed coverage area in procedure (4). Check the interference area in which the RPR is below the recommended protection ratio for a DAB or DMB system.

(6) Calculate the ratio of the interference area to the overall coverage area for the desired area.

(7) After changing a previous desired area to an undesired area and a previous undesired area to a desired area, repeat procedures (3)–(6).

(8) Change the CCI or ACI deployment scenario and repeat (2)–(7).

4.1.2. Simulation Results and Discussion. Table 6 presents the analysis results for the considered CCI and ACI deployment scenarios between allocated DAB ensembles, as shown in Figure 4. Figures 6(a) and 6(b) depict CCI analysis results between areas B4 and C9 in No. 2, respectively. In Figure 6, the part marked in green indicates the calculated coverage area in the analysis procedure (4). The red spots in the blue circle indicate the calculated interference area in the analysis procedure (5). The part that is unmarked represents the area that the desired signal cannot cover. That is, the ratio of the interference area marked in red in a blue circle to the coverage area marked in green for area C9 is 3.18%, as obtained in procedure (6). The interference-area ratio of area B4 is 0.31% in No. 2. Area C9 in which ensemble 10B is allocated is most affected by allocated ensemble 10A for the nationwide SFN in area C8, as shown in No. 5 of Table 6. Because two areas are close together despite ACI, the interference-area ratio for area C9 is 4.77%. Figures 6(c) and 6(d) show the CCI analysis results for areas C8 and G17, respectively, in No. 7. As the mountains are located between these two areas, the CCI effect for each of the two areas is small compared with No. 2. The

Table 6: Interference-area ratio for CCI and ACI between Allocated DAB ensembles (DAB ↔ DAB).

No.	Local Area	Allocated Ensembles	Interference-area ratio (%)
1	A1	10A	0.06%
	B4	10B	0.78%
2	B4	10B	0.31%
	C9	10B	3.18%
3	B4	10B	0%
	B6	10A	0.16%
4	C9	10B	1.49%
	C10	10A / 10C	1.66%
5	C8	10A	0.32%
	C9	10B	4.77%
6	C8	13B	0.24%
	H18	13C	0.01%
7	C8	13A	0.37%
	G17	13A	1.32%
8	E12	13C	0.57%
	H18	13C	0.74%
9	D11	10A	0%
	E13	10B	0.11%
10	E12	10A	0.24%
	E13	10B	3.31%
11	E12	13C	0.08%
	F14	13B	0.02%
12	E13	10B	0.71%
	F14	10A	0.52%
13	I19	10A / 11B	0.01%
	J21	10B / 11C	0.15%
14	G17	10A	0.45%
	J21	10B	1.58%
15	F16	10A	0.03%
	J21	10B	0%

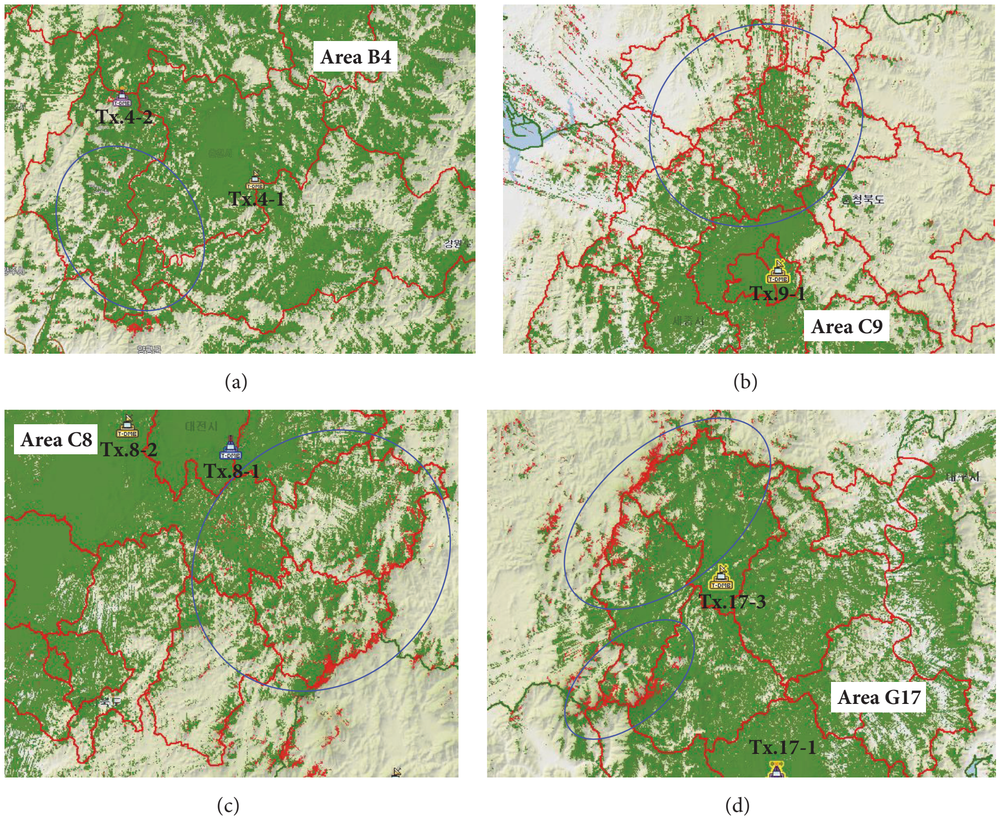


Figure 6: Areas affected by CCI or ACI between allocated DAB ensembles (DAB ↔ DAB): (a) No. 2: interference area of area B4 (10B) by area C9 (10B), (b) No. 2: interference area of area C9 (10B) by area B4 (10B), (c) No. 7: interference area of area C8 (13A) by area G17 (13A), and (d) No. 7: interference area of area G17 (13A) by area C8 (13A).

interference-area ratio for areas C8 and G17 is 0.37% and 1.32%, respectively. The number of areas affected by channel interference between allocated DAB ensembles is 15 among the 22 local radio broadcasting areas, and the interference-area ratio for most areas is <1%.

Table 7 shows the all analysis results for the considered CCI and ACI deployment scenarios between the allocated DAB ensemble and the existing DMB ensemble, as shown in Figure 5. The interference-area ratio caused by ACI is 0% for all the considered channel-interference deployment scenarios. Area C has the highest interference-area ratio in No. 5 among all the results, as shown in Table 7. The interference-area ratio for area C is 4.47%. Figures 7(a) and 7(b) depict the CCI analysis results between allocated DAB ensemble 11B for area I19 and DMB ensemble 11B for area C, respectively, as shown in No. 5 of Figure 5. The southern part of area C and northern part of area I19 are most affected by CCI. The number of areas affected by the channel interference between the allocated DAB ensemble and the existing DMB ensemble is seven among the 22 local radio broadcasting areas and six among the 11 DMB areas.

4.2. Self-Interference Analysis for Nationwide SFN

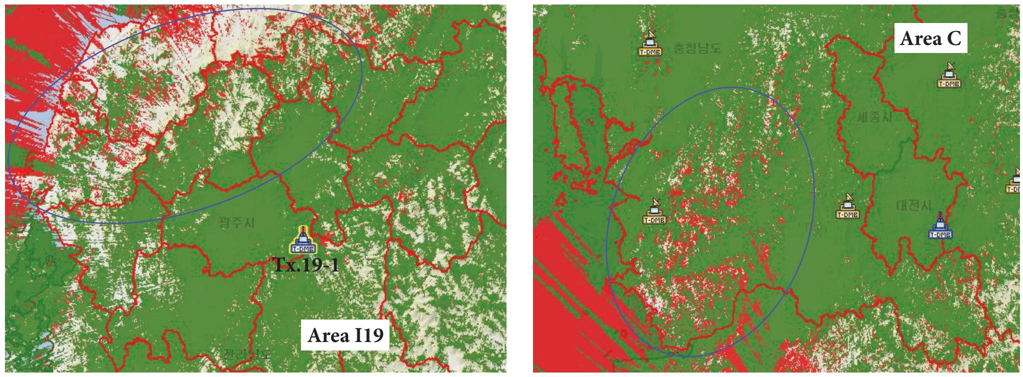
4.2.1. Detailed Interference Analysis Procedure. The self-interference analysis is performed for the considered self-interference deployment scenarios shown in Table 4. For the self-interference analysis, we utilize the derived maximum SFN delay time according to the reception-power difference of signals transmitted in the SFN in the laboratory test of [14]. Theoretically, the maximum SFN delay time of a DAB system in transmission mode I is 246 μs [2]. However, according to the laboratory test result of [14], the maximum SFN delay time caused by the power-difference values between the main signal and the delayed signal for the SFN is given in Table 8. As the power difference is increased (as the power of the delayed signal is decreased), the maximum delay time increases, as shown in Table 8. According to the maximum SFN delay time derived via a laboratory test, in this study, the self-interference analysis is performed using the SMIs. The procedure is as follows:

(1) Select one case among the considered self-interference deployment scenarios shown in Table 4.

(2) Apply simulation parameters and the information for two transmitters of a selected case, as shown in Table 5.

(3) Compute the coverage area of each transmitter.

(4) Compute the RPR and the reception-time difference between the main signal and delayed signal at an interval of the district of 200 m × 200 m for the overall coverage area of the two transmitters.



(a) (b)

Figure 7: Areas affected by CCI between the allocated DAB ensemble and the existing DMB ensemble (DAB ↔ DMB): (a) No. 5: interference area of area I19 (11B) by area C (11B) and (b) No. 5: interference area of area C (11B) by area I19 (11B).

Table 7: Interference-area ratio for CCI and ACI between allocated DAB ensemble and existing DMB ensemble (DAB ↔ DMB).

No.	Local Area	Considered Interference Ensembles	Interference-area ratio (%)
1	D11 Area	12B	1.88%
	A Area	12B	0.03%
2	C8 Area	13B	3.82%
	B Area	13B	2.58%
3	B7 Area	8C	2.17%
	A Area	8C	0.33%
4	B6 Area	7A	1.49%
	E Area	7A	0.5%
5	I19 Area	11B	3.3%
	C Area	11B	4.47%
6	I20 Area	9A	0.26%
	G Area	9A	0.92%
7	F16 Area	8B	1.56%
	I Area	9B	0.61%

The interference-area ratio for ACI is 0% from Nos. 1 to 7.

(5) Compare the maximum SFN delay time, as shown in Table 8, with the calculated RPR and reception-time difference for the overall coverage area in procedure (4).

(6) Check the districts affected by the self-interference in which the calculated RPR and reception-time difference exceed the criterion, as shown in Table 8.

(7) Change the self-interference deployment scenario and repeat (2)–(6)

4.2.2. Simulation Results and Discussion. Table 9 presents the self-interference analysis results for all the considered self-interference deployment scenarios shown in Table 4. In No. 3, the separation distance between Tx.8-1 of area C8 and Tx12-1 of area E12 is 113.63 km, and the maximum delay time of signals transmitted from two transmitters is approximately 379 μs. Therefore, if the RPR is >2 dB for the coverage area of the two transmitters, as per (3)–(5) of the analysis procedure, stable reception is possible in the SFN. However, if the RPR is <2 dB, analysis procedure (6) should be executed. Figures 8(a) and 8(b) show the self-interference analysis results for self-interference deployment scenario No. 3 in Table 4. The part marked in blue indicates districts in which the RPR is >2

Table 8: Maximum delay time and separation distance for SFN.

Power difference	Maximum delay time for SFN	Maximum separation distance for SFN
0 dB	332 μs	99.6 km
-1 dB	353 μs	105.9 km
-2 dB	383 μs	114.9 km
-3 dB	401 μs	120.3 km

Table 9: Areas affected by self-interference in nationwide SFN.

No.	Adjacent transmitters in which the self-interference analysis is needed		Self-interference area
1	Tx.2-1 of A2	Tx.8-4 of C8	area A2
2	Tx.2-1 of A2	Tx.8-3 of C8	None
3	Tx.8-1 of C8	Tx.12-1 of E12	None
4	Tx.8-1 of C8	Tx.17-3 of G17	None
5	Tx.9-1 of C9	Tx.11-1 of D11	None
6	Tx.10-1 of C10	Tx.11-1 of D11	None
7	Tx.11-2 of D11	Tx.13-1 of E13	None
8	Tx.12-1 of E12	Tx.14-1 of F14	None
9	Tx.12-1 of E12	Tx.17-3 of G17	areas E12 and G17
10	Tx.20-1 of I20	Tx.21-1 of J21	None
11	Tx.20-1 of I20	Tx.21-3 of J21	area J21
12	Tx.20-1 of I20	Tx.22-1 of K22	areas I20 and K22

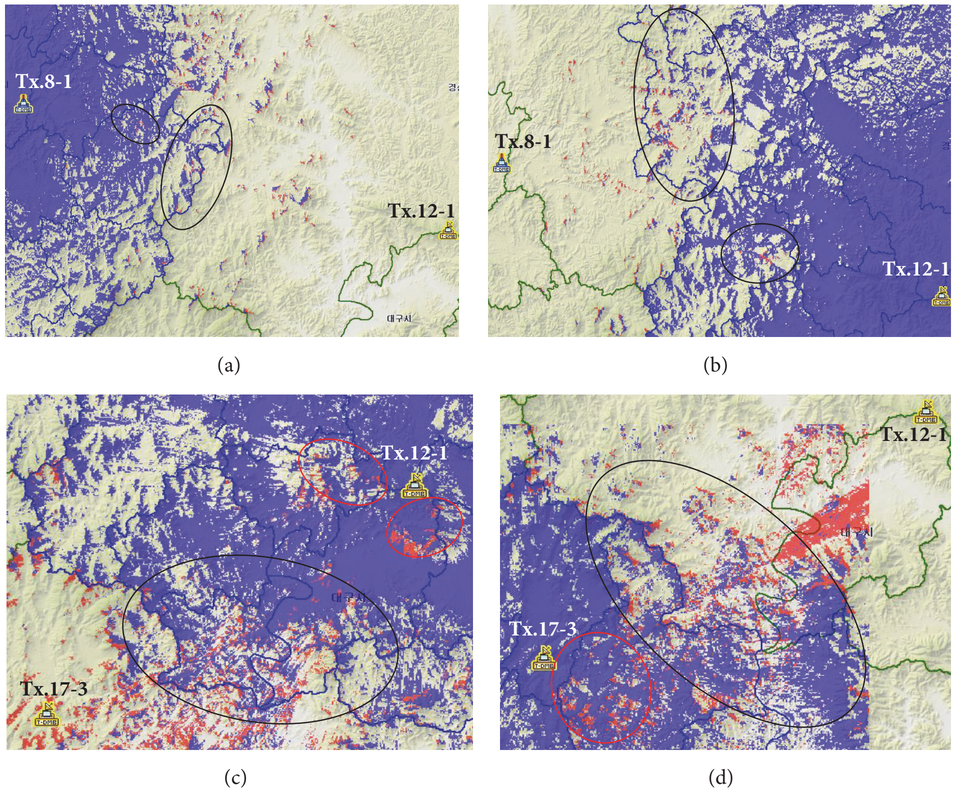


Figure 8: Areas affected by self-interference in the nationwide SFN: (a) No. 3: interference area of area C8 (Tx.8-1), (b) No. 3: interference area of area E12 (Tx.12-1), (c) No. 9: interference area of area E12 (Tx.12-1), and (d) No. 9: interference area of area G17 (Tx.17-3).

dB in the calculated coverage area. The districts marked in red in a black circle indicate the area with a calculated coverage area of <2 dB. For the districts marked in red in a black circle, the RPR is maximized at 20 dB, and the delay time ranges from approximately 82.9 to 118.8 μs. Therefore, the nationwide SFN without the self-interference is possible for the overall coverage area given by Tx.8-1 and Tx12-1 because the delay time is within the GI of 246 μs. Figures 8(c) and 8(d) show the self-interference analysis results for self-interference deployment scenario No. 9 in Table 4. The separation distance between Tx.12-1 of area E12 and Tx.17-3 of area G17 is 83.66 km. The maximum delay time of signals transmitted from two transmitters is approximately 279 μs. Therefore, the nationwide SFN without the self-interference is possible in the coverage area where the RPR is >0 dB. In Figures 8(c) and 8(d), the part marked in blue represents the coverage area without the self-interference, in which the RPR is >0 dB. The strength of the main received signal is low for districts marked in red in the coverage area of both transmitters owing to the signal attenuation by the mountains. The red districts in black and red circles represent areas in which the RPR is <0 dB. However, the reception-time difference of signals for the districts marked in red in a black circle is within the GI, as per analysis procedure (5). For districts marked in red in a red circle, it is approximately 257 μs. Consequently, parts of areas E12 and G17 are affected by the self-interference in the nationwide SFN. In all results, six local broadcasting areas among the 22 local broadcasting areas have partial areas affected by the self-interference.

5. Conclusions

This paper proposes the channel-allocation plan considering the nationwide SFN for local and national T-DAB services in VHF Band III and an approach for broadcasting channel-interference analysis. CCI and ACI deployment scenarios involving allocated DAB ensembles or existing DMB ensembles are investigated. For the implementation of the nationwide SFN, the approach for the self-interference analysis using the SFN channel is investigated. These results provide insights and a method for the frequency planning of various wireless communication systems, including new digital broadcasting systems, as well as an approach for nationwide SFN planning.

On the basis of the results of this study, a method for acquiring more available channels in VHF Band III will be investigated. Furthermore, in-band channel-allocation planning with diverse digital-radio broadcasting services such as T-DMB audio or DRM+ with T-DAB can be investigated.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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