Improving the Reception Performance of Legacy T-DMB/DAB Receivers in a Single-Frequency Network with Delay Diversity

Myung-Sun Baek, Yong-Hoon Lee, Namho Hur, Kyung-Seok Kim, and Yong-Tae Lee

This paper describes a simple delay diversity technique for terrestrial digital multimedia broadcasting (T-DMB) and digital audio broadcasting in a single-frequency network (SFN). For the diversity technique, a delay diversity scheme is adopted. In the delay diversity scheme, a non-delayed signal is transmitted in the first antenna, and delayed versions of the signal are transmitted in each additional antenna. For an SFN environment with multiple transmitters, delay diversity can be executed by controlling the emission times of the transmitters. This SFN delay diversity scheme does not require any hardware changes in either the transmitter or receiver, and perfect backward compatibility can be acquired. To evaluate the performance improvement, laboratory tests are executed with various types of commercial T-DMB receivers as well as a measurement receiver. The improvement in the bit error rate performance is evaluated using a measurement receiver, and an improvement of the threshold of visibility value is evaluated for commercial receivers. Test results show that the T-DMB system can obtain diversity gain using the described technique.

Keywords: Single frequency network, delay diversity, T-DMB/DAB, laboratory test.

I. Introduction

Digital broadcasting techniques have replaced conventional analog broadcasting and can provide improved picture and sound quality. Digital audio broadcasting (DAB) can provide CD-like audio quality and multimedia information, such as photos, electronic newspapers, and traffic information [1]-[4]. Since DAB is designed for mobile reception, it can provide high-quality audio at a very high mobile speed of up to 200 km/h [5]. Terrestrial digital multimedia broadcasting (T-DMB) was developed based on the Eureka-147 DAB system [2], [4]. T-DMB can provide various multimedia services in a mobile environment. Both DAB and T-DMB use coded orthogonal frequency-division multiplexing (COFDM). COFDM is an effective technique for wireless mobile broadcasting with a high data rate and can support a single-frequency network (SFN). Since an SFN broadcasting environment can provide high spectral efficiency [6]-[8], DAB and T-DMB consider an SFN broadcasting environment.

Multiple antennas can be applied to a COFDM system to obtain spatial diversity [9]-[11]. A very simple and elegant method called delay diversity was proposed [12]-[16] and has been used in many system designs in which low-cost implementation is an important issue. With the use of delay diversity, a randomization of the channel frequency response increases the frequency selectivity of the resulting channel transfer function, thereby significantly reducing the likelihood of deep fading [14]-[16].

However, in a system using a delay diversity technique, owing to the use of multiple antennas, it is necessary to change

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Manuscript received Aug. 30, 2013; revised Dec. 2, 2013; accepted Dec. 16, 2013.

Myung-Sun Baek (phone: + 82 42 860 5887, sabman@etri.re.kr), Yong-Hoon Lee (lee.y.h@etri.re.kr), Namho Hur (namho@etri.re.kr), and Yong-Tae Lee (ytlee@etri.re.kr) are with the Broadcasting & Telecommunications Media Research Laboratory, ETRI, Daejeon, Rep. of Korea.

Kyung-Seok Kim (kseokkim@cbnu.ac.kr) is with the Department of Electrical and Electronics Engineering, Chungbuk National University, Cheongju, Rep. of Korea.

http://dx.doi.org/10.4218/etrij.14.2113.0045

the hardware of both the transmitters and the receivers. Furthermore, it is very hard to apply multiple antennas to existing systems owing to compatibility, size, cost, and/or hardware limitations.

In an SFN environment, multiple transmitters (base stations) are synchronized with each other, and the transmitters jointly deliver a signal to a common service area in the SFN. Therefore, in the SFN area, users can receive a broadcasting signal from multiple transmitters that build the SFN. This paper presents a method to obtain diversity gain in an SFN environment. In an SFN environment, multiple transmitters adjust the transmission times. By selecting the proper delay time, multiple transmitters can execute a delay diversity technique. The receivers of an SFN area can obtain delay diversity gain by adjusting delay values for each transmitter. The performance improvement is shown through laboratory test results. For the laboratory test, a board-type measurement receiver that can measure various system parameters, including the bit error rate (BER), received signal strength indicator (RSSI), and audio cyclic redundancy check (CRC), is used. Furthermore, for more practical information, the laboratory tests consider various kinds of commercial receivers, that is, a car navigator, personal multimedia player (PMP), cellular phone, and a T-DMB receiver for an iPhone or iPad.

From the laboratory test results, the presented SFN delay diversity technique can acquire about a 3-dB diversity gain for the measurement receiver at BER = 10^{-4} in a 6-tap typical urban (TU6) channel model. In addition, on average, about a 1.6-dB diversity gain is acquired for various commercial receivers.

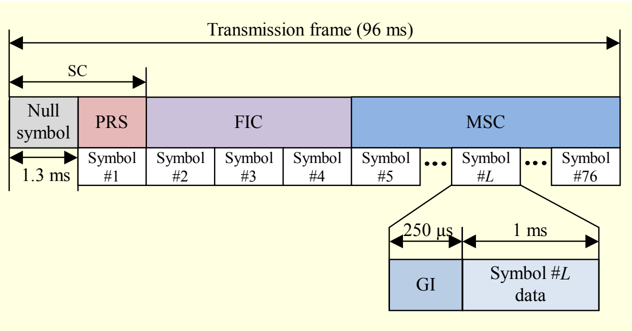

Fig. 1. Transmission frame of T-DMB/DAB system.

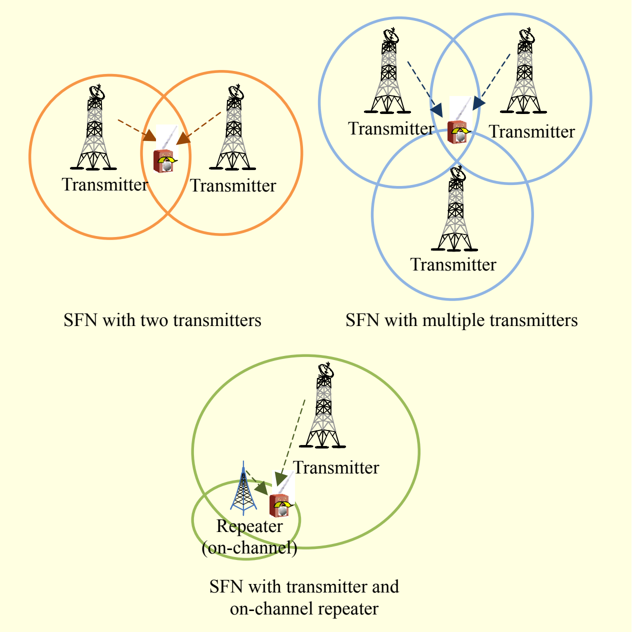

Fig. 2. Various SFN environments of T-DMB/DAB system.

II. T-DMB/DAB System in SFN Environment

The transmission signal of a T-DMB/DAB system is arranged into a transmission frame, as shown in Fig. 1 [1], [17]. The first OFDM symbol of a transmission frame is a null symbol, which is the duration of no signal transmission. The second OFDM symbol is the positioning reference signal (PRS), which has fixed magnitudes and a known phase on each subcarrier. These two symbols comprise the synchronization channel (SC). The main service channel (MSC) is used to transmit each service, which is individually encoded and time-interleaved. The fast information channel (FIC) is used to transmit the control data necessary for demultiplexing and decoding of the MSC part in each transmission frame. The frame consists of 76 OFDM symbols, and each OFDM symbol has a 1-ms data part and 250-µs guard interval (GI) part.

At the transmitter, complex differential quadrature phase-shift keying (DQPSK) symbols are modulated by means of the inverse fast Fourier transform (IFFT) on K parallel subcarriers, and the transmitted signal, x_m, can then be expressed as follows:

$$x_m = \sum_{k=0}^{K-1} X_k e^{j2\pi \frac{km}{K}}, \qquad (1)$$

where X_k represents a DQPSK symbol in the k-th subcarrier. In addition, K and m are the number of subcarriers and the index of the time domain sample, respectively. For the transmission, the last K_G samples are preceded as the GI, and $K + K_G$ samples are transmitted during $T_S = T + T_G$, where T is the duration of an OFDM symbol and T_G is the GI duration. For T-DMB, T is 1 ms, T_G is 0.25 ms, and T_S is 1.25 ms.

In an SFN environment, multiple transmitters use an identical frequency to transmit a broadcasting signal [6], [18]-[19]. As shown in Fig. 2, there are various SFN environments, and the receiver in the overlapped area receives the

Table 1. TU6 (non-hilly) area.

Tap no.	Delay (µs)	Power (dB)	Doppler category
1	0.0	–3	CLASS
2	0.2	0	CLASS
3	0.5	–2	CLASS
4	1.6	–6	GAUS1
5	2.3	–8	GAUS1
6	5.0	–10	GAUS1

broadcasting signal from multiple transmitters. Since the broadcasting signal is transmitted at the same frequency, the received signal is the superposition of the signals transmitted from multiple transmitters. The received signal can be written as

$$r_k = \sum_{n=1}^{N_t} h_k^{(n)} \otimes x_k^{(n)} + w_k , \qquad (2)$$

where r_k (for k=0,…, K–1) is the k-th received signal, w_k is additive white Gaussian noise (AWGN), ⊗ is a circular convolutional calculation, $x_k^{(n)}$ is the k-th transmitted signal of the n-th transmitter, and $h_k^{(n)}$ is the channel impulse response from the n-th transmitter, which can be written as

$$h_k^{(n)} = \left[h_k^{(n)}(\tau_1), \ldots, h_k^{(n)}(\tau_{\max}) \right], \qquad (3)$$

where τ_l is the delay time of the l-th path and $\tau_{\max}$ is the delay value of the last path of $h_k^{(n)}$. In this paper, a TU6 channel model and one-path Rayleigh channel model are used. Table 1 describes the TU6 channel model [20]. In Table 1, “CLASS” indicates a classical Jakes’ Doppler spectrum, and “GAUS1” is a bi-Gaussian Doppler spectrum [20]. As shown in Table 1, the channel has six paths, and the delay value of the last path is 5 µs. Therefore, in the TU6 channel, $\tau_{\max}$ is 5 µs.

Since each signal is transmitted from a different transmitter, it is very hard to transmit the signal at the same time. Of course, there are transmission time differences in each transmitter. Considering a time difference, the received signal can be rewritten as

$$r'_k = \sum_{n=1}^{N_t} h_k^{(n)} \otimes x_{k+T_D(n)}^{(n)} + w_k , \qquad (4)$$

where r'_k is the received signal from a delayed transmitted signal, and $T_D(n)$ is the transmission delay value of the n-th transmitter.

To prepare the superposition of multiple signals, the transmitters have to adjust the transmission times and time differences from each other. Generally, the time difference has to be less than the GI. As shown in Fig. 1, since the GI of T-DMB/DAB is 250 µs, the time difference should be within 250 µs.

III. SFN Delay Diversity Technique for T-DMB/DAB System

There are many different diversity techniques for wireless communications and broadcasting, such as a space-time block code [21] and space-time trellis code [22]. Although these two techniques can provide a very high diversity gain, a change in the receiver structure is required. It is therefore very hard to adopt the above techniques in existing broadcasting systems. Among the diversity techniques, the delay diversity technique [14] is very simple and easy and does not change the receiver structure. In general, delay diversity is based on a multiple transmit antenna system and executed by adopting a delay value in each transmitting antenna, as shown in Fig. 3(a). By selecting the proper delay value, it is possible to obtain full spatial diversity. However, owing to the use of multiple transmitting antennas, the transmitter requires additional hardware and various changes. It is therefore hard to adopt this delay diversity technique with multiple antennas to existing systems. In the SFN environment with multiple transmitters, since the receiver can receive a transmitted signal from multiple transmitters, the delay diversity can be executed by multiple transmitters with a single antenna. Fig. 3(b) describes the SFN delay diversity technique with multiple transmitters.

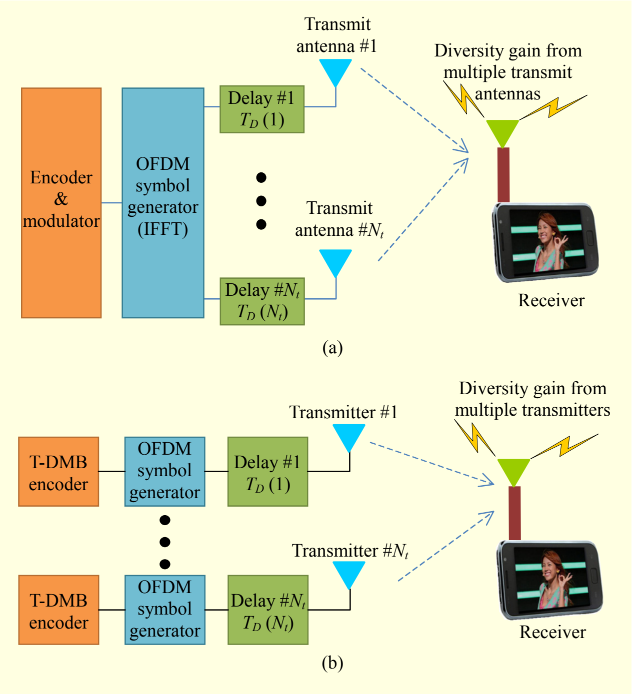

Fig. 3. Delay diversity techniques with multiple (a) antennas and (b) transmitters.

In this SFN environment with a delay diversity technique, the proper delay value has to be considered to obtain full spatial diversity gain. To maximize the frequency diversity of a transmitted signal, all paths have to be obtained for all transmitters. Furthermore, to prevent inter-symbol interference (ISI), the delay value has to be less than the GI duration (T_G). In an SFN environment with two transmitters, the condition of the proper delay time can thus be written as

$$\tau_{\max} < \mathrm{all}(T_D) < T_G \,, \tag{5}$$

where $\mathrm{all}(T_D)$ indicates all delay values, which are $[T_D(1) \cdots T_D(N_t)]$. If all N_t transmitters use an identical delay value, that is, T_D, the received signal can be written as

$$y_k = (x_k \otimes h_k^{(1)} + x_{k-T_D} \otimes h_k^{(2)} + \cdots + x_{k-N_t \cdot T_D} \otimes h_k^{(N_t)}) + w_k \,, \tag{6}$$

where y_k is the k-th received signal and x_k is k-th transmitted signal. In addition, the above equation can be written in the frequency domain as follows:

$$Y_k = \sum_{n=1}^{N_t} H_k^{(n)} e^{-j(2\pi/K)^{k \cdot n \cdot T_D}} X_k + Z_k \,, \tag{7}$$

where Y_k is the received signal of the frequency domain, $Y_k = FFT(y_k)$, $H_k^{(n)}$ is the frequency response of the channel, $H_k^{(n)} = FFT(h_k^{(n)})$, and Z_k is the AWGN of the frequency domain, $Z_k = FFT(z_k)$.

The effective channel of the received signal is as follows:

$$H_k = \sum_{n=1}^{N_t} H_k^{(n)} e^{-j(2\pi/K)k \cdot n \cdot T_D} \,. \tag{8}$$

A simple presentation of the received signal in the frequency domain can be written as

$$Y_k = H_k X_k + Z_k \,. \tag{9}$$

To detect the transmitted signal, the soft-decision variable for X_k becomes

$$V_k = H_k^* \cdot Y_k \,. \tag{10}$$

From frequency response H_k of the channel, the phase change causes a time delay of the time-domain channel impulse response [14]. The channel impulse response of the time domain can be written as

$$h_k = h_k^{(1)} + h_{k-T_D}^{(2)} + \cdots + h_{n-N_t \cdot T_D+1}^{(N_t)} \,. \tag{11}$$

With the assumption that h_k is an independently and identically distributed complex Gaussian random process, the expected value of each channel response is

$$E\left[| h_k^{(1)} |^2 \right] = \cdots = E\left[| h_{k-N_t \cdot T_D}^{(N_t)} |^2 \right] = 0 \,. \tag{12}$$

The receiver can obtain

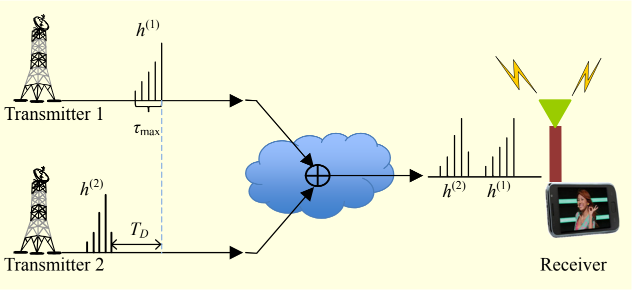

Fig. 4. Effect of SFN delay diversity technique.

$$E\left[| h_k |^2 \right] = E\left[| h_k^{(1)} |^2 \right] + \cdots + E\left[| h_{k-N_t \cdot T_D}^{(N_t)} |^2 \right], \tag{13}$$

where $E\left[| h_{k-n \cdot T_D}^{(n)} |^2 \right]$ is the average power gain of the channel between the n-th transmitter and receiver at time k. The receiver can acquire additional paths from the use of multiple transmitters. In the case of L paths, h_k can have LN_t paths. Figure 4 shows an example of delay diversity with two transmitters. As Fig. 4 indicates, using this simple delay process, the receiver can acquire LN_t diversity order. As mentioned, the delay value has to be more than $\tau_{\max}$ to obtain full diversity order.

IV. Laboratory Test Environment

For an evaluation of the delay diversity technique in an SFN environment, a laboratory test is executed. For the laboratory test, the SFU of Rohde and Schwarz [23] and a measurement receiver are used. Figure 5 describes the testbed used for the laboratory test. The SFU generates multipath fading and transmits a T-DMB signal through the fading channel. Since the SFU can support multiple transmitters, the laboratory test of the diversity technique can be executed using just one SFU. In

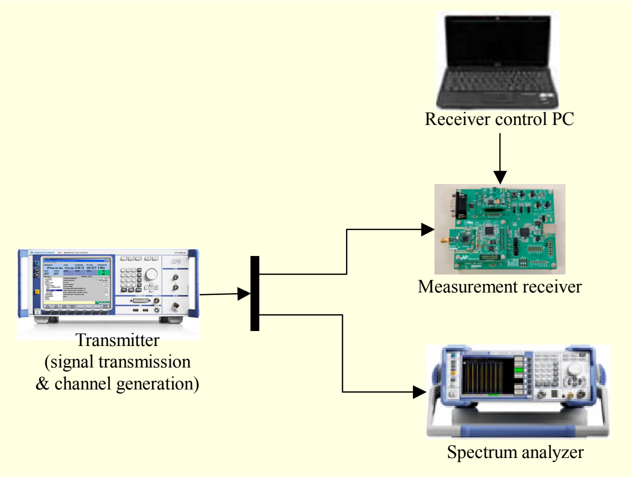

Fig. 5. Testbed for laboratory test with measurement receiver.

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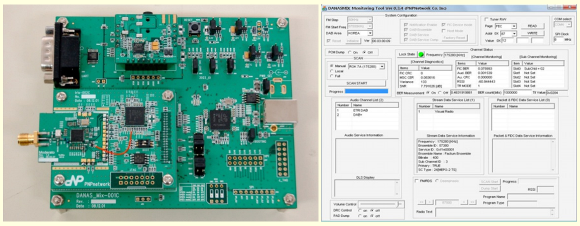
(a) (b)

Fig. 6. (a) Measurement receiver and (b) operating program.

the SFU, multiple T-DMB signals are transmitted to the measurement receiver. The measurement receiver is controlled by a PC running a receiver operation program. In addition, the performance of the transmitted signal is evaluated by the measurement receiver. In the case of multiple transmitters, each emission time is controlled to obtain the diversity gain. The performance is measured according to the difference in emission time. The performance of the diversity technique is evaluated based on the BER. To measure the BER value, an ensemble transport interface frame is built using a known pattern. The measurement receiver shown in Fig. 5 is designed according to this known pattern. Therefore, the SFU sends the predefined data pattern to the measurement receiver, and the received data sequence is compared with the same known pattern. Figure 6(a) shows the measurement receiver feature. To operate the measurement receiver, the operating program is built as shown in Fig. 6(b). Using the measurement receiver and operating program, various performance items can be measured (for example, BER, RSSI, and audio CRC). Two transmitters are considered in this test. For the channel model between transmitters and receiver, the TU6 channel model and one-path Rayleigh channel model are used. In this test, to obtain the delay diversity with two transmitters, the receiver is fixed in the SFN area. Therefore, Doppler frequency shifts are not considered in the TU6 channel and one-path Rayleigh channel environments. Two SFN environments can therefore be considered as follows:

1. Tx 1 → Rx: TU6, Tx 2 → Rx: TU6;
2. Tx 1 → Rx: one-path Rayleigh channel, Tx 2 → Rx: one-path Rayleigh channel.

The test process is executed as follows:

1. Operate one T-DMB transmitter of SFU in the TU6 channel model.
2. Measure the performance of the received signal according to the C/N value.
3. Operate two T-DMB transmitters of the SFU in the TU6 channel model.
4. Add a delay value to the emission time of the second transmitter.
5. Measure the performance of the received signal according to the C/N value.
6. Increase the delay value of the second transmitter, and repeat 5.
7. Change the TU6 channel model to a one-path Rayleigh fading channel, and repeat steps 1 through 6.


(a)

(b)

Fig. 7. Laboratory testbed with (a) transmitter and spectrum analyzer and (b) various kinds of commercial T-DMB receivers.

To measure the performance improvement of commercial receivers, a laboratory test with various types of commercial receivers is executed, as shown in Fig. 7. Four kinds of cellular phones, one car navigator, one PMP, and one T-DMB receiver for an iPhone/iPad are used as commercial receivers. In this test, the receiver sensitivity of each receiver was measured to check the threshold of visibility improvement. First, the receiver sensitivities of all receivers are measured in a single-transmitter environment. The receiver sensitivities of all receivers are then evaluated in a two-transmitter environment using the SFN delay diversity technique. The receiver sensitivities between single- and two-transmitters environment are compared, and the diversity gains of the presented technique are calculated for all receivers. To obtain reliable results, this test is repeated many times, and the results are recorded and averaged.

V. Laboratory Test Results

Figure 8 shows the BER performance of the SFN delay diversity technique in a two-transmitter environment, using a TU6 channel model. As shown in Table 1, the maximum channel delay value of TU6 is 5 µs, and multiple paths with high power (0 dB to –3 dB) exist from 0 µs to 0.5 µs. In the case of low delay values (0.4 µs and 0.5 µs), since the two channels overlap, the delayed signal interferes with the original signal. The performances of SFN delay diversity with low delay values are worse than that of one transmitter. From a 0.7-µs delay value, the performance of SFN delay diversity is highly improved because the high power channel paths do not overlap. As the delay value increases, the receiver can acquire a higher diversity gain. The performance with a 2.6-µs delay value is about 2 dB better than that of the one-transmitter model at BER = 10^{-3}.

Figure 9 depicts the BER performance of the delay diversity technique with a high delay value (250 µs to 350 µs). To prevent ISI, the delay value, T_D has to be less than the GI duration T_G. A 250-µs delay value means $T_D = T_G$. Therefore, the performance degradation is not high in the case of a delay value of 250 µs. However, a very high performance degradation can be shown for delay values of 300 µs and 350 µs.

Figure 10 shows the BER performance of the SFN delay diversity technique with two transmitters in a one-path Rayleigh channel model. Since the channel has just one path, there is no channel duration. Therefore, diversity gain is obtained by a much smaller delay value. All delay values have a very similar BER performance of about 1.2 dB better than that of a single- transmitter. Figure 11 depicts the BER performance of the delay diversity technique with a high delay value (250 µs to 350 µs). In the case of a 250-µs delay value, the SFN delay diversity technique obtains about a 1.2 dB gain. However, with an increase in the delay value, the BER performance is significantly decreased.

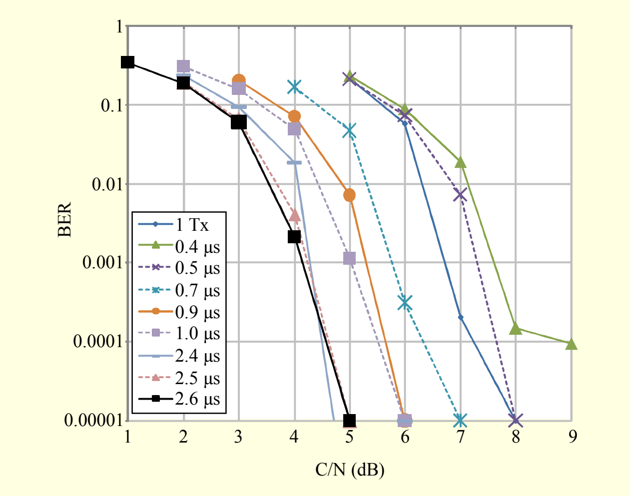

Fig. 8. BER performance of SFN delay diversity technique in a two-transmitter environment, using a TU6 channel model (low delay value).

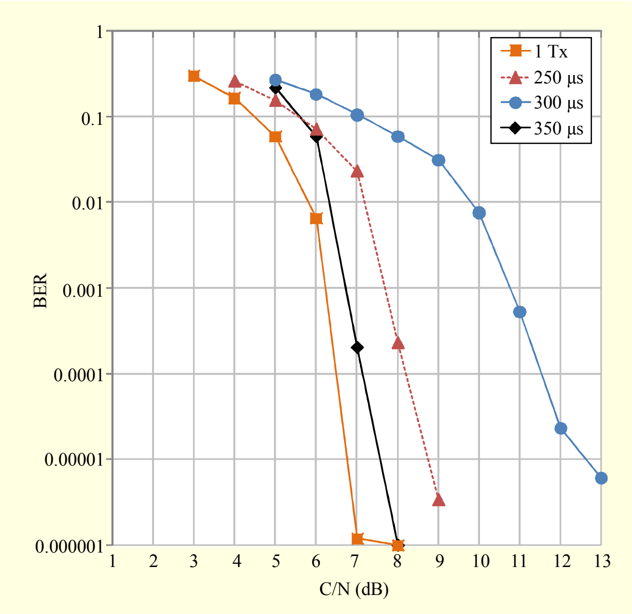

Fig. 9. BER performance of SFN delay diversity technique with two transmitters in TU6 (high delay value).

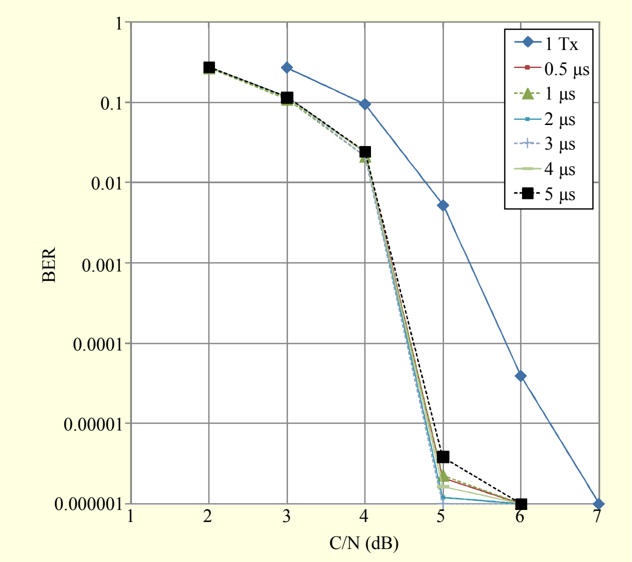

Fig. 10. BER performance of SFN delay diversity technique with two transmitters in one-path Rayleigh channel (low delay value).

Table 2 depicts the laboratory test results with various commercial receivers. In the laboratory test, seven kinds of

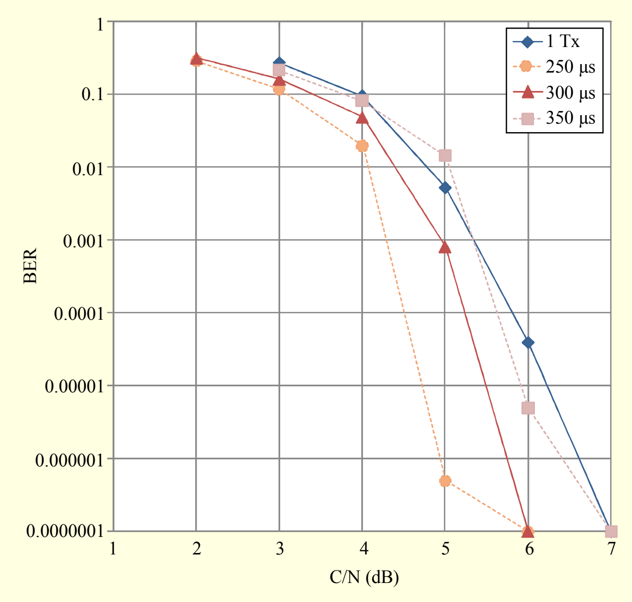

Fig. 11. BER performance of SFN delay diversity technique with two transmitters in one-path Rayleigh channel (high delay value).

Table 2. Laboratory test results of commercial T-DMB receivers.

T-DMB receiver type	Index of test receivers	Receiver sensitivity with 1 Tx	Receiver sensitivity with delay diversity	Diversity gain
Navigation	N1	–32.6 dB	–34.1 dB	1.5 dB
PMP	P1	–32.5 dB	–34.8 dB	2.3 dB
Receiver for iPhone/iPad	i1	–44.9 dB	–46.4 dB	1.5 dB
Cellular phone	C1	–41.1 dB	–41.5 dB	0.4 dB
	C2	–41.6 dB	–43.6 dB	2.0 dB
	C3	–41.6 dB	–43.4 dB	1.8 dB
	C4	–45.3 dB	–46.7 dB	1.4 dB

commercial receivers are considered. The channel model, TU6 is selected (Tx 1 → Rx: TU6, Tx 2 → Rx: TU6), and a 2.6-μs delay value is applied to the second transmitter. As a result, the SFN delay diversity technique can provide a diversity gain of 0.5 dB to 2.3 dB over the diversity value in a one-transmitter environment. Notably, the SFN delay diversity technique can give about a 1.6-dB diversity gain on average.

VI. Conclusion

This paper described a delay diversity technique for a legacy SFN environment. The presented technique does not require additional hardware in either the transmitters or receivers. In particular, there is no change in the receiver structure. To check the improvement of the presented diversity technique, various laboratory tests were executed using both commercial receivers and a measurement receiver. The experiment results show that the diversity gain can be obtained by controlling the emission times of the transmitters in an SFN. In the case that the delay value is lower than the GI, the BER performance of SFN delay diversity is better than that of the one-transmitter model in both the TU6 channel and one-path Rayleigh channel. The maximum SFN diversity gains of the TU6 channel and one-path Rayleigh channel are about 2 dB and 1.2 dB, respectively, compared to the one-transmitter model. In the test results of commercial receivers, the SFN delay diversity technique can give 0.5 dB to 2.3 dB diversity gain compared to a one-transmitter environment. The results of this paper can offer information on an optimization of the emission time for establishing an SFN, not only for T-DMB but also for a digital broadcasting transmission system.

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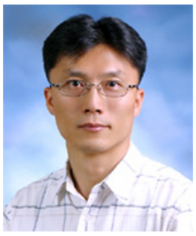
Myung-Sun Baek was born in Seoul, Rep. of Korea, in 1980. He received his BS, MS, and PhD degrees in information and communication engineering from Sejong University, Seoul, Rep. of Korea, in 2003, 2005, and 2009, respectively. Since 2009, he has been with the Broadcasting System Research Department, ETRI, where he is a senior engineer. His research interests are in the areas of wireless communication system design, data communications, MIMO signal processing, UWB communication, and digital broadcasting.

Yong-Hoon Lee received his BS degree in electronics engineering from Hanbat National University, Daejeon, Rep. of Korea, in 2005, and his MS and PhD degrees from the school of electrical and computer engineering at Chungbuk National University, Cheongju, Rep. of Korea, in 2007 and 2013, respectively. Since 2001, he has been with the Broadcasting System Research Department, ETRI, where he is a member of the research staff. His current research interests include digital signal processing, digital broadcasting protocols, digital multimedia broadcasting systems, and digital television systems.

Namho Hur received his BS, MS, and PhD degrees in electrical and electronics engineering from Pohang University of Science and Technology (POSTECH), Pohang, Rep. of Korea, in 1992, 1994, and 2000, respectively. He is currently with the Broadcasting and Telecommunications Media Research Laboratory, ETRI, Daejeon, Rep. of Korea. He is the managing director of the Broadcasting System Research Department in ETRI. He was an executive director of the Association of Realistic Media Industry (ARMI) in the Republic of Korea. ARMI was established to promote realistic media industry, including the 3DTV and UHDTV broadcasting industry. Also, he has been an associate professor with the Department of Mobile Communications and Digital Broadcasting, University of Science and Technology (UST), Daejeon, Rep. of Korea, since September 2005. For the collaborative research in the area of multi-view video synthesis and the effect of object motion and disparity on visual comfort, he was with the Communications Research Centre, Canada (CRC) from 2003 to 2004. His main research interests are in the field of next-generation digital broadcasting systems, such as the terrestrial UHD broadcasting system, the UHD digital cable broadcasting system, the mobile HD broadcasting system, and the backward-compatible 3D-TV broadcasting systems for mobile, portable, and fixed 3D audio-visual services.



Kyung-Seok Kim received his PhD degree in electrical and electronics engineering form Surrey University, UK, in 2002. He worked for ETRI from 1989 to 1998 and from 2002 to 2004. He is currently working as a professor at Chungbuk National University, Cheongju, Rep. of Korea. His research interests include SDR, cognitive radio, power line communication, digital radio, and MIMO wireless channels.

Yong-Tae Lee received his BSEE and MSEE from Korea Aerospace University in 1993 and 1995, respectively. Since 1995, he has been with the Radio Signal Processing Department and Broadcasting System Research Department, ETRI, where he is a principal researcher. He received his PhD from Yonsei University, Seoul, Rep. of Korea, in 2007. He is a member of the IEEE Transactions on Consumer Electronics Publications Editorial Board. His research interests are in the areas of digital signal processing and RF signal processing, in particular, signal processing for digital broadcasting systems and digital communication systems.