VSB-Based Digital On-Channel Repeater with Interference Cancellation System

Jaekwon Lee, Young-Woo Suh, Jin-Yong Choi, and Jong-Soo Seo

This paper investigates the design and performance of a digital on-channel repeater (DOCR) for use in Advanced Television Systems Committee (ATSC) digital television (DTV) broadcasting. The main drawback of a DOCR is the echo interference caused by coupling between transmitter and receiver antennas, which induces system instability and performance degradation. In order to overcome this problem, an echo canceller based on the adaptive echo channel estimation (ECE) technique has been researched and applied for a DOCR. However, in the case of ATSC, the pilot signal, which is used for carrier synchronization, may cause a DC offset error and reduce the isolation performance of the echo canceller for a DOCR in an ATSC network. Moreover, since the multipath fading effect of a radio channel usually occurs in a real environment, it should be minimized to improve the overall performance of a DOCR. Therefore, due to the limited isolation performance of echo canceller and the multipath fading effect, an interference cancellation system (ICS) is proposed for a DOCR in an ATSC network. The performance of the proposed DOCR with an ICS is evaluated by software simulation and hardware test results.

Keywords: DOCR, ICS, ATSC.

Manuscript received Sept. 13, 2010; revised Nov. 17, 2010; accepted Dec. 9, 2010.

This work was supported by the IT R&D program of MKE/KCC/KEIT [10035158, Quality monitoring and quality assurance for multimedia and 3D applications].

Jaekwon Lee (phone: +82 2 781 5264, email: breeze@kbs.co.kr) and Young-Woo Suh (email: yush@kbs.co.kr) are with the Technical Research Institute, Korean Broadcasting System, Seoul, Rep. of Korea.

Jin-Yong Choi (email: jeeney@yonsei.ac.kr) and Jong-Soo Seo (email: jsseo@yonsei.ac.kr) are with the Department of Electrical and Electronics Engineering, Yonsei University, Seoul, Rep. of Korea.

http://dx.doi.org/10.4218/etrij.11.0110.0539

I. Introduction

Single frequency networks (SFNs) can be applied to Advanced Television System Committee (ATSC) digital television (DTV) services in order to improve the service availability as well as quality of service without using additional spectrum resources [1]. In order to design an SFN DTV broadcasting system, relay stations such as digital on-channel repeaters (DOCRs) are necessary to extend the service coverage and to reduce a shadowing area. A DOCR re-broadcasts signals on the same frequency that it is receives them, so it does not require a frequency translation and could be implemented for reasonable cost. In a DOCR, high isolation is required between transmitter and receiver antennas to minimize unwanted echo interference and to prevent the degradation of signal to noise ratio (SNR) performance.

Various techniques have been researched for reducing the echo interference [2]-[7]. The simplest and most widely used technique is to increase the physical distance between the two antennas of a DOCR [2]. However, this is not sufficient to reduce the echo interference, and it requires a large space for setting up the DOCR. Recently, the adaptive echo channel estimation (ECE) technique has been proposed and implemented to reduce the echo interference. It can easily eliminate the unwanted echo interference using an adaptive filter and be realized by digital signal processing in real time. However, the isolation performance and stability of echo canceller are affected by the reference signal quality picked up by the output of a DOCR. Nevertheless, many broadcasting standards, such as DAB, DVB-T/H, and T-DMB, have commonly used the adaptive ECE technique for their DOCRs due to its simplified hardware implementability.

On the other hand, in the case of an ATSC, it is hard to adopt this technique directly due to the DC offset error caused by the pilot signal. Thus, it cannot guarantee the required isolation performance of the echo canceller in ATSC network. Additionally, in general, the input of a DOCR is distorted not only by echo interference but also by multipath fading effect of radio channel. If these distortions are not removed timely and properly, the output of a DOCR still suffers a degradation of SNR performance and service coverage. Since the echo canceller cannot eliminate the multipath fading effect, it should be removed by using an equalization technique [8]-[10].

This paper mathematically analyzes the effect of an ATSC pilot signal on the isolation performance of echo canceller and presents the proposed DOCR with an interference cancellation system (ICS), which is composed by both an improved echo canceller and channel equalizer, used for the ATSC network. The proposed DOCR with an ICS not only compensates the multipath fading effect but also enhances the isolation performance of the echo canceller in various channel environments.

The remainder of this paper is organized as follows. Section II presents a brief analysis of the conventional echo canceller for a DOCR. Section III describes the proposed DOCR with an ICS, and the simulation and hardware test results are shown in section IV. Finally, the conclusion is presented in section V.

II. System Model

SFN is a set of several transmitters to operate on the same frequency in order to cover a given broadcasting service area. It can make an economical use of the scarce frequency resources because only a single channel frequency is required to provide the same broadcasting service throughout the whole network. Thus, SFN is considered a good candidate for use in future terrestrial broadcasting, and it can be implemented by using multiple DOCRs.

The simple block diagram of a DOCR including an echo canceller is shown as Fig. 1. The receiver antenna of a DOCR receives a weak signal from the main transmitter and retransmits an amplified version of this signal on the same frequency using the transmit antenna of the DOCR. The main drawback of a DOCR is the antenna coupling effect, which results in instability and oscillation of the overall system. One effective echo cancellation technique is the adaptive ECE technique, which estimates the echo channel impulse response (CIR) using an adaptive filter and subtracts it from the input signal of the DOCR. As a result, the output signal of the DOCR can provide a high-quality retransmitting signal.

The adaptive filter coefficients are calculated approximately by cross-correlating the input and output signals of a DOCR and simply updated by the least mean square (LMS) algorithm

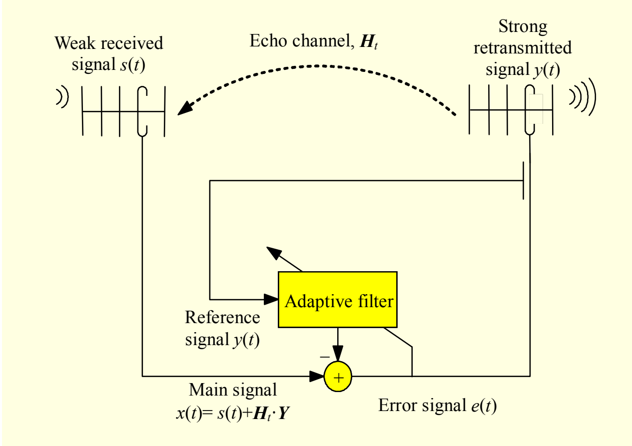


Fig. 1. Block diagram of echo canceller.

[11]. It is an approximation to the gradient-based steepest descent algorithm, which results in low computational complexity. However, it has a low convergence speed to reach the near-optimum echo cancellation performance due to its predefined gain for updating the LMS adaptive filter. If a small value is chosen for a predefined gain, the convergence speed becomes lower, but the SNR performance becomes better and vice versa. Thus, it is required to choose a proper gain for updating the LMS adaptive filter.

In this paper, a normalized LMS algorithm has been proposed which enables to obtain the same effect as a variable gain control for rapid convergence.

The aim of the normalized LMS adaptive filter is to minimize the error $e(t)$ between the main signal $x(t)$ and the reference signal $y(t)$, thus leaving only the received signal $s(t)$. The error signal can be given as

$$e(t) = x(t) - \boldsymbol{H}_t^e \boldsymbol{Y}, \tag{1}$$

where $\boldsymbol{H}_t^e = [h_1, h_2, \cdots, h_K]$ is the K-length adaptive filter coefficients used to estimate the echo CIR and $\boldsymbol{Y} = [y(t), y(t-1), \cdots, y(t-K+1)]^T$ is the reference vector. The adaptive filter coefficients are updated with an appropriately scaled conjugate of the instantaneous value of the derivative:

$$\boldsymbol{H}_{t+1}^e = \boldsymbol{H}_t^e + \frac{\mu}{\alpha + \|\boldsymbol{Y}\|^2} e(t) \boldsymbol{Y}^*, \tag{2}$$

where μ is the step-size, α is a small positive constant to prevent divergence during the update process of adaptive filter coefficients, and [ ]* denotes conjugate transpose. As described in (2), since the step-size factor is divided by the energy of the reference vector, the gain for updating the normalized LMS adaptive filter is varied according to the retransmitted signal power of a DOCR. For this reason, the normalized LMS typically converges faster than the standard LMS [12]. Also, due to its adaptation property, it provides the efficient reduction of echo interference, ease of implementation, and the continuous tracking of echo channel variation caused by the Doppler effect. However, the estimation of echo CIR relies on the quality of reference signal, and the poor quality of reference signal will affect the isolation efficiency and stability.

III. DOCR with ICS

1. Effect of ATSC Pilot on the Echo Canceller

As shown in section II, the adaptive-ECE-technique-based echo canceller has guaranteed a high isolation performance and a low implementation complexity. This technique is widely used in many broadcasting standards, such as DAB, DVB-T/H, and T-DMB. However, despite the simplicity of its implementation, this echo canceller cannot be used for the DOCR in ATSC network which is DTV broadcasting standard in South Korea. The ATSC is based on the North American digital terrestrial television broadcasting system, which has adopted 8-vestigial sideband (VSB) modulation and trellis encoder. In the ATSC standard, a small DC pilot tone is added to every DTV symbol to recover the carrier and phase synchronization. Consequently, the main and reference signals of DOCR can be divided into DTV payload data and pilot tone, and the error signal which is described in (1) can be rewritten as

$$e(t) = x(t) - \boldsymbol{H}_t^e \boldsymbol{Y} = x_d(t) + x_p(t) - \boldsymbol{H}_t^e(\boldsymbol{Y}_d + \boldsymbol{Y}_p), \quad (3)$$

where $x_d(t)$ and $\boldsymbol{Y}_d$ denote the DTV payload data of the main and reference signals of DOCR, and $x_p(t)$ and $\boldsymbol{Y}_p$ denote the pilot tone of main and reference signals of DOCR, respectively, and $\boldsymbol{H}_t^e$ is K-length adaptive filter coefficients. According to the normalized LMS algorithm, the update formula of the echo canceller can be rewritten as

$$\begin{aligned}\boldsymbol{H}_{t+1}^e &= \boldsymbol{H}_t^e + \frac{\mu}{\alpha + \|\boldsymbol{Y}\|^2} \frac{\partial E|e(t)|^2}{\partial \boldsymbol{H}_t^e} \\ &= \boldsymbol{H}_t^e + \frac{\mu}{\alpha + \|\boldsymbol{Y}\|^2}[x_d(t) + x_p(t) - \boldsymbol{H}_t^e(\boldsymbol{Y}_d + \boldsymbol{Y}_p)](\boldsymbol{Y}_d + \boldsymbol{Y}_p)^* \\ &= \boldsymbol{H}_t^e \cdot \left(1 - \frac{\mu}{\alpha + \|\boldsymbol{Y}\|^2}\|\boldsymbol{Y}\|^2\right) \\ &\quad + \frac{\mu}{\alpha + \|\boldsymbol{Y}\|^2}[x_d(t)\boldsymbol{Y}_d^* + x_p(t)\boldsymbol{Y}_d^* + x_d(t)\boldsymbol{Y}_p^* + x_p(t)\boldsymbol{Y}_p^*].\end{aligned} \quad (4)$$

After N times iteration of the update process, the adaptive filter coefficients can be reached the convergence level and be expressed as

$$\begin{aligned}\boldsymbol{H}_N^e &= \boldsymbol{H}_1^e \left(1 - \frac{\mu}{\alpha + \|\boldsymbol{Y}\|^2}\|\boldsymbol{Y}\|^2\right)^{N-1} \\ &+ \sum_{t=1}^{N-1}\left\{\left(1 - \frac{\mu}{\alpha + \|\boldsymbol{Y}\|^2}\|\boldsymbol{Y}\|^2\right)^{N-1-t} \cdot \frac{\mu}{\alpha + \|\boldsymbol{Y}\|^2}\right. \\ &\left.\times [x_d(t)\boldsymbol{Y}_d^* + x_p(t)\boldsymbol{Y}_d^* + x_d(t)\boldsymbol{Y}_p^* + x_p(t)\boldsymbol{Y}_p^*]\right\}.\end{aligned} \quad (5)$$

Assuming that initial adaptive filter coefficients $\boldsymbol{H}_1^e$ are all-zero vector $\alpha \ll \|\boldsymbol{Y}\|^2$ and $\mu \ll 1$, (5) can be approximately expressed as

$$\boldsymbol{H}_N^e \cong \sum_{t=1}^{N-1} \frac{\mu}{\|\boldsymbol{Y}\|^2}[x_d(t)\boldsymbol{Y}_d^* + x_p(t)\boldsymbol{Y}_d^* + x_d(t)\boldsymbol{Y}_p^* + x_p(t)\boldsymbol{Y}_p^*]. \quad (6)$$

As described in (6), the adaptive ECE technique of the echo canceller can be simplified as a cross-correlation of the main and reference signals. On the right side of (6), the first term represents the cross-correlation of DTV payload data of main and reference signals. It positively contributes to estimate the echo CIR. The second and third terms represent the cross-correlation between DTV payload data and pilot tone of the main and reference signals, or vice versa. These have almost zero level due to the uncorrelated characteristics. Thus, the contribution of these terms for estimating the echo CIR becomes minimal. The last term shows the cross-correlation of pilot tone of main and reference signals. This term contributes negatively by estimating the echo CIR and causes a constant level, which is called the DC offset. It increases the estimated adaptive filter coefficients to the DC offset level, which means that the estimated echo CIR will not be optimized properly. This is the main reason why the adaptive ECE technique is not directly applicable for the DOCR in the ATSC network.

2. Proposed DOCR with ICS

Before discussing the design issues of the DOCR with ICS for ATSC networks, the requirements of ICS should be preferentially considered and focused on the following conditions. Firstly, the ICS should guarantee high isolation between transmitter and receiver antennas to remove the echo interference. If the isolation is not sufficient enough, it may cause system oscillation and reduce the output power of DOCR. Secondly, the ICS should remove the inband signal distortion caused by a multipath fading effect of radio channel. Although the echo interference is perfectly removed, the retransmitted signal quality of the DOCR depends on the multipath fading effect. By eliminating the multipath fading effect, the weak received signal of the DOCR may be perfectly

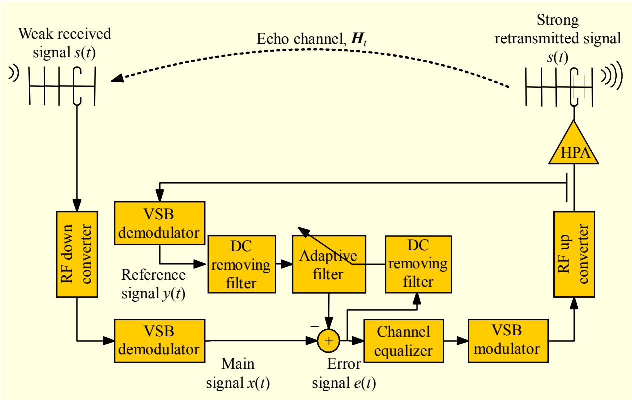


Fig. 2. Block diagram of proposed VSB based DOCR with ICS.

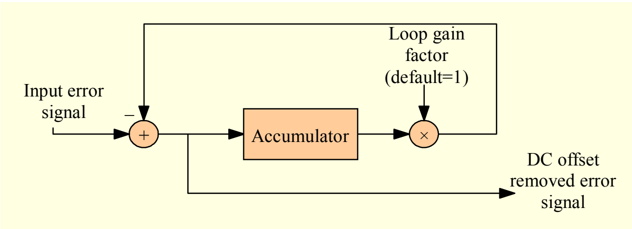


Fig. 3. Block diagram of DC removing filter.

regenerated and closed to the original main transmitter signal. As a result, service coverage of the DOCR will be improved. Finally, the total system delay of the ICS should be as short as possible due to the equalization performance of legacy receiver. If the total system delay is larger than the equalization range of the legacy receiver, it causes additional burdens on the legacy receiver. Therefore, all the above mentioned requirements should be satisfied in the proposed DOCR with ICS, and Fig. 2 shows a functional block diagram.

The proposed DOCR with ICS simply consists of RF up and down converters, VSB modem, echo canceller, and a channel equalizer. The weak received signal with echo interference is fed into the input of DOCR. The RF down converter and VSB demodulator convert the passband main signal to the baseband.

The VSB demodulator is generated by a pair of square root raised cosine filters which have a roll-off factor of 0.1152. Since the baseband main signal contains echo interference, it should be reduced by employing the adaptive ECE technique based echo canceller. In this case, the reference signal obtained from a coupler in the output of DOCR is also required to estimate the echo CIR. However, as mentioned in subsection III.1, it is not guaranteed the maximum isolation performance due to the DC offset error caused by ATSC pilot signal. Here, the adaptive ECE technique with DC removing filter is proposed as an improved adaptive-ECE-technique-based echo canceller for increasing the isolation performance. The DC removing filter, depicted in Fig. 3, is added prior to the adaptive ECE technique and reduces the DC offset of the error and reference signals. After going through the DC removing filter, the adaptive filter coefficients of echo canceller can estimate the echo CIR more precisely. Also, even if the echo interference is fluctuated by time condition, adaptive filter coefficients can still track the echo CIR due to the iterative updating feature. The error signal can be obtained by subtraction of the estimated echo interference from the baseband main signal.

After that, the error signal and channel equalizer are utilized to eliminate the inband signal distortion caused by multipath fading effect. Here, the decision feedback equalizer (DFE), which is composed of the feed-forward and feedback filters, is adopted as a channel equalizer due to its good trade-off between complexity and performance. The output equalized signal is remodulated and stabilized by the VSB modulation and the automatic gain controller. Finally, it is passed to the RF up converter and the high power amplifier, and then it is broadcasted to the transmit antenna of the DOCR.

To analyze the mathematical behavior of the proposed DOCR with an ICS, updating formulas can be solved by the following steps. Assuming that the perfect VSB demodulation, the baseband main signal which consists of the weak received signal from main transmitter $s(t)$ and echo interference from the transmit antenna of DOCR is given by

$$x(t) = s(t) + \boldsymbol{H}_t \boldsymbol{Y}, \tag{7}$$

where $\boldsymbol{H}_t$ is the echo CIR between the transmitter and receiver antennas of the DOCR. As the weak received signal is influenced by multipath fading effect and additive white Gaussian noise (AWGN), (7) can be rewritten as

$$x(t) = \sum_{\tau=0}^{L-1} d(t-\tau)\cdot c(\tau) + \boldsymbol{H}_t \boldsymbol{Y} + n(t), \tag{8}$$

where $d(\cdot)$, $c(\cdot)$, and L are the original main transmitter signal, multipath fading channel, and memory length of the multipath fading channel, respectively. AWGN, which is assumed as an independent and identically distributed statistically, is denoted by $n(t)$.

Since the second term of the right side of (8) causes the system instability and oscillation, it can be reduced by subtracting the estimated echo interference, which is calculated by inner product of the adaptive filter coefficients and the reference vector. Thereby, the resulting error signal can be obtained as

$$\begin{aligned} e(t) &= \sum_{\tau=0}^{L-1} d(t-\tau)\cdot c(\tau) + \boldsymbol{H}_t \boldsymbol{Y} + n(t) - \boldsymbol{H}_t^e \boldsymbol{Y} \\ &\cong \sum_{\tau=0}^{L-1} d(t-\tau)\cdot c(\tau) + n(t). \end{aligned} \tag{9}$$

In order to minimize the expectation of the square of the error signal, the adaptive filter coefficients can be updated based on the normalized LMS algorithm and DC-removing filter which is expressed as

$$\boldsymbol{H}_{t+1}^{e} = \boldsymbol{H}_{t}^{e} + \frac{\mu}{\alpha + \|\boldsymbol{Y}\|^{2}} \hat{e}(t) \cdot \widetilde{\boldsymbol{Y}}^{*}, \quad (10)$$

$$\tilde{e}(t) = e(t) - \delta \cdot \sum_{i=1}^{t} \tilde{e}(i-1), \quad (11)$$

where δ is a loop gain, and $\tilde{e}(t)$ and $\widetilde{\boldsymbol{Y}}^{*}$ are the DC-removing filtered-error signal and reference vector, respectively. Since the DC-removing filter is applied to reduce the pilot tone of error and reference signals, the adaptive filter coefficients are not biased by the DC offset and obtain the minimum difference between the real and estimated echo CIR. Thus, in the DOCR for the ATSC network, the use of a DC removing filter easily improves the isolation performance of echo canceller.

After subtracting the echo interference, the error signal goes through the DFE which compensates the multipath fading effect, and the output equalized signal can be obtained by

$$r(t) = \sum_{i=0}^{N_f - 1} f_i(t) \cdot e(t-i) - \sum_{j=1}^{N_b - 1} b_j(t) \cdot \hat{r}(t-j) \cong d(t), \quad (12)$$

where $f_i(t)$ and $b_j(t)$ are feed-forward and feedback filters of the equalizer, respectively, N_f and N_b are the number of taps of each filter, respectively, and $\hat{r}(\cdot)$ is a tentatively decided signal by a decision device. The updating formulas of the feed-forward and feedback taps of the DFE have been addressed in [13], [14]. As the feed-forward and feedback taps of DFE are updated iteratively, the output equalized signal is accurately closed to the original main transmitter signal. The remaining process steps of DOCR are similar to the transmitter process.

IV. Performance Analysis

The performance of the proposed DOCR with an ICS is evaluated via software simulation and hardware test. In the software simulation, echo CIR models, such as the rural area with 6 paths (RA6), Brazil E channel, and finite impulse response (FIR) channel under bad isolation, are used to evaluate the isolation performance, as summarized in Table 1. Since the RA6 channel has a lower level of echo impulse response than the main impulse response, it can be easily reduced by an equalization technique. Thus, generally, the echo canceller is not a necessary but a sufficient condition for a DOCR. However, Brazil E channel and FIR channel under bad isolation have an equal or higher level of echo impulse response than main impulse response. This situation can happen when transmitter and receiver antennas of a DOCR are located very close to each other. In this case, it is difficult to get enough isolation to maintain the system stability, and an echo canceller is necessary condition for a DOCR. Also, Brazil A and E channels are considered as the multipath fading channel and it should be reduced by the Kalman-based DFE [14]. In order to analyze the reasonable performance of the proposed ICS, we assumed that the synchronization error caused by the frequency and timing offset is completely recovered by using the VSB demodulator. The proposed echo canceller consists of the normalized LMS based adaptive ECE technique and DC removing filter. The step-size μ and positive constant α of the normalized LMS are 0.1 and 0.0001.

Table 1. Power delay profiles of echo channel.

RA6 channel		Brazil E channel		FIR channel	
Delay (μs)	Relative power (linear)	Delay (μs)	Relative power (linear)	Delay (μs)	Relative power (linear)
0	1	0	1	0	0
0.1	0.4	1	1	0.5	100
0.2	0.16	2	1		
0.3	0.06				
0.4	0.03				
0.5	0.01				

The performance of the proposed echo canceller can be measured by the normalized mean rejection ratio (MRR) defined as

$$MRR = \frac{1}{K} \sum\nolimits_{n=1}^{K} \left| CIR_r - CIR_e \right|, \quad (13)$$

$$MRR_{\text{norm}}(\text{dB}) = 10\log_{10}(MRR) - 10\log_{10}\left(\frac{1}{k} \sum_{n=1}^{K} \left| CIR_e \right| \right), \quad (14)$$

where CIR_r is the echo CIR model described in Table 1, CIR_e is the estimated echo CIR calculated by the echo canceller, and K is the number of adaptive filter coefficients of the echo canceller. Figure 4 shows the normalized MRR performance. It is shown that long delay and bad isolation channels such as Brazil E and FIR channels might require a large number of iteration to be converged. Also, the normalized MRR performance of the conventional echo canceller is converged to the level of –3 dB in RA6 channel, –8 dB in Brazil E channel, and –29 dB in FIR channel. On the other hand, that of the proposed echo canceller is converged to the level of –15 dB in RA6 channel, –20 dB in Brazil E channel, and –35 dB in FIR channel.

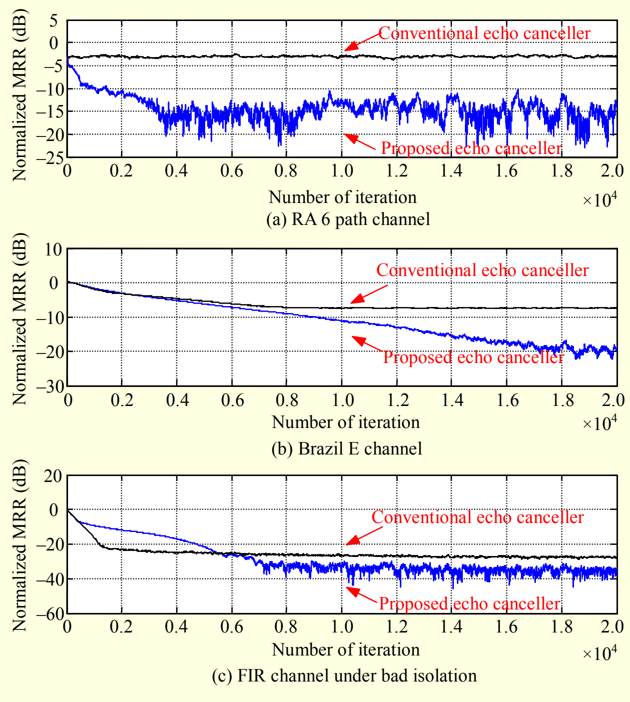


Fig. 4. Normalized MRR performance in different channel conditions.

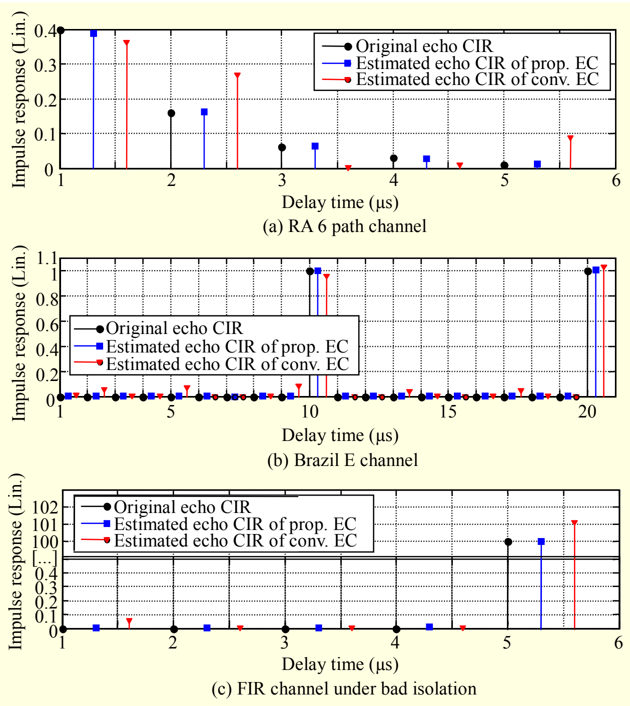


Fig. 5. CIR performance in different channel conditions.

Hence, using the DC removing filter, the proposed echo canceller can obtain a high isolation gain and shows the better normalized MRR performance than the conventional echo canceller in various echo channel conditions. Figure 5 shows the original echo CIR model and the estimated echo CIR when

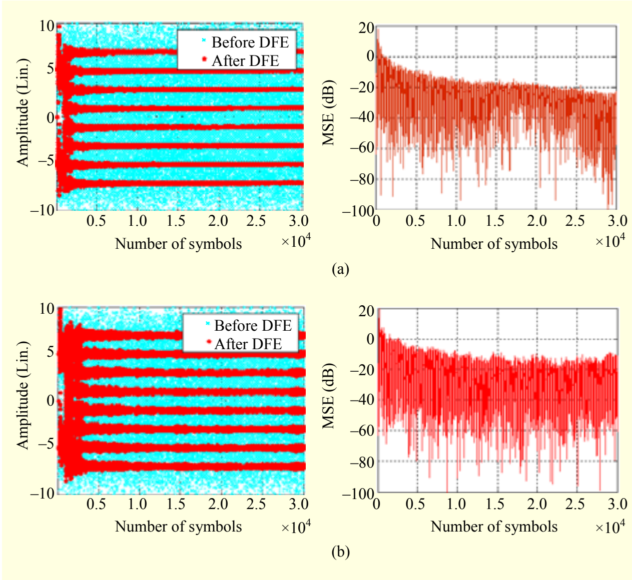
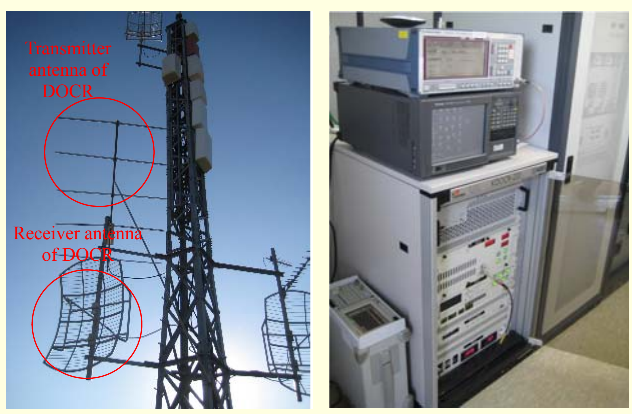


Fig. 6. Performance of the proposed equalizer with FIR echo channel and multipath fading: (a) DFE performance with FIR echo channel and Brazil A fading channel and (b) DFE performance with Brazil E echo channel and Brazil E fading channel.

the iterative update process of echo canceller is converged to a steady state level. To make analysis easy, the delay times of estimated echo CIRs of the proposed and conventional echo cancellers are shifted forcibly up by 0.3 μs and 0.6 μs, respectively. As seen in Fig. 5, the estimated echo CIR obtained by the proposed echo canceller is almost the same as the original echo CIR model for all different channel conditions. However, that of the conventional echo canceller is quite different from those original echo CIR models. As we prove in section III.1, if the cross-correlation of ATSC pilot tone is not removed properly, the estimated echo CIR still remains distorted, resulting in a quite difference compared with the original echo CIR. Thus, it is expected that a sufficient isolation gain can be achieved by using the proposed echo canceller for use in ATSC network.

After eliminating the echo interference, the multipath fading effect of the radio channel would be removed by the Kalman DFE. It is composed of the 64 feed-forward taps/192 feedback taps and uses the field sync segment of DTV symbol as a training sequence. Figure 6 shows the symbol constellation and mean square error (MSE) performance of Kalman DFE in Brazil A and E channels. SNR before and after DFE showed about 4.3 dB and 36.8 dB in Fig. 6(a) and 2.1 dB and 30.3 dB in Fig. 6(b), respectively. Thus, the Kalman DFE can reduce the multipath fading effect and the equalized output is perfectly regenerated like the original main transmitter signal. In addition, the SNR performance of the retransmitted signal of the proposed DOCR with an ICS can be guaranteed at the receiver side.



(a) Antenna structure (b) Proposed DOCR

Fig. 7. Information of Yeo-su TVR: (a) antenna structure and (b) proposed DOCR.

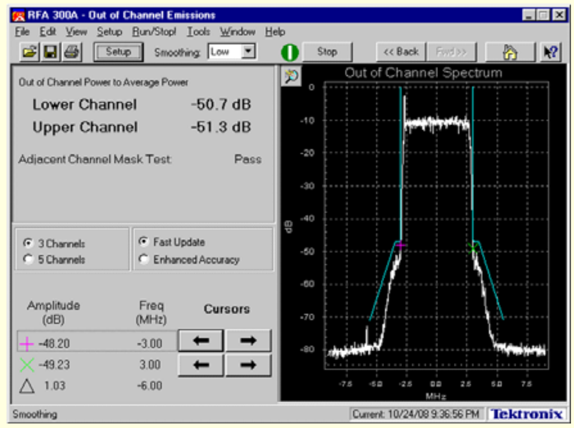


Fig. 9. Spectrum performance of proposed DOCR.

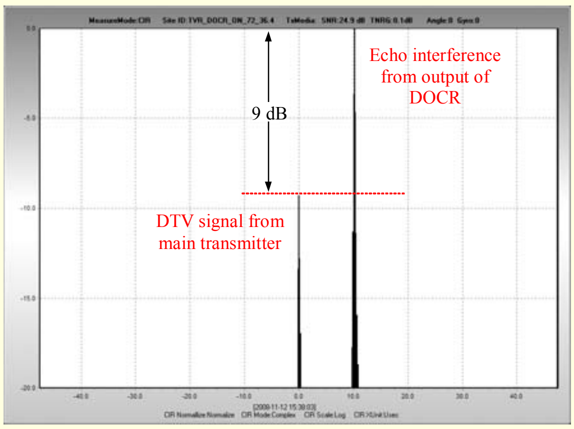


Fig. 8. Measured echo CIR in DOCR.

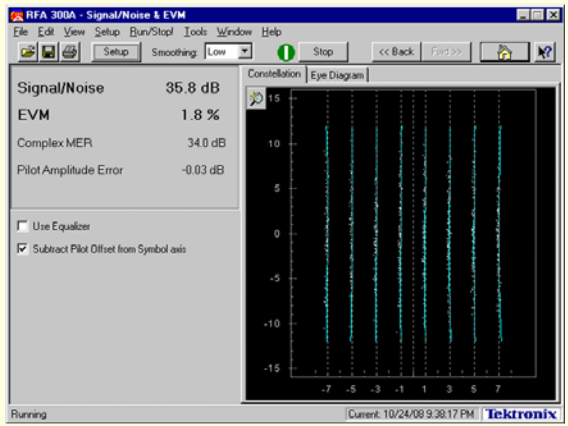


Fig. 10. SNR performance of proposed DOCR.

On the completion of the software simulation, hardware is implemented and tested to validate the proposed DOCR with ICS. The implemented DOCR consists of the proposed echo canceller and DFE to obtain high isolation and SNR gains. Because the Kalman DFE has a large complexity, the feed-forward and feedback filter taps of the DFE are calculated based on the LMS DFE and intelligent slicer [15]. To analyze the performance of the proposed DOCR in the field, the proposed DOCR, illustrated in Fig. 7, was installed at the Yeo-Su DTV repeater site in Korea, and the output signal of the proposed DOCR was measured by Tektronix RFA300A, which is the VSB test and measurement equipment. Figure 8 shows the actual input CIR of the proposed DOCR, which is measured by using an integrated measurement and analysis system (IMAS) [16].

As seen in Figs. 7 and 8, since the physical distance of the transmitter and receiver antennas of the proposed DOCR is not enough to guarantee the required isolation, the echo interference has a 9 dB larger power level as compared to the received signal from main transmitter. Thus, it should be limited under an acceptable level to avoid significant degradation of the output signal of the proposed DOCR. As shown in Fig. 9, the spectrum of the proposed DOCR can obtain more than 48 dB below the total average DTV power at the band edge. Thus, it can meet the emission mask requirement and does not cause the adjacent channel interference. Also, since the echo interference and multipath fading effect are clearly removed, the inband spectrum of the proposed DOCR can achieve an almost flat equalized response. Figure 10 shows the SNR performance of the proposed DOCR. According to Fig. 10, the SNR of the proposed DOCR has about 35.8 dB. In the DTV regulation of Korea, the output signal of wireless stations must be guaranteed to be no more than 28 dB of SNR. Thus, it is expected that the proposed DOCR can meet the SNR requirement and prevent the service coverage reduction. Also, since the proposed DOCR has a relatively simple structure of echo canceller and equalizer, the total system delay of the proposed DOCR has less than 10 μs, as shown in Fig. 7. Since this system delay is included in the equalization range of legacy receiver, additional burdens caused by system delay can be prevented at the receiver side [17]. From these results, the proposed DOCR can satisfy the various requirements of ICS, which are described in subsection III.2 and produce a high quality retransmitted signal.

V. Conclusion

The design and performance of the proposed DOCR with ICS for use in an ATSC network was investigated. Since the input signal of a DOCR contains not only the weak received signal from main transmitter but also echo interference from the antenna coupling, an echo canceller is required to minimize the echo interference. However, in the case of the ATSC, the pilot signal would degrade the performance of echo canceller. Hence, a DC-removing filter is proposed to improve the echo cancellation performance. Moreover, the multipath fading effect of a radio channel should be minimized by a channel equalizer to improve the SNR performance of output signal of the DOCR. Software simulation in various echo channel environments shows that the proposed echo canceller has better MRR performance than a conventional echo canceller. Moreover, it can effectively eliminate the large echo interference as well as multipath fading effect. The hardware test results demonstrates that the proposed DOCR provides a high SNR retransmitted signal, the satisfaction of emission mask regulation, and a relatively short system delay. Currently, the proposed DOCR is operated by the Korean Broadcasting System (KBS). It is expected that the proposed DOCR with an ICS would have a more efficiently designed SFN for the ATSC network.

References

[1] A. Mattsson, "Single Frequency Networks in DTV," *IEEE Trans. Broadcast.*, vol. 51, no. 4, Dec. 2005, pp. 413-422.

[2] K. Imamura et al., "A Study of Coupling Loop Interference Canceller for Relay Stations in Single Frequency Network–Toward Effective Use of Frequency Resources by Single Frequency Retransmission Relay," *NHK R&D Giken*, vol. J89-A, no. 10, Nov. 2001, pp. 801-813.

[3] A. Wiewiorka and P.N. Noss, "Digital On-Channel Repeater for DAB," BBC R&D White Paper 120, Sept. 2005.

[4] Y.-J. Lee et al., "Performance of Feedback Cancellers for T-DMB On-Channel Repeaters," *IEEE Trans. Broadcast.*, vol. 55, no. 4, Dec. 2009, pp. 810-817.

[5] K.M. Nasr et al., "Performance of an Echo Canceller and Channel Estimator for On-Channel Repeaters in DVB-T/H Networks," *IEEE Trans. Broadcast.*, vol. 53, no. 3, Sept. 2007, pp. 609-618.

[6] S.W. Kim et al., "Equalization Digital On-Channel Repeater in the Single Frequency Networks," *IEEE Trans. Broadcast.*, vol. 52, no. 2, June 2006, pp. 137-146.

[7] J.K. Lee et al., "Performance of Feedback Canceller for Digital On Channel Repeaters in ATSC DTV System," *Int. Conf. BroadcastAsia*, 2009, pp. 1-7.

[8] H.M. Kim et al., "Modulation and Pre-Equalization Method to Minimize Time Delay in Equalization Digital On-Channel Repeater," *IEEE Trans. Broadcast.*, vol. 54, no. 2, June 2008, pp. 249-256.

[9] S.I. Park et al., "Equalization On-Channel Repeater for Terrestrial Digital Multimedia Broadcasting System," *IEEE Trans. Broadcast.*, vol. 54, no. 4, Dec. 2008, pp. 752-760.

[10] S.I. Park et al., "Novel Equalization On-Channel Repeater with Feedback Interference Canceller in Terrestrial Digital Multimedia Broadcasting System," *ETRI J.*, vol. 31, no. 4, Aug. 2009, pp. 357-364.

[11] S. Haykin and B. Widrow, *Least-Mean-Square Adaptive Filters*, New York: Wiley-Interscience, 2003.

[12] Ali H. Sayed, *Adaptive Filters*, New York: Wiley-IEEE Press, 2008.

[13] H.M. Kim et al., "Near-Optimum Blind Decision Feedback Equalization for ATSC Digital Television Receivers," *ETRI J.*, vol. 26, no. 2, Apr. 2004, pp. 101-111.

[14] B. Mulgrew and C. Cowan, "An Adaptive Kalman Equalizer: Structure and Performance," *IEEE Trans. Acoustics, Speech Signal Process.*, vol. 35, no. 12, Dec. 1987, pp. 1727-1735.

[15] Y.T. Lee et al., "A Design of Equalization Digital On-Channel Repeater for Single Frequency Network ATSC System," *IEEE Trans. Broadcast.*, vol. 53, no. 1, Mar. 2007, pp. 23-37.

[16] Y.W. Suh et al., "A Novel Integrated Measurement and Analysis System for Digital Broadcasting," *IEEE Trans. Consum. Electron.*, vol. 55, no. 1, Feb. 2009, pp. 56-62.

[17] T. Laud et al., "Performance of 5th Generation 8-VSB Receivers," *IEEE Trans. Consum. Electron.*, vol. 50, no. 4, Nov. 2004, pp. 1076-1080.

Jaekwon Lee received his BS in electronics and radio engineering from Chungnam National University, Daejeon, Rep. of Korea, and MS in mobile communication and digital broadcasting engineering from University of Science & Technology, Rep. of Korea, in 2006 and 2008, respectively. In 2006, he joined ETRI as a student researcher. Since 2008, he has been working for Korean Broadcasting System as a research staff member. His research interests are in next generation radio transmission technology, cognitive radio, digital RF, TxID, and UHDTV.

Young-Woo Suh received his BS and MS in electrical and electronics engineering from Seoul National University, Seoul, Rep. of Korea, in 1995 and 1997, respectively. Since 1997, he has been working for KBS, Rep. of Korea, for the development of DTV and T-DMB transmission and measurement systems. Since 2007, he has been in the PhD program of the Electrical and Electronic Engineering Department at Yonsei University, Rep. of Korea. His main research interests include digital signal processing and control for the broadcasting and communication systems.

Jin-Yong Choi received his BS and MS in electronics engineering from Yonsei University, Rep. of Korea, in 2004 and 2007, respectively. Since 2006, he has been with the Department of Electrical and Electronics Engineering at Yonsei University, Rep. of Korea, where he is a PhD candidate. His main research interests include channel estimation, equalization, and interference cancelation techniques for various multiple antenna systems for providing high-quality communication and broadcasting services, such as HDTV, 3DTV, UHDTV, and mobile TV.

Jong-Soo Seo received his BS in electronics engineering from Yonsei University, Rep. of Korea, in 1975, and the MS and PhD from the University of Ottawa, Canada, in 1983 and 1988, respectively. He worked for IDC and CAL, Canada, for digital satellite communications and data broadcasting systems for six years. Since 1995, he has been with the Department of Electrical and Electronics Engineering at Yonsei University, Rep. of Korea, where he is a professor. He was a director of the Center for Advanced Broadcasting Technology from November 2001 to April 2010. His current research interests include multimedia broadcasting systems. Since 2007, he has been an associate editor for *IEEE Transactions on Broadcasting*. Since January 2009, he has been an advisory committee member of Korea Communications Commission (KCC).