Modulation and Pre-Equalization Method to Minimize Time Delay in Equalization Digital On-Channel Repeater

Heung Mook Kim, Sung Ik Park, Jae Hyun Seo, Homin Eum, Yong-Tae Lee, Soo In Lee, and Hyuckjae Lee

***Abstract*—This paper presents novel modulation and pre-equalization methods to minimize a signal processing time delay in the Equalization Digital On-Channel Repeater (EDOCR) for the ATSC terrestrial digital TV system. The proposed modulation method uses Equi-Ripple (ER) filter for Vestigial Side Bands (VSB) pulse shaping instead of conventional Square Root Raised Cosine (SRRC) filter. And the proposed pre-equalization method calculates pre-equalizer filter coefficients by comparing a baseband signal as a reference signal and a demodulated repeater output signal, and then creates new VSB pulse shaping filter coefficients by the convolution of the ER filter and the pre-equalizer filter coefficients. The new VSB pulse shaping filter minimizes the time delay of EDOCR by adjusting the number of its pre-taps and also compensates the linear distortions due to the use of the ER filter and mask filter.**

***Index Terms*—ATSC, modulation, on-channel repeater, pre-equalization, SFN.**

I. Introduction

Terrestrial television broadcasters in general operate transmitters and translators according to the geographical locations of their coverage areas. In both analog and digital television broadcasting, Multiple Frequency Networks (MFNs) that assign different channels to each transmitter and translator have been used to cover service areas. However, the use of MFNs is very inefficient in the aspect of using frequencies since it is unable to share channels among a number of transmitters and translators unless the distance between two coverage areas is far enough.

Therefore, Single Frequency Networks (SFNs) that operate multiple transmitters and repeaters on the same frequency is desirable for the efficient use of frequencies. Especially, in the recent transition period from analog to digital broadcasting, the need of SFNs is unavoidable due to the lack of frequencies for additional transmitters and repeaters. SFNs provide not only high Signal to Noise Ratios (SNR), but trigger the mobile DTV services [1], [2]. Recently, SFNs are considered for use in terrestrial Advanced Television System Committee (ATSC) Digital Television (DTV) services because of the performance improvement of DTV receiver which are able to compensate for the long-time delay and high level ghost [3].

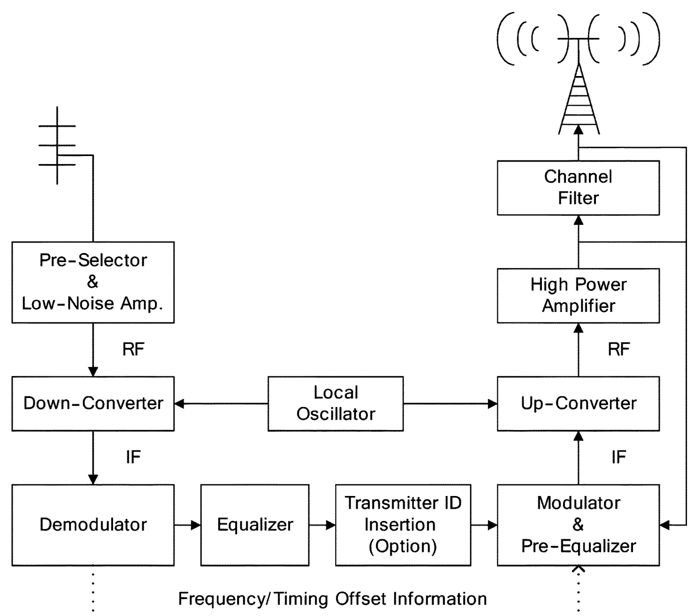

Fig. 1. Block diagram of EDOCR.

In the ATSC 8-VSB system, SFNs can be implemented with DTxT (Distributed Transmitters) that uses the same frequency among a number of transmitters, and/or with Digital On-Channel Repeaters (DOCRs) that uses the same frequency between transmitters and repeaters [4], [5]. The disadvantages of DTxT are that some devices maintaining the frequency synchronization between SFN transmitters must be added to existing transmitters and that the distance between the transmitters can be restricted by the limited equalization range of receivers. DOCRs do not need to change existing transmitters, but they produce limited output power and low quality of signal. As complementary to existing DOCRs, the Equalization DOCR (EDOCR) has been proposed [6], [7].

This paper presents the operational requirements of the EDOCR modulator and pre-equalizer, and proposes its configuration to meet the requirements. The proposed modulation and pre-equalization method is analyzed by computer simulations, and it is also confirmed by laboratory tests.

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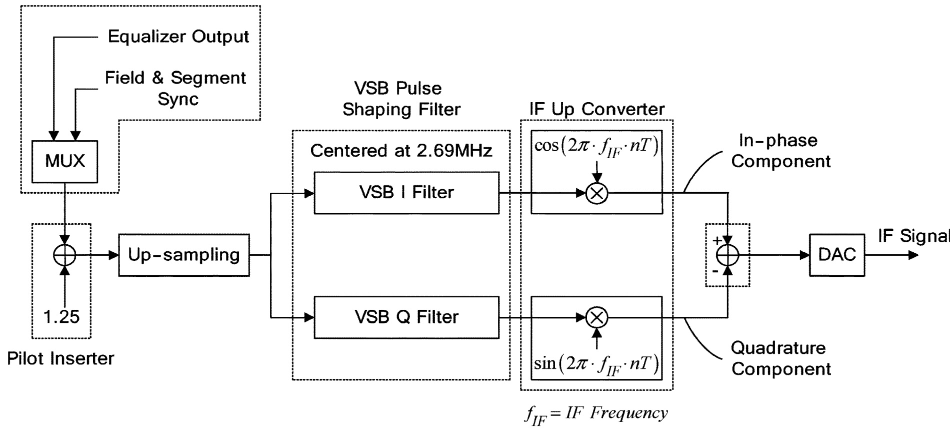

Fig. 2. Block diagram of VSB modulator.

II. Characteristics of EDOCR

DOCRs are used to fill in coverage gaps and to extend coverage areas which transmitter can not cover. Conventional DOCRs such as the RF processing DOCR and the IF processing DOCR offer a short processing time, but they provide limited transmitting power, low quality of output signal, and inadequate adjacent channel rejection. The EDOCR has been proposed to overcome such disadvantages of conventional DOCRs and its configuration is shown in Fig. 1. The EDOCR system takes the following advantages:

- Since the EDOCR does not use Forward Error Correction (FEC) decoding and encoding, it does not have the ambiguity problem in which the DOCR output symbol stream differs from its input symbol stream.
- The EDOCR has good selectivity of the received signal due to utilizing a matched filter in demodulation. That is, it is capable of rejecting adjacent channels.
- The EDOCR uses a blind Decision Feedback Equalizer (DFE), which includes the trellis decoder as a decision device with TBD (Trellis Back Depth) of 1 [8]. The DFE is able to remove noise and multipath signals caused by the signal paths between the main transmitter and the EDOCR, so that the quality of output signal is better than that of the input signal. Also, since the equalizer rejects feedback signal due to low isolation between transmitting and receiving antennas, the transmitting power of EDOCR can be increased more than 10 times higher than that of the conventional DOCRs.
- Because of the re-modulation and pre-equalization, the EDOCR can transmit good quality of signal.

The EDOCR involves a lot of digital signal processing, which possibly causes a long time delay between transmitted and received signals compared with conventional DOCRs. Due to the non-inclusion of FEC decoding and encoding, however, its signal processing time can be limited within 6 [5], [6]. The time delays of each module are 1 in the demodulator, 1 in the equalizer, 3 in the modulator, and 1 in the RF systems and cables.

III. EDOCR Modulator and Pre-Equalizer

A. EDOCR Modulator

The block diagram of a VSB modulator used in the ATSC terrestrial DTV transmitter or repeater is shown in Fig. 2, and its operation has following procedure:

- Step 1: The data consisting of the equalizer output, the field sync and the segment sync is up-sampled after pilot insertion.
- Step 2: The up-sampled data is filtered by a VSB I/Q pulse shaping filter.
- Step 3: The VSB filtered I/Q components with the center frequency of 2.69 MHz is up-converted to the center frequency of f_{IF}, and combined to form the IF signal.

A SRRC filter is generally used for VSB pulse shaping filter in the ATSC system and the VSB I/Q filters based on the SRRC filters are

$$\text{VSB I Filter}: g(n) \cdot \cos(2\pi \cdot f_{VSB} \cdot nT)$$
$$\text{VSB Q Filter}: g(n) \cdot \sin(2\pi \cdot f_{VSB} \cdot nT)$$

where n is a time index, $g(n)$ is a SRRC filter coefficient according to the time index, f_{VSB} is 2.69 MHz, and T is a symbol time (about 93 ns).

The VSB modulated signal must meet the FCC emissions mask shown in Fig. 3 and maintain the output SNR greater than 27 dB [9]. Assuming that the up-sampling rate for VSB filtering is 4, Fig. 4 shows the output SNR and the spectrum shoulder amplitude according to the number of SRRC filter taps. The shoulder amplitude is the power difference between the amplitude of the spectral regrowth spectrum at the channel's edge and the total average DTV power.

To meet the emissions mask requirement, the shoulder amplitude must be greater than 47 dB. Suppose that the number of taps of the matched filter is 121 to measure the SNR while observing 200,000 symbols through an ideal channel. According to the Fig. 4, the VSB pulse shaping filter based on the SRRC filter should theoretically have more than 420 taps to meet the output SNR and emissions mask requirements simultaneously. However, when the symbols are over-sampled at 4 times the ATSC

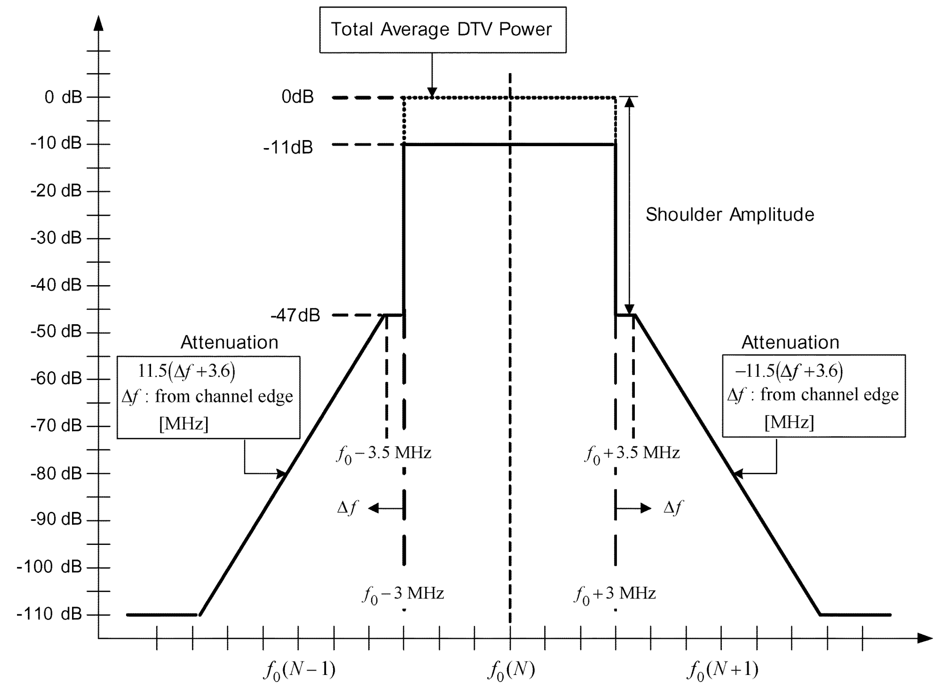

Fig. 3. FCC emissions mask.

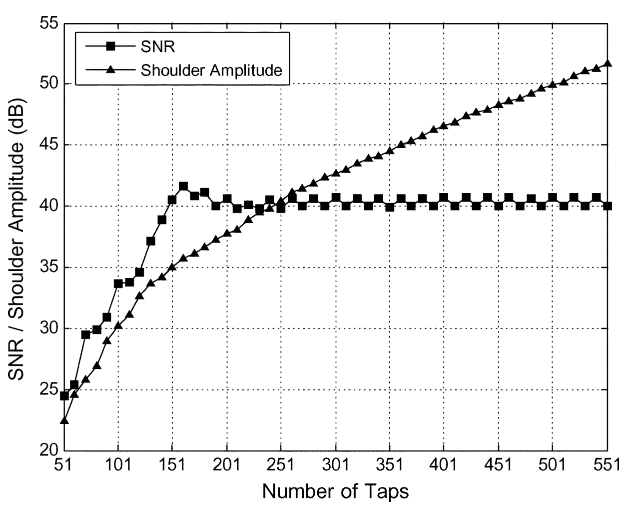

Fig. 4. SNR and shoulder amplitude according to the number of the SRRC filter taps.

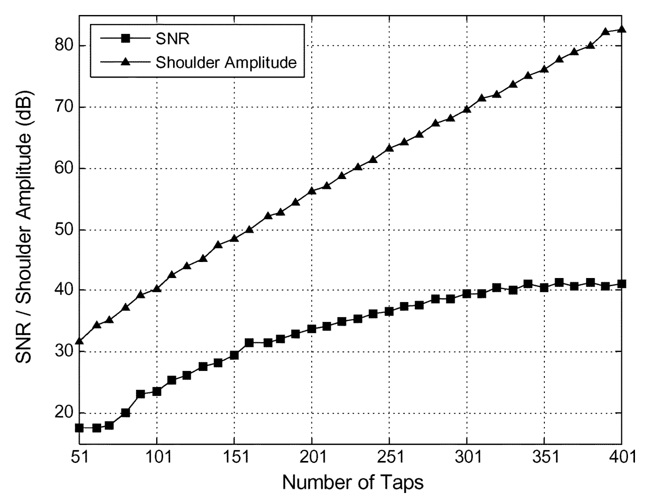

Fig. 5. SNR and shoulder amplitude according to the number of the ER filter taps.

system symbol rate, it causes a time delay of about 4.9 which results in a relatively long delay in the EDOCR system. Since the time delay is critical, a new pulse shaping filter is required for the EDOCR modulator. Since the number of filter taps to satisfy the requirements is determined by the shoulder amplitude rather than the SNR according to the Fig. 4, the new pulse shaping filter must be designed to have large shoulder amplitude while maintaining the number of taps as small as possible.

An ER filter that has good capability of out-of-band suppression while allows relatively lots of in-band ripples can be used as a pulse shaping filter in the EDOCR system for a short time delay. The VSB I/Q filters based on the ER filter are

$$\text{VSB I Filter} : e(n) \cdot \cos(2\pi \cdot f_{VSB} \cdot nT)$$
$$\text{VSB Q Filter} : e(n) \cdot \sin(2\pi \cdot f_{VSB} \cdot nT)$$

where n is a time index, $e(n)$ is an ER filter coefficient according to the time index, f_{VSB} is 2.69MHz, and T is a symbol time. Fig. 5 shows the output SNR and the shoulder amplitude according to the number of ER filter taps, and ER filter coefficients are calculated by Parks-McClellan algorithm [10], [11]. The ER filter with greater than about 140 taps can meet the output SNR and emissions mask requirements simultaneously according to the Fig. 5. When the symbols are over-sampled at 4 times the symbol rate, it causes a time delay of about 1.6 which is adequate as a pulse shaping filter in the EDOCR system. The ER filter has good capability of out-of-band suppression, but it causes lots of in-band ripples which are not ideal characteristic of Nyquist pulse shaping filter. Therefore, the output SNR of

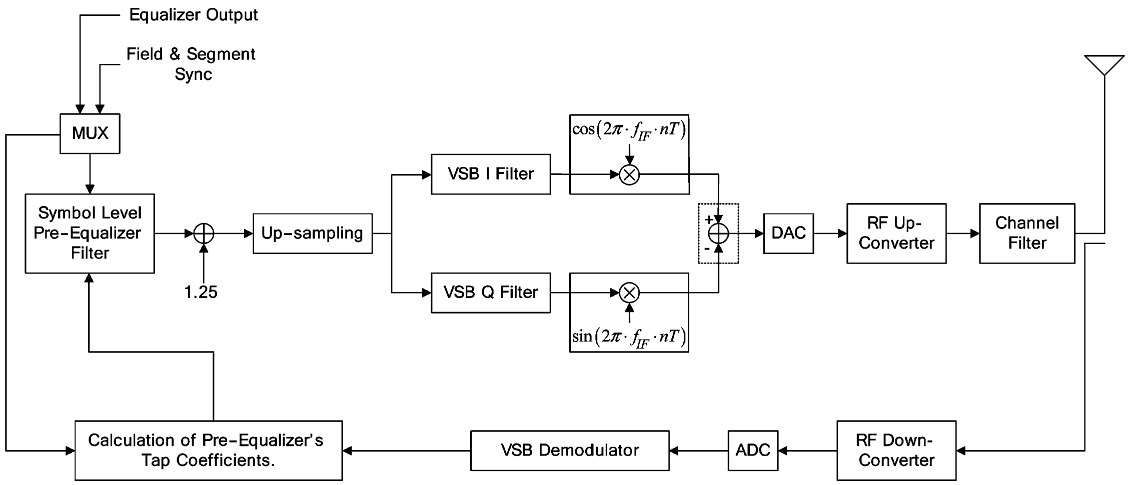

Fig. 6. The modulator and conventional pre-equalizer.

the ER filter is lower than that of the SRRC filter when the same number of taps is used.

B. Pre-Equalization Method

To meet the FCC emissions mask requirement, an EDOCR uses a mask filter which is capable of out-of-band suppression after a high power amplifier. The mask filter with good out-of-band suppression capability causes a lot of in-band group delay which degrades the output signal quality. Also, there is a possibility of additional SNR degradation due to the use of an ER filter as a pulse shaping filter. To compensate these SNR degradations, a pre-equalizer is used. Fig. 6 shows the configuration of the modulator and the conventional pre-equalizer. In the pre-equalizer, its filter coefficients are calculated by comparing the baseband signal to be transmitted and the demodulated channel filter output signal of the EDOCR.

A pre-equalizer filter in general is a linear filter and its coefficients can be calculated using Least Mean Square (LMS) algorithm. To update the coefficients, the following variables must be defined.

$x[k]$: baseband signal to be transmitted at time k,
$\hat{x}[k]$: demodulated signal after channel filtering at time k,
$y[k]$: pre-equalizer output signal at time k,
$c_i[k]$: i-th filter tap coefficient of pre-equalizer at time k.

Thus, the pre-equalizer output is

$$y[k] = \sum_{i=0}^{N-1} c_i[k] \cdot x[k-i]$$

where N is the number of the pre-equalizer filter taps. The number of taps is determined by the degree of linear distortion such as group delay. To obtain the update formula for filter tap coefficients, the error signal $e[k]$ is defined

$$e[k] = x[k] - \hat{x}[k].$$

The filter tap coefficients are updated as

$$c_i[k+1] = c_i[k] - \mu \cdot e[k] \cdot x[k-i], \qquad i = 0, 1, \ldots N-1$$

where μ is a step size which determines convergence speed and steady state Mean Square Error (MSE). For a large step size value the convergence speed is fast, but the steady state MSE is large. Otherwise, for a small step size value the steady state MSE is small, but the convergence speed is slow. To update the tap coefficients, the EDOCR uses known symbols as a training sequence, instead of the decision symbols of the VSB Demodulator output in Fig. 6. Therefore, it is recommended to use a small step size for a small steady state MSE although the convergence speed is slow [12]. The modulator including the pre-equalizer can compensate the linear distortions and reduce the ripples caused by the use of a mask filter and an ER filter, so that the output SNR of EDOCR can be improved.

C. Combination of Pre-Equalizer Filter and Pulse Shaping Filter

The symbol level pre-equalizer filter shown in Fig. 6 is one of the factors causing a time delay in the EDOCR. To minimize the time delay, the method of combining the pre-equalizer filter and the pulse shaping filter, and adjusting the number of the combined filter's pre-taps is proposed in this section. Precisely, the time delay can be minimized by truncating the number of pre-taps after convolution of the pre-equalizer filter and the pulse shaping filter. The configuration of the EDOCR modulator including the proposed pre-equalizer is shown in Fig. 7, and the process of combining two filters and adjusting the number of pre-taps of combined filter is shown in Fig. 8.

Assume that there are a pre-equalizer filter in which the total number of taps is $(\mathrm{N1+M1+1})$ and the main tap is positioned at $(\mathrm{N1+1})$, and a VSB I/Q filter in which the total number of taps is $(\mathrm{N2+M2+1})$ and the main tap is positioned at $(\mathrm{N2+1})$. After convolution of the pre-equalizer filter and the VSB I/Q filter, a combined VSB I/Q filter functioning pre-equalization in which the total number of taps is $(\mathrm{N1+N2+M1+M2+1})$ and the main tap is positioned at $(\mathrm{N1+N2+1})$ is created. And some of the left most filter coefficients of the combined VSB I/Q filter are truncated to reduce the processing time delay of EDOCR. So the truncated VSB I/Q filters have the total number of taps of $(\mathrm{N3+M3+1})$ and its main tap is positioned at $(\mathrm{N3+1})$ where

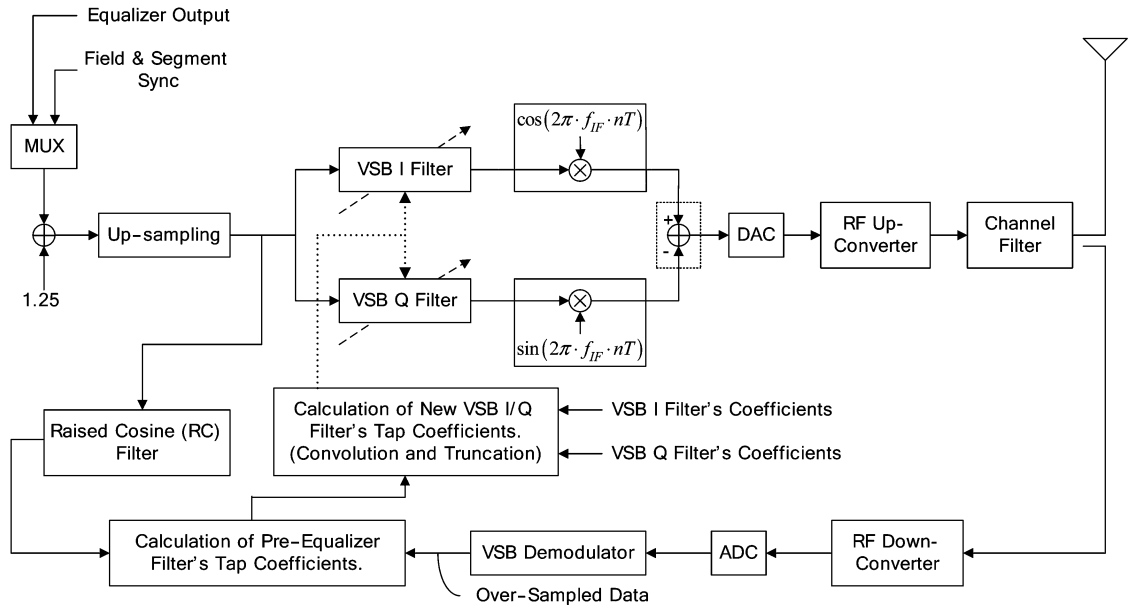

Fig. 7. The configuration of modulator and proposed pre-equalizer.

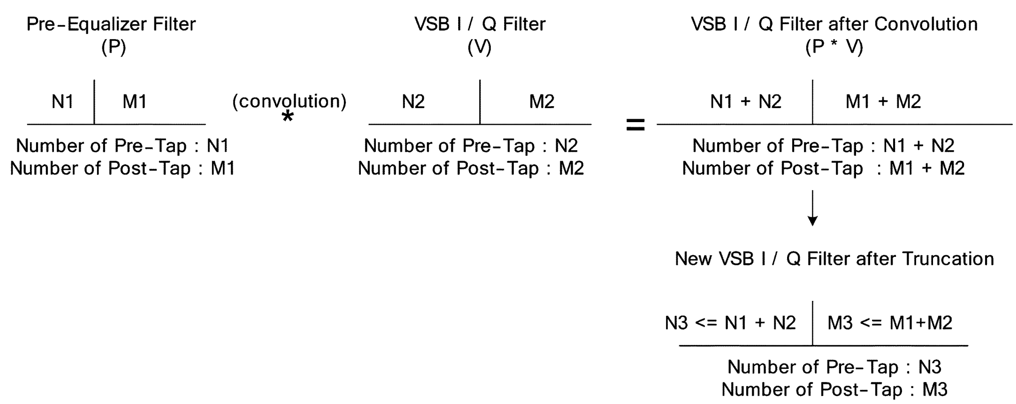

Fig. 8. Process of combining pre-equalizer filters and pulse shaping filter and adjusting the number of pre-taps.

$N3 <= N1 + N2$ and $M3 <= M1 + M2$. The post-taps can also be truncated to be accommodated in limited hardware resources. By such adjustment of the pre-taps, the truncated VSB pulse shaping filter can minimize the time delay in the EDOCR. Due to the pre-equalization, it can also compensate the linear distortions and reduce the in-band ripples so that the output SNR of the EDOCR can be significantly improved.

IV. Simulation and Laboratory Test Results

A. Simulation Results

The computer simulations have been performed based on the configuration of the EDOCR modulator shown in Fig. 7. The up-sampling rate for VSB filtering was assumed as 4, and the ER filter with 191 taps was used as a pulse shaping filter. The linear distortions which can be caused by a high power amplifier were not considered, and the mask filter was modeled as the 8th order Chebyshev filter. Fig. 9 shows the magnitude and group delay characteristic of the designed mask filter.

To calculate the pre-equalizer filter coefficients, the LMS algorithm was used. The total number of the pre-equalizer filter taps was set to 101 and its main tap was positioned at 51 to maintain the output SNR greater than 35 dB in symbol rate data. The time delay of the pre-equalizer filter itself is 4.74. that is relatively long. The number of taps of the matched filter was set to 121 to measure the SNR and an ideal channel with no multi-path and no additive noise was assumed while observing 200,000 symbols. Fig. 10 shows the simulation results of the pre-equalization when the pre-equalizer filter and the pulse shaping filter were used separately as shown in Fig. 6. Fig. 10(a) shows the EDOCR output constellation before pre-equalizing, in which the output SNR is about 14.1 dB, and Fig. 10(b) shows that after pre-equalizing, in which the output SNR is about 35.3 dB. The output SNR after pre-equalizing is greater than that of the ER filter with 191 taps (32.88 dB) in the Fig. 5 since the pre-equalizer can reduce in-band ripples due to the use of the ER filter. Fig. 11 shows the SNR and the shoulder amplitude in case of adjusting the number of the pre-taps after convolution of the pre-equalizer filter and the pulse shaping filter. In order to maintain the shoulder amplitude

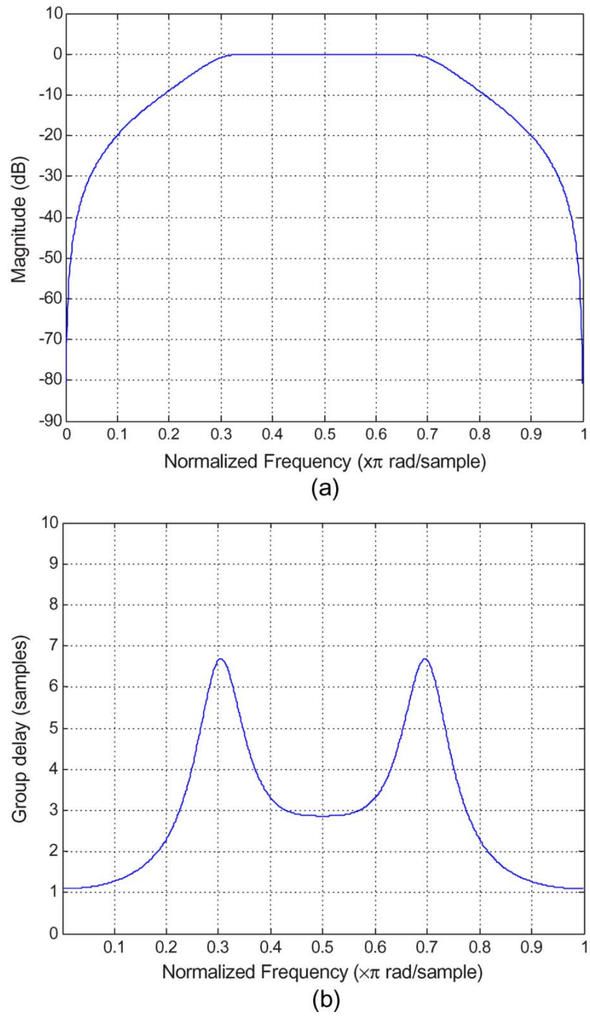

Fig. 9. Magnitude and group delay characteristic of 8th order Chebyshev filter. (a) Magnitude characteristic. (b) Group delay characteristic.

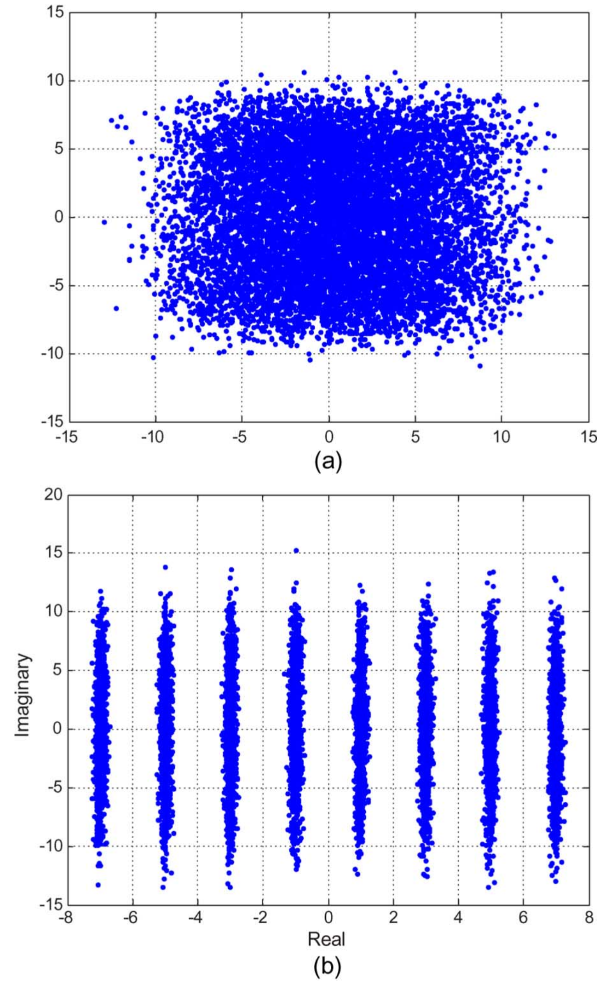

Fig. 10. Constellation of EDOCR output signal before and after pre-equalization. (a) Constellation of EDOCR output signal without pre-equalization $(\mathrm{SNR} = 14.1\ \mathrm{dB})$. (b) Constellation of EDOCR output signal with pre-equalization $(\mathrm{SNR} = 35.2\ \mathrm{dB})$.

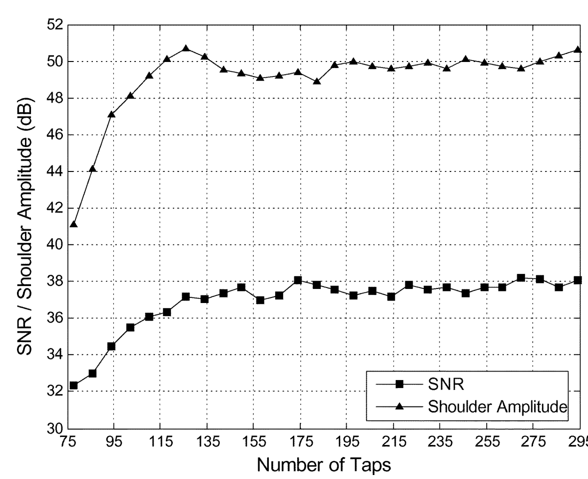

Fig. 11. SNR and shoulder amplitude according to the number of pre-taps after convolution of pre-equalizer filter and pulse shaping filter.

greater than 47 dB and the SNR greater than 27 dB, the number of the combined filter's pre-taps should be greater than 95 and then the time delay becomes about 2.21. Therefore, the newly created filter by adjusting the number of the pre-taps after convolution of the pre-equalizer filter and the pulse shaping filter minimizes the time delay while maintaining the required SNR and shoulder amplitude.

B. Laboratory Test Results

To verify the performance of the proposed modulator and pre-equalizer in the EDOCR, a hardware was implemented and the EDOCR output was measured by RFA300A, the VSB test and measurement equipment. The implemented EDOCR system used the ER filter with 191 taps and the pre-equalizer filter in which its main tap was positioned at 51 in symbol rate was calculated by LMS algorithm. To reduce the time delay as possible without violation of the EDOCR requirements, the number of the pre-taps was adjusted as 95 which is the same number of the pre-taps of the ER filter after convolution of the ER filter and the pre-equalizer filter. Thus, the time delay in the modulator including the pre-equalization is 2.21 that are the same as in the ER filter only. The EDOCR output signal was verified by RFA300A, and its spectrum, frequency response, group delay, and constellation before and after pre-equalization are shown in Fig. 12. Fig. 12 proves that the EDOCR output meets the

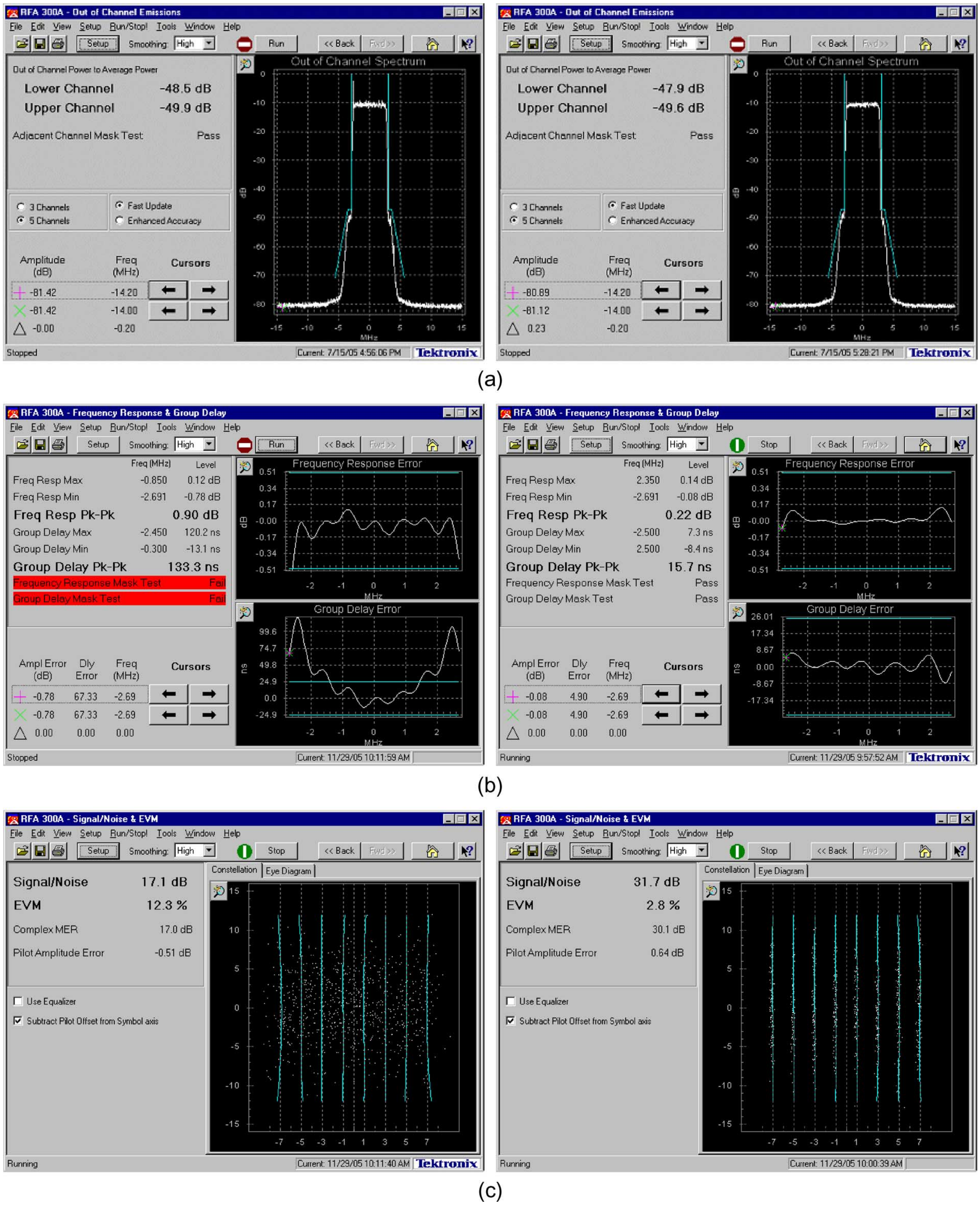

Fig. 12. Spectrum, frequency response, group delay, and constellation before and after pre-equalization. (a) Spectrum of EDOCR output signal (Left: before pre-equalization, Right: after pre-equalization). (b) Frequency response and group delay of EDOCR output signal (Left: before pre-equalization, Right: after pre-equalization). (c) Constellation of EDOCR output signal (Left: before pre-equalization, Right: after pre-equalization).

spectrum mask and SNR requirements. Usually the linear distortions caused by mask filter and other RF components in repeater system are not so severe that they can be compensated by a linear filter with relatively small number of taps compared to that of the VSB pulse shaping filter. According to the laboratory test results, it can be predicted that if the effective number of pre-taps of the combined filter is greater than that of the original pulse shaping filter, the proposed system would not perform as well as when the two filters are not combined but it still meets the FCC requirements.

V. Conclusions

This paper presents the modulation and pre-equalization methods to minimize the time delay of the EDOCR. The proposed modulation method uses an ER filter as a VSB pulse shaping filter instead of a conventional SRRC filter. And the proposed pre-equalization method calculates the pre-equalizer filter coefficients by comparing a baseband signal as a reference signal and a repeater output signal, and then creates new VSB pulse shaping filter coefficients by the convolution of the ER filter and the calculated pre-equalizer filter coefficients. According to the computer simulation and laboratory test results, the proposed methods have met the FCC requirements without causing significant system delay.

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