A Complexity Reduction Scheme for Interference Cancellation Radio Repeaters

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When applying the real time interference cancellation (ICAN) technique to a radio repeater, the most urgent task is to reduce the complexity of an ICAN system in the radio repeater. For complexity reduction, polyphase filters with a folded structure are used to perform downsampling and upsampling, and input and output filtering for spectrum control simultaneously. Frequency translation of the signal to avoid aliasing due to downsampling is efficiently executed by a Hilbert transform. The complexity of the proposed scheme is roughly one-fourth that of the conventional scheme with negligible deterioration of the signal quality and the power spectrum of the ICAN system.

Interference cancellation, complexity, polyphase, repeater, downsampling, Hilbert transform.

I. INTRODUCTION

Repeaters in mobile communication systems have been utilized as cost effective alternatives to base stations (BSs) for coverage expansion or clearance of shadow areas within the coverage [1]. But radio repeaters using the same frequency for transmission and reception of the signal have not been able to transmit the maximum available output power due to insufficient isolation between the transmit and receive antennas [1]. Therefore, interference cancellation (ICAN) techniques for radio repeaters have been studied as a means of increasing isolation between transmit and receive antennas. Some analog and digital ICAN techniques have been reported [2]-[4]. The performance of a real time ICAN repeater is determined by how accurately and timely the ICAN algorithm in the repeater can estimate the feedback signal and cancel it with the estimated signal over time varying conditions. Hence, the reduction of computational complexity required for the ICAN techniques is critical to obtain the desired ICAN performance.

In this work, we propose a complexity reduction scheme for an interference cancellation system (ICANS) in radio repeaters. To reduce the complexity of the ICANS, polyphase filters with a folded structure are used to perform down/up-sampling as well as input and output filtering for spectrum control simultaneously. Frequency translation of the signal to avoid aliasing due to downsampling is efficiently executed by a Hilbert transform. For performance evaluation, the complexity analysis of the proposed scheme and computer simulation for the error vector magnitude and the power spectrum of the ICANS's output signal are performed.

II. THE CONVENTIONAL ICAN SYSTEM

A. *The Structure of the Conventional ICAN Repeater*

The structure of the conventional ICAN radio repeater is shown in Fig. 1. It is composed of a radio frequency (RF) receiver, an ADC, an ICANS, a DAC, and a RF transmitter. The RF receiver perform amplification, frequency down-conversion to an intermediate (IF) frequency, and filtering for the incoming signal in the analog domain. The ADC converts the analog IF signal to a digital signal. The ICAN is performed by the ICANS in the digital domain. The DAC again transforms the interference cancelled digital signal to an analog signal. The RF transmitter then performs filtering, frequency upconversion to RF frequency, and power amplification that is necessary to radiate the RF signal into the air in the analog domain [3]-[4].

In the downlink, the output signal radiating from the repeater's transmit antenna toward mobile stations (MSs) is reflected on objects around the repeater and enter the receive antenna of the repeater. This feedback signal is there combined with the input signal coming from the BS and enters the RF receiver. If the repeater's gain is larger than the isolation between the transmit and receive antennas, the repeater will go into feedback oscillation if it does not have an ICANS. However, if the ICANS in the repeater cancels the feedback signal every time it enters the repeater, the repeater will not oscillate.

The main function of a radio repeater is to relay all signals that a specified service provider needs for service and to remove all the other signals. Therefore, the necessary band selection is normally performed by a surface acoustic wave (SAW) filter operating at the IF range before the ADC operation owing to the excellent out-band rejection capability of a SAW filter. When the input signal is a wideband such as the wideband code division multiple access (WCDMA) signal that has four frequency assignments (FAs) over 20 MHz

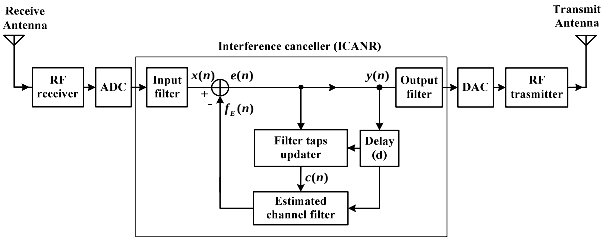

Fig. 1 The structure of the conventional ICANS for a radio repeater.

frequency band, the entire input signal is filtered by a SAW filter and converted to a digital signal by the ADC to make analog parts simple. Frequency conversion is then performed to translate the IF signal to a baseband signal, because more accurate estimation and cancellation of the feedback signal can be obtained there.

In general, a wideband signal changes faster than a narrow band signal in the time domain if two signals have the same center frequency. Hence, the estimation and cancellation of a fast varying signal are more difficult than those of a slowly varying signal. For this reason, a wideband signal such as a WCDMA signal with four FAs is split into four different narrowband signals with one FA before ICAN. The ICAN is subsequently performed for each narrowband signal with one FA. The four interference cancelled signals are again combined to a wideband signal. Accordingly, an input filter that has a sharp band selection characteristic is used to select a necessary frequency band out of the wideband input signal before ICAN. On the other hand, insufficient rejection by an input filter due to its imperfect frequency response and inaccurate cancellation of the feedback signal by the ICANS at the transition band can cause partial oscillation frequency components to appear on the frequency spectrum of the ICANS's output signal. Hence, an output filter is needed before the DAC to remove these unwanted out-band frequency components.

In this work, it is assumed that the ICAN repeater relays a WCDMA signal with four FAs over 20 MHz band. A sampling rate of 50 MHz is used to avoid aliasing due to the ADC and to allow some filtering margin for post-signal processing.

B. *Interference Cancellation Algorithm*

The conventional ICANS for a radio repeater is based on an adaptive filter on which an iterative algorithm such as the least mean square (LMS) algorithm or the normalized LMS algorithm [5]-[6] is implemented for ICAN, as shown in Fig. 1. The adaptive filter is made up of a filter tap updater (FTU), an estimated channel filter, a delay block, and a summation block. The adaptive filter estimates the feedback channel between transmit and receive antennas of the repeater. It then generates the estimated feedback signal using the estimated channel filter and uses it to cancel the actual feedback signal. If the ICAN is accurately performed by the adaptive filter, the output signal of the ICAN repeater will be only the amplified version of the input signal coming from the BS.

In this work, the use of the LMS algorithm for ICAN is briefly described due to low complexity [5]-[6]. The FTU in the adaptive filter calculates the coefficient vector $\mathbf{c}(n+1)$ with a length of N using the error signal $e(n)$, the delayed output signal vector $\mathbf{y}(n\text{-}d)$, and the previous coefficient vector $\mathbf{c}(n)$,

$$\mathbf{c}(n+1) = \mathbf{c}(n) + \mu e(n)\mathbf{y}(n-d). \tag{1}$$

In (1), μ is a parameter to control the convergence rate and the excess mean square error of the LMS algorithm. The delay of the dominant feedback signal component d may be obtained by correlating the input signal $x(n)$ and the output signal $y(n)$ of the repeater. In (1), $e(n) = x(n) - f_E(n)$. The estimated feedback signal $f_E(n)$ is generated by the estimated channel filter with the coefficient vector $\mathbf{c}(n)$ provided by the FTU, which is given by

$$f_E(n) = \mathbf{c}^T(n)\cdot\mathbf{y}(n-d). \tag{2}$$

In (2), $\mathbf{c}^{\mathrm{T}}(n)$ indicates the transpose of the coefficient vector $\mathbf{c}(n)$ and the symbol · denotes the dot product. The feedback signal $f(n)$ in the input signal $x(n)$ is cancelled by the estimated feedback signal $f_E(n)$ at the adder block. The LMS algorithm works so as to minimize the mean square of the error $e(n)$.

III. THE PROPOSED COMPLEXITY REDUCTION SCHEME

In this work, we propose a complexity reduction scheme for the ICANS that processes only a narrow band signal with one FA in a radio repeater that relays a wideband signal such as a WCDMA signal with four FAs. The ICANS based on the proposed complexity reduction scheme is shown in Fig. 2.

The complexity of the ICANS is determined by the ADC sampling rate as well as the complexity of the input and output filters and the adaptive filter for the ICAN algorithm. Therefore, considerable complexity reduction can be obtained by reducing the sampling rate through downsampling in the digital domain after the ADC sampling. Prior to downsampling, a decimation filter is needed to avoid aliasing of the input signal due to downsampling. Hence, the input filter can be also used to act as the decimation filter. Following ICAN, upsampling is necessary to restore the reduced sampling rate to the original sampling rate. An interpolation filter is needed to remove image spectrums of the ICANS's output signal after upsampling [7]. Therefore, the output filter can be also used to work as an interpolation filter.

The decimation filter calculates unnecessary products that would be discarded later due to decimation. Similarly, the interpolation filter performs unnecessary computations related to zero products made by interpolation. These computational inefficiencies may be avoided by using polyphase filters for the decimation and interpolation filtering [7]-[8].

A polyphase filter based on polyphase decomposition is a special sample rate conversion filter that performs filtering and downsampling simultaneously [7]-[8]. To apply polyphase decomposition to a N-tap decimation filter with a decimation factor M, its transfer function $H(z) = h_0 + h_1\mathrm{z}^{-1} + h_2\mathrm{z}^{-2} + \ldots + h_{N\text{-}1}\mathrm{z}^{-(N\text{-}1)}$ can be expressed as follows:

$$\begin{aligned}
H(z) &= h_0 + h_M\left(z^M\right)^{-1} + h_{2M}\left(z^M\right)^{-2} + \cdots + h_{(N/M-1)M}\left(z^M\right)^{-(N/M-1)} \\
&+ \left[h_1 + h_{1+M}\left(z^M\right)^{-1} + h_{1+2M}\left(z^M\right)^{-2} + \cdots + h_{1+(N/M-1)M}\left(z^M\right)^{-(N/M-1)}\right]z^{-1} \\
&\quad \cdots \\
&+ \left[h_{M-1} + h_{2M-1}\left(z^M\right)^{-1} + h_{3M-1}\left(z^M\right)^{-2} + \cdots + h_{N-1}\left(z^M\right)^{-(N/M-1)}\right]z^{-(M-1)}.
\end{aligned} \tag{3}$$

Equation (3) may be simplified as

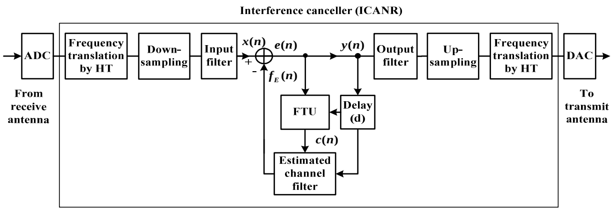

Fig. 2 The ICANS based on the proposed complexity reduction scheme.

$$H(z) = E_0(z^M) + E_1(z^M)z^{-1} + \cdots + E_{M-1}(z^M)z^{-(M-1)}. \quad (4)$$

Equation (4) expresses the transfer function $H(z)$ as the sum of delayed polyphase component filters $E_k(z^M)$,

$$E_k(z^M) = e_{k,0} + e_{k,1}z^{-M} + e_{k,2}z^{-2M} \cdots + e_{k,P_k-1}z^{-(P_k-1)M} \quad (5)$$

where k = 0, 1, 2, … M-1. In (5), the number of the kth polyphase component filter coefficients P_k is expressed by

$$P_k = \begin{cases} floor(N/M)+1 & ,k < (N\,modulo\,M) \\ floor(N/M) & ,otherwise \end{cases}. \quad (6)$$

The polyphase components $e_{k,\,l}$ in (5) becomes $e_{k,\,l} = h_{lM+k}$, where l = 0, 1, 2, … M-1 and h_k are coefficients of the impulse response for a N-tap decimation filter. From (4), the decimation filter structure based on polyphase decomposition can be obtained, as shown in Fig. 3. If the filter structure in Fig. 3 is used to the implementation of input and output filters in Fig. 1 and the operation order for filtering and downsampling or upsampling is interchanged by the identity of downsampling or upsampling [8], the ICANS structure will be changed to that in Fig. 4. Since the input and output filters as well as the LMS algorithm are now running at the reduced sampling rate, the complexity of the ICANS is considerably decreased.

For additional complexity reduction, the input and output polyphase filters are implemented based on a folded structure [7]. If the decimation filter is symmetrical and implemented using polyphase decomposition in (4), the polyphase component filters of the decimation filter in (5) will have symmetrical structure in pairs.

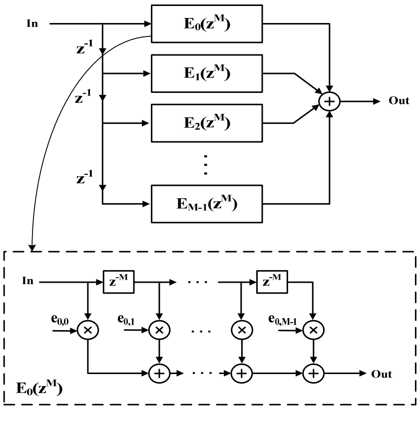

Fig.3. The decimation filter structure based on polyphase decomposition.

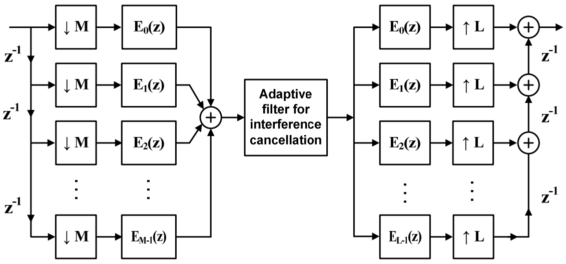

Fig. 4 The ICANS structure after applying polyphase decomposition, downsampling and upsampling identities to the input and output filters.

If the property that the polyphase component filters of a polyphase filter are symmetrical in pairs is exploited in the implementation of the ployphase filters in Fig. 4, the ICANS structure in Fig. 4 may be changed to that in Fig. 5. The input polyphase filter in Fig. 5 is realized based on a folded structure, where one input data sequence (in1) coming from one direction and another input data sequence (in2) coming from the opposite direction are added before multiplication. As a result, even though the number of additions for two cases with and without a folded structure is identical, the number of multiplications for the case with a folded structure is reduced by half compared with that of the case without a folded structure. Similarly, the output polyphase filter with a folded structure in Fig. 5 saves the same number of multiplications as the input polyphase filter with a folded structure does. However, in this case, delay elements whose number is the same as that of multiplications are necessary.

The center frequency of the input signal should be moved to a proper position prior to the decimation filtering. Otherwise, duplicates of the input signal's power spectrum will partially overlap each other. Such center frequency translation can be efficiently executed by a Hilbert transform (HT) [7]. The HT is a mathematical process performed on a real signal to generate a complex time-domain signal called an analytic signal that has no negative-frequency spectral components.

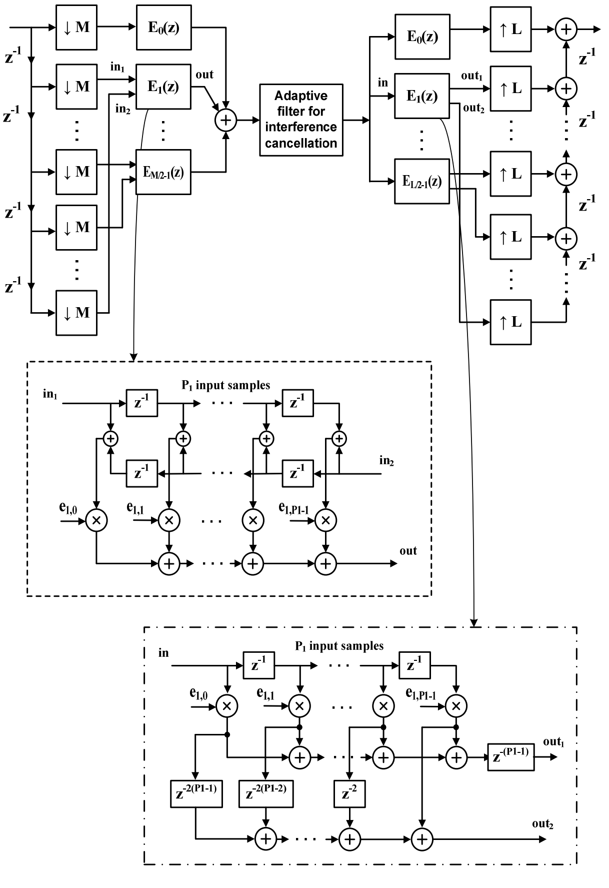

Fig. 5 The input and the output filters implemented based on a folded structure in the proposed ICANS structure.

For the frequency translation of the input signal, an analytic signal for the real input signal is first made by adding a 90^o phase-shifted version of the input signal generated by the HT to the input signal, as indicated in Fig. 6. The frequency translation is then executed by multiplying the analytic input signal by a complex exponential $e^{j2\pi f_o t}$ with a frequency offset f_o. The frequency offset f_o is the difference between the center frequency of a desired FA in the input signal and the target frequency at the positive frequency domain. Lastly, the real part of the frequency translated analytic signal is taken to obtain the real input signal with positive and negative frequency spectrums at the desired center frequency. After the ICAN followed by output filtering, the center frequency of the interference cancelled baseband signal is again translated to the original position by employing the HT, as shown in Fig. 6.

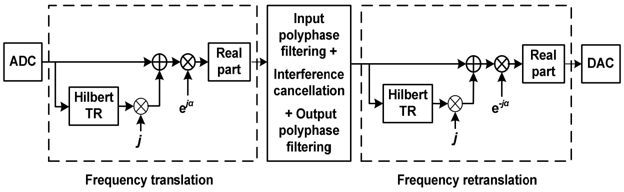

Fig. 6 Frequency translation of the input and output signals by the HT in the proposed ICANS structure.

IV. COMPLEXITY AND PERFORMANCE

For complexity analysis and performance verification, a signal generator that produces a WCDMA signal with 4 FAs and a receiver that measures the error vector magnitude (EVM) of the repeater's output signal are implemented on a computer [4]. It is assumed that only one FA out of four FAs in the WCDMA input signal is selected by the input filter, and only the selected FA is processed by the ICAN algorithm. An identical LMS algorithm is used for the conventional and the proposed schemes of the ICANS. The input and output filters for both cases above are implemented by finite impulse response (FIR) filters with a folded structure and their length is the same for fair comparison, that is, N_{CBPF} = 121 for the conventional scheme, and N_{PBPF} = 121 for the proposed scheme. The filter length has been selected to meet the in-band and out-band requirements of the output power spectrum for the repeater [9]. The decimation and interpolation factor $M = 5$ is used. It is also assumed that the input signal power to the repeater is -70 dBm and the input signal to noise ratio is 25dB.

For the conventional scheme shown in Fig. 1, the estimated channel filter length $N_{CLMS} = 50$ and a control parameter $\mu = 100$ for the LMS algorithm are used to meet the EVM requirement of the repeater's output signal [9]. In the proposed scheme in Fig. 2, the estimated channel filter length N_{PLMS} = 29 and the control parameter $\mu = 150$ are chosen to obtain almost the same ICAN performance. The Hilbert transform filter's length $N_{Hilbert}$ is 31.

The complexity for the conventional and proposed schemes is summarized in Table I. The number of multiplications and additions per sample for each function block in the ICANS is calculated using (1)-(2), (4), and (5) and is expressed in terms of the number of various filter coefficients, N_{CLMS}, N_{CBPF}, N_{PLMS}, N_{PBPF}, $N_{Hilbert}$, and the decimation factor M. The million instruction per second (MIPS) is computed on the assumption that the number of instruction cycles required for multiplication and addition is the same. The complexity of the LMS algorithm block for the proposed scheme is much lower than that of the conventional scheme. This is because the ICAN algorithm runs at the reduced sampling rate and the length of the estimated channel filter is reduced in the proposed scheme. The complexity of folded polyphase filters is also considerably low compared to that of folded FIR filters, because of sampling rate difference and computation efficiency. Overall, the complexity of the ICANS based on the proposed scheme is reduced to about one-fourth that of the conventional structure.

TABLE I
COMPUTATIONAL COMPLEXITY COMPARISON

	Function block	The number of multiplications per sample	The number of additions per sample	MIPS
The conventional structure	LMS algorithm block	$2N_{CLMS}+1$	$2N_{CLMS}-1$	10,000
	2 folded FIR filters	$2[(N_{CBPF}-1)/2+1]$	$2(N_{CBPF}-1)$	18,100
	Total	LMS algorithm block and 2 folded FIR filters		28,100
The proposed structure	LMS algorithm block	$2N_{PLMS}+1$	$2N_{PLMS}-1$	1,160
	2 folded polyphase filters	$2N_{PBPF}/M/2$	$2(N_{PBPF}/M+M-2)$	3,930
	2 frequency translation blocks[a]	$2(N_{Hilbert}/2+2)$	$2N_{Hilbert}$	2,700
	Total	LMS algorithm block, 2 folded polyphase filters, and 2 frequency conversion blocks		7,790

[a] The Hilbert transform is used.

Two feedback channel models are used in this work. The simple delay channel model emulates 0.005 us-spaced two direct feedback paths with equal gain. The multipath fading channel model is comprised of 4 multipaths with relative time delays of 0 us, 0.1 us, 0.2 us, and 0.3 us, and relative power levels of 0 dB, -3 dB, -10 dB, and -20 dB, respectively. The Doppler frequency in the fading channel model is 5.6 Hz [10].

To verify the performance of the ICANSs for different repeater's gain, the output power spectrums of the ICANSs are plotted in Fig. 7 and Fig. 8 for the gain of 10 dB and 20 dB. The output power spectrum of the conventional ICANS is shown to be about 10 dB higher than its input power spectrum at the first FA band for the gain of 10 dB, as shown in Fig. 7. However, when the repeater's gain is 20 dB, a symptom of oscillation starts to appear on the output power spectrum.

The proposed ICANS shows almost the same tendency as the conventional ICANS in Fig. 8. However, in this case, residual frequency components appear close to FA1 and near FA4. The residual frequency components close to FA1 are generated owing to insufficient image rejection by the interpolation filter. The residual spectral components near FA4 are produced by the imperfect frequency response of the Hilbert transform, which may be improved at the cost of complexity.

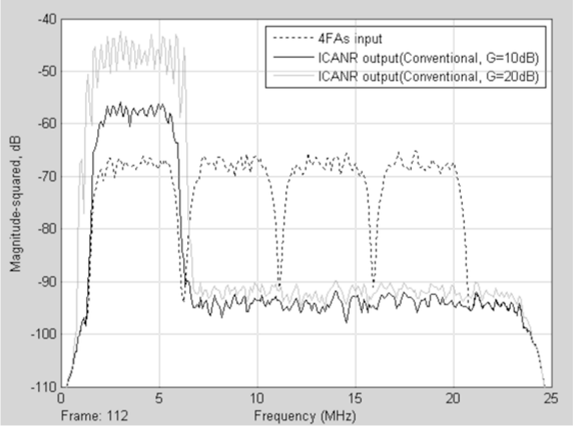

Fig. 7 Power spectrums for the input signal with 4 FAs, and the output signal of the conventional ICANS when the gain of the repeater is 10 dB or 20 dB.

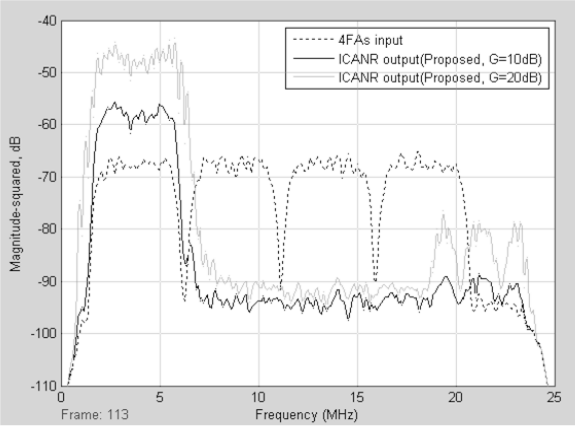

Fig. 8. Power spectrums for the input signal with 4 FAs, and the output signal of the proposed ICANS when the gain of the repeater is 10 dB or 20 dB.

The EVM of the repeater indicating the signal quality is

$$\mathbf{EVM} = \sqrt{\frac{\sum_{k=0}^{L-1} \left|\mathbf{e}_k\right|^2}{\sum_{k=0}^{L-1} \left|\mathbf{R}_k\right|^2}} \times 100\ \%. \tag{7}$$

In (7), $\mathbf{e}_k(n)$ is the error vector between the kth QPSK symbol vector recovered in the receiver and the kth reference symbol vector $\mathbf{R}_k(n)$ generated in the signal generator [11]. L is the number of QPSK symbol vectors needed to get a reliable EVM value. L = 1,280 is used in the simulation.

The EVMs for the output signals of the conventional and proposed ICANSs are plotted for the repeater's gain of 10 dB in Fig. 9. The EVM of the proposed ICANS under the simple delay channel is shown to be about 9.9 %, which is slightly higher compared to that (i.e., 8.4 %) of the conventional ICANS. The EVM of the proposed ICANS under the multipath fading channel shows slight variation over the measured period of time and its mean values of 10.3 % is slightly higher than that (i.e., 8.7 %) of the conventional ICANR, which still meets the specification of 12.5 % [9]. The EVM degradation of the ICANS with the proposed scheme is due to reducing the length of the estimated channel filter after the sampling rate reduction

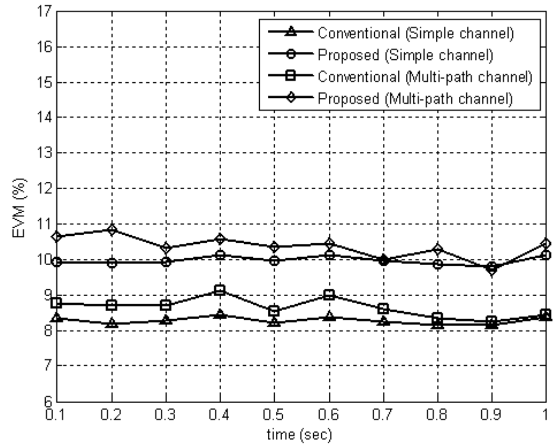

Fig. 9 The EVMs of the output signals for the proposed and conventional ICANSs under simple and fading feedback channels.

The reason for doing this is that the sampling rate reduction causes time span between dada samples to increase so that the identical delay spread of the multipath channel can be covered by the shorter length of the estimated channel filter. However, the EVM can be improved by increasing the length of the estimated channel filter, leading to complexity increase. The simulation results show that the performance of the ICANS based on the proposed scheme is slightly degraded due to the complexity reduction.

V. CONCLUSION

We propose a complexity reduction scheme for the ICANS in a radio repeater. Polyphase filters with a folded structure are used to perform both downsampling & upsampling, and input and output filtering. The considerable complexity reduction is achieved by the proposed scheme with negligible deterioration of the EVM and the power spectrum of the output signal.

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