An Efficient Hardware Simulator for the Design of a WCDMA Interference Cancellation Repeater

Moohong Lee, Byungjik Keum, Yunmok Son, and Hwang Soo Lee, Member, IEEE
Division of Electrical Engineering of EECS
KAIST, Daejeon 305-701, Korea
wildgoosemh@mmpc.kaist.ac.kr

Ju Tae Song and Joo-Wan Kim, Member, IEEE
R&D Center, SK Telesys
Seongnam, Gyeonggi-Do 463-825, Korea
kjw@sktelley.com

Abstract—An efficient hardware simulator for the design of a WCDMA interference cancellation repeater (ICR) is presented. The ICR, which is composed of a digital interference canceller and analog parts, is a time-varying system that reacts to a time-varying input signal. The design of the digital interference canceller is time-consuming due to the need for many iteration cycles of debugging, tuning, and performance verification. Furthermore, its performance, which is represented by the error vector magnitude (EVM) and the output power spectrum, can be verified only after it is implemented on a digital board, integrated into the repeater hardware with analog parts, and hooked up with expensive test equipment. Hence, a special computerized simulator is needed for fast and efficient verification of the interference canceller’s design. The simulator consists of a signal generator, which emulates a base station, the ICR with an interference canceller, a feedback channel that models wireless fading channels, and a receiver that measures the EVM of the ICR. The accuracy of the simulator is verified by showing that the EVM and the output power spectrum of a reference interference canceller measured on this simulator match well within an error range of less than 8% with the corresponding values measured on the repeater hardware. The usefulness of the simulator is also confirmed by simulating the EVM performance of the ICR under various multipath fading channel conditions.

Interference cancellation, canceller, repeater, simulator, feedback channel.

I. INTRODUCTION

Repeaters in mobile communication systems have been considered a cost effective solution for problems of coverage expansion and shadowing within the coverage area [1]-[4]. Thus, various types of repeaters such as radio frequency (RF) repeaters, optical repeaters, and microwave repeaters have been developed and deployed according to application. However, the isolation between the transmit and receive antennas of an RF repeater with the same transmission and reception frequency is critical for preventing the oscillation of the RF repeater and utilizing its maximum power [1]-[3].

Analog interference cancellation techniques have been used to increase the isolation between the transmit and receive antennas of an RF repeater; such techniques cancel out the feedback signal by using a signal generated with the same amplitude and anti-phase as the feedback signal [5]-[6]. The performance of analog interference cancellation repeaters (ICRs) is determined by how accurately the interference canceller (ICAN) can estimate the amplitude, phase, and time delay of the feedback signal, and how well it cancels the feedback signal using the signal generated with the estimated values. Some digital interference cancellation techniques estimate and cancel the feedback signal based on an adaptive filter on which an iterative algorithm for interference cancellation is implemented [7]-[9]. Their performance depends on the ability of the iterative algorithm to track channel variation and on computational complexity.

Because the input signal coming from a base station or mobile stations and the feedback signal are both time-varying, it is considerably difficult to verify the real-time performance of an ICR, which reacts to these time-varying signals in order to cancel the feedback signal. Normally, an ICR consists of an ICAN and analog parts, and its performance is expressed by the error vector magnitude (EVM) and the power spectrum of the output signal. Thus, the performance of the ICAN on which the interference cancellation algorithm runs is normally verified after the ICAN is implemented on a digital board, integrated into the repeater with analog parts, and hooked up with expensive test equipment. Furthermore, the design of the ICAN is time consuming due to the many iteration cycles for code implementation and parameter tuning on the hardware.

We present an efficient simulator that speeds up the design and performance verification of an ICAN for a wideband code division multiple access (WCDMA) RF repeater by quickly and efficiently measuring the EVM and the power spectrum of the RF repeater’s output signal at the simulator level. The concept of an ICR is briefly described in Section II. Section III presents the structure of an efficient simulator for the design of an ICR. The accuracy of the simulator is verified by comparing the EVMs and the output power spectrums of a reference ICAN on the simulator and on the repeater hardware in Section IV. Finally, we present conclusions in Section V.

II. THE CONCEPT OF AN INTERFERENCE CANCELLATION REPEATER

A. The Structure of an Interference Cancellation Repeater

The structure of an ICR is shown in Fig. 1. It is composed of a downlink block, an uplink block, a set of a duplexer and a
In this section, we discuss interference cancellation in WCDMA uplink and downlink paths. In general, good interference cancellation performance can be obtained at a low frequency range because at that range signals can be more accurately estimated and cancelled. Moreover, RF repeaters should select only a given frequency band allocated for a specified service provider. Such a band selection function is normally implemented with the aid of a surface acoustic wave filter, which operates at the IF range to reduce the computational complexity of the ICAN. Hence, the frequency conversion from the IF to the baseband frequency is performed after the ADC or by bandpass sampling of the ADC so that the ICAN can run at the baseband frequency range.

B. Interference Cancellation Algorithm

The interference cancellation algorithm is implemented based on an adaptive filter, which is made up of an adaptive weight controller (AWC), a transversal filter, a delay block, and a summation block, as shown in Fig. 2. Parts of the output signal $x(t)$, which is radiated from the transmit antenna, go through the feedback channel $h_f(t)$ between the transmit and receive antennas and enter into the receive antenna. The feedback signal $y_f(t)$ is combined with the input signal $i(t)$, which comes from a base station or mobiles, and enters the receive antenna. The combined input signal of $c(t) = y_f(t) + i(t)$ is transformed to the combined digital input signal of $c(n) = y_f(n) + i(n)$ by means of the ADC after RF front-end signal processing.

The adaptive filter estimates the impulse response of the feedback channel $h_f(n)$ by using the AWC, which is a digital version of the analog time-varying feedback channel $h_f(t)$. The adaptive filter then generates the estimated feedback signal $y_f(n)$ with the transversal filter and the coefficient vector $w(n)$ that are provided by the AWC. The estimated feedback signal $y_f(n)$ is subsequently used to cancel the actual feedback signal $y_f(n)$ in the combined digital input signal $c(n)$. An iterative algorithm such as the least mean square (LMS) algorithm tries to minimize the mean square of the error $e(n)$ between $c(n)$ and $y_f(n)$.

In our work it is assumed that the ICR relays a WCDMA signal with a 20 MHz bandwidth containing four frequency assignments (FA) for a specified service provider. Therefore, we use a sampling rate of 50 MHz.
To cancel the actual feedback signal using the estimated feedback signal, it is important to ensure that the delay estimation of the feedback signal is exact. The delay of the feedback signal is the sum of the propagation delay between the transmit and receive antennas, and the system delay caused by various filters and signal processing blocks in the repeater. The delay may be obtained by correlating the input signal \( c(n) \) and output signal \( x(n) \) of the RF repeater in Fig. 2.

The LMS algorithm for interference cancellation is briefly described as follows [10]-[12]: The LMS algorithm in the AWC calculates the coefficient vector \( w(n+1) \) for the transversal filter that has a length of \( N \). The calculation is based on the error signal \( e(n) \), the delayed output signal vector \( x(n-d) \), and the previous coefficient vector \( w(n) \). Thus,

\[
w(n+1) = w(n) + \mu e(n)w(n-d).
\]

In (1), \( \mu \) is a parameter that controls the convergence rate and the excess mean square error of the LMS algorithm and \( d \) is the delay of the dominant feedback signal component. The error \( e(n) \) between the input signal \( c(n) \) and the estimated feedback signal \( y_E(n) \) is given by

\[
e(n) = c(n) - y_E(n).
\]

The transversal filter with the coefficient vector \( w(n) \), which emulates the estimated feedback channel \( h_E(n) \), estimates the feedback signal \( y_E(n) \) from the delayed output signal vector \( x(n-d) \) as follows:

\[
y_E(n) = w^T(n) \cdot x(n-d).
\]

In (3), \( w^T(n) \) indicates the transpose of the coefficient vector \( w(n) \) and the symbol \( \cdot \) denotes the dot product. The feedback signal \( y_E(n) \), which is buried in the combined input signal \( c(n) \), is then cancelled by the estimated feedback signal \( y_E(n) \) in the summation block. If the interference cancellation process is accurately performed by the adaptive filter, the output signal \( x(n) \) of the ICR is an amplified version \( G\hat{d}(t) \) of the input signal that comes from a base station or mobiles. The \( G \) is the gain of the RF repeater.

III. THE STRUCTURE OF THE SIMULATOR

Because the ICAN of an RF repeater is a time-varying system that reacts to a time-varying input, the whole process of design, code implementation, and performance verification for the ICAN requires a considerable amount of time. In particular, the tasks to debug implemented codes and to tune optimal parameters for a time-varying system on a digital board take many iteration cycles. Furthermore, performance verification is possible only after the digital board is integrated into the repeater with analog parts and hooked up with expensive test equipment, such as a fading channel emulator, a signal generator, and a spectrum analyzer with a special option to measure EVM. Hence, a computer-based simulator is needed to do design and performance verification of the ICAN speedily and efficiently. The simulator should perform the following functions:

- To debug implemented codes of the ICAN
- To tune parameters of the ICAN for optimal performance
- To measure the performance of the ICAN in terms of the EVM and the power spectrum for the output signal of the ICR containing the ICAN
- To monitor performance change of the ICAN under various feedback channel conditions.

The simulator is made up of a signal generator, a feedback channel, a receiver, an ICR, and a target ICAN, which is to be designed, as shown in Fig. 3. In the signal generator, which emulates a base station that transmits an input signal to the ICR, random bits from a random generator are quadrature phase shift keying (QPSK) modulated. A WCDMA signal with one FA is generated after the QPSK symbols are filtered by a root-raised cosine (RRC) filter. The other three WCDMA baseband signals with one FA are generated by the same process. Subsequently, they are multiplexed after frequency upconversion to make a four-FA WCDMA signal with an IF center frequency [13]-[14].

The receiver that measures the EVM of the interference cancelled output signal is composed of a synchronization block, a frequency downconversion block, an RRC filter, and an EVM measurement block. The synchronization block compensates for the total time delay caused by various filters and signal processing blocks in the simulator. The output signal from the ICAN is translated to zero frequency by the frequency downconversion block and then filtered by the RRC filter to produce a baseband signal with one FA, which is made up of QPSK modulated symbols. For these recovered QPSK symbols, the EVM measurement block measures the output signal quality of the ICR.

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![Fig. 3. The simulator used to verify the performance of the designed ICAN.](image-url)
The signal quality is expressed by the EVM as follows:

$$\text{EVM} = \frac{\sqrt{\sum_{k=0}^{L-1} |e_k|^2}}{\sqrt{\sum_{k=0}^{L-1} |R_k|^2}} \times 100 \% .$$  \hspace{1cm} (4)

In (4), $e_k(n)$ is the error vector between the $k$th QPSK symbol vector recovered in the receiver and the $k$th reference symbol vector $R_k(n)$ generated in the signal generator [15]. $L$ is the number of QPSK symbol vectors needed to get a reliable EVM value. $L = 1,280$ is used in the simulation.

The feedback channel models the time-varying fading channel between the transmit and receive antennas of the RF repeater. The time-varying fading channel is formed by the characteristics of the transmit and receive antennas, and by the pointing direction and separation distance of two antennas as well as the surroundings of the RF repeater. The surroundings of the outdoor RF repeaters is composed of fixed and moving reflectors, such as mountains, buildings, trees, and moving vehicles. In feedback channel model, dominant delay components are assumed to be generated by fixed reflectors, such as mountains and buildings, which seldom change. In addition, minor delay components are assumed to be formed by fixed reflectors far away from the repeater and by moving vehicles near the RF repeater; thus, they may or may not change, depending on the type of reflectors. The effect of moving reflectors can be emulated by independent faders with a Doppler frequency [16].

In addition to the digital ICAN, the ICR has an RF receiver part, an ADC, a DAC, and an RF transmitter part, as shown in Fig. 3. The effects of these blocks should be taken into account in the simulator. An additive white Gaussian noise (AWGN) block is used to give the noise figure effect of the RF repeater and the amplifier block provides the necessary gain. The bandpass sampling effects of the ADC and the DAC are offered by the downsampling and upsampling blocks, respectively. Two IF filters are required for anti-aliasing filtering before the ADC and post-filtering after the DAC.

The simulator is used to perform debugging, tuning, and performance verification of the ICAN after the initial design of the ICAN. Thus, the ICAN is implemented in a fixed point and all the other parts of the simulator shown in Fig. 3 are implemented in a floating point.

IV. PERFORMANCE VERIFICATION

The accuracy of the implemented simulator is verified by comparing the EVMs and the output power spectrums for a reference ICAN on the simulator and on a simplified repeater hardware where the reference ICAN is implemented. For that purpose, we configured the signal generator of the simulator to generate a WCDMA signal that has four FAs with center frequencies at 53.75 MHz, 58.75 MHz, 63.55 MHz, and 68.35 MHz, respectively. For precise comparison of the ICAN’s performance on the simulator and on the hardware, we used a simple channel model to represent a direct feedback path with no delay and with AWGN. The reason we use this type of a channel model is that both the multipath fading channel model and the commercial fading channel emulator have a random property; hence, only the average performance measured over a very long period can be compared with the two cases just mentioned.

The LMS algorithm is used for interference cancellation in the reference ICAN due to its low computational complexity. Furthermore, we chose a transversal filter with a length of $N = 65$ for the LMS algorithm [10]-[11]. This length is based on the fact that the data sample resolution is 0.02 us due to the sampling rate of 50 MHz in the ADC and the maximum delay spread of the feedback channel model to be used later is 1 us. The delay of 1 us corresponds to 50 taps of the transversal filter. The control parameter of $\mu = 1,000$ was determined by tuning. Furthermore, as shown in Fig. 3, we used a finite impulse response (FIR) bandpass filter to pass the first two FAs and to reject the remaining two FAs out of the input signal with four FAs at the front of the reference ICAN. The length of the input FIR filter, $N_{\text{FIR}} = 121$, was selected to meet the in-band and out-band characteristics of the output signal’s power spectrum [15].

For a real performance measurement on the repeater hardware, the reference ICAN is implemented in a hardware description language code and is ported onto an Altera Stratix II field programmable gate array (FPGA) chip mounted on a digital board. We made a simplified repeater by attaching an analog amplifier to the digital board. A direct feedback path is then formed by connecting the output of the simplified repeater to its input with an RF cable and two power splitters. A commercial signal generator is configured to generate the same WCDMA signal with four FAs as that from the simulator. A spectrum analyzer with a special option is used to measure the EVM for the output signal of the simplified repeater. The test setup for the performance verification of the reference ICAN in the simplified repeater is shown in Fig. 4. The reference ICAN is implemented with finite precision of 16 bits on both the simulator and the hardware.

To make sure that the reference ICAN cancels the feedback signal as expected, the repeater’s gain is adjusted to be 10 dB larger than the isolation between the donor and service antenna ports in Fig. 3. As a result, the repeater will oscillate if the reference ICAN does not work properly.

Fig. 4. Test setup for the performance verification of the reference ICAN in the simplified repeater.
The power spectrums for the input signal with four FAs and the output signal with two FAs of the simplified repeater on the simulator are shown in Fig. 5. They are measured after the ADC and before the DAC of the simulator, respectively. Thus, the spectrums are displayed in the baseband frequency region. Because the input filter in the reference ICAN passes only the first two FAs out of four FAs in the input signal, these two FAs from the output port of the ICR go back to its input port through the direct feedback path. They are then added to the input signal with four FAs that come from the signal generator, as shown in Fig. 3. The output signal with two FAs is about 10 dB larger than the input signal with four FAs. However, there is no further increase in the output signal because the reference ICAN cancels the feedback signal. On the other hand, spurious frequency components appear in the place of the third FA of the output power spectrum of the simplified repeater due to insufficient cutoff characteristics of the input filter at the transition band.

The power spectrums for the input signal with four FAs, which comes from the real signal generator, and the output signal with two FAs of the simplified repeater hardware are shown in Fig. 6. They are measured before the ADC and after the DAC on the digital board. Except for the power level difference, the in-band output power spectrum on the hardware is almost the same as that on the simulator. However, we also observed other spurious components, which look like spikes, in the place of the third FA of the out-band output power spectrum. These spurious components seem to be caused by two factors: firstly, the input filter has theoretically insufficient rejection at the out-band frequencies and, secondly, the implemented rejection performance is not the same as the theoretical rejection performance over the out-band frequencies. However, these spurious components on the out-band output power spectrum can be removed if another filter is placed after the reference ICAN to provide a greater level of rejection at the transition and out-band frequencies.

The EVM of the second FA output signal measured on the simulator over a given period of time is shown in Fig. 7. The average EVM is about 8.7 %, which is smaller than the specification of 12.5 % in [15]. Furthermore, the average EVM of the second FA output signal on the repeater hardware is 9.43 %, as shown in Fig. 8. The EVM for the repeater hardware is slightly degraded compared to the EVM of the simulator because of the in-band ripple of an analog amplifier in the repeater hardware, which does not exist in the simulator.
The spurious components over the out-band frequency range do not affect the EVM because the receivers of the simulator and the spectrum analyzer remove them with a RRC filter or something similar before the EVM is measured. The error between two average EVM values measured on the simulator and on the hardware is less than 8%.

Overall, on the basis of the EVM results and the output power spectrum, we may conclude that the implemented simulator is accurate enough in measuring the EVM as well as the output power spectrum of the ICR. As a result, the simulator may be used to quickly and efficiently verify the performance of the designed ICAN on the computer.

To show the usefulness of the simulator, we briefly present the EVM performance of the ICR with the reference ICAN, which is obtained on the simulator, under various feedback channels. The following three channel models with different power delay profiles and AWGN are used for this purpose. The first channel model has two fixed multipath components with equal power and a spacing of 0.1 us. The second channel model is composed of four fixed multipath components with relative time delays of 0 us, 0.1 us, 0.8 us, and 1 us, and relative power levels of 0 dB, -8 dB, -15 dB, and -20 dB, respectively. The third channel model has an identical power delay profile as the second channel model except that the last two delay components are changing with a Doppler frequency of 55.6 Hz. This effect occurs when a vehicle moving at a speed of 42 km/h toward the transmit antenna at an angle of 45° reflects the signal radiating from the transmit antenna.

The EVM performance of the ICR with the reference ICAN under various feedback channel conditions is shown in Fig. 9. The first two channel models have almost the same EVM value of around 9.2%. The EVM for the last feedback channel model has some fluctuation over time due to the fading effect applied to the last two delay components in the channel model. The maximum EVM value is about 13.5%, which does not meet the specification of 12.5% in [15].

V. Conclusion

We presented an efficient hardware simulator for the design of a WCDMA ICR that reacts to a time varying input signal. With the aid of the simulator, the design and performance verification of the ICAN can be expedited by quick and efficient measurement of the EVM and the power spectrum of the output signal. The efficient tuning of parameters in the ICAN for optimum performance is also possible with the simulator, which can save a considerable amount of development time and cost. The accuracy of the simulator has been verified by showing that the EVM and the output power spectrum of the reference ICAN on the simulator match well within an error range of less than 8% with the corresponding values measured on the repeater hardware.

REFERENCES