A Radio Repeater Interference Cancellation Model for Mobile Communication Systems

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Abstract

When the gain of a radio repeater is larger than the isolation between the transmit and receive antennas of the repeater, the feedback signal that comes into the receive antenna from the transmit antenna of the repeater causes the repeater to go into feedback oscillation regardless of the input signal. To prevent feedback oscillation of the repeater by interference cancellation (ICAN), a feedback oscillation model of a radio repeater is first formulated. An ICAN model is then derived from that model. According to the ICAN model, iterative algorithms such as the least mean square (LMS) algorithm using the minimum mean square error criterion can be applied to perform the necessary ICAN. The validity of the ICAN model is confirmed by a computer simulation that shows the relationship among the level of ICAN, the repeater's gain, the estimated delay, and the filter length for the LMS algorithm.

1. Introduction

In the case of a radio repeater that uses the same frequency for transmit and receive signals, the feedback interference signal that comes into the receive antenna from the transmit antenna of a radio repeater causes the radio repeater to go into feedback oscillation. Even when there is no input signal to the repeater, the repeater can go into feedback oscillation due to the noise radiating from the transmit antenna, if the repeater's gain is larger than the isolation between the transmit and receive antennas of the repeater. Therefore, the feedback oscillation of a radio repeater prevents the use of the repeater's maximum available output power [1]-[2]. In addition, it makes installation of the repeater difficult as large isolation should be secured between the transmit and receive antennas of the repeater.

Some interference cancellation (ICAN) techniques to increase the isolation between the transmit and receive antennas of radio repeaters have been reported [3]-[7]. Among them, analog ICAN techniques cancel the feedback signal using a generated signal with the same amplitude and anti-phase as the feedback signal [3]-[4]. Digital ICAN techniques based on an adaptive filter have also been implemented [5]-[7].

In this work, we propose an ICAN model for a radio repeater that goes into feedback oscillation when the gain of the radio repeater is larger than the isolation between the transmit and receive antennas of the repeater. According to the ICAN model, iterative algorithms such as the least mean square algorithm based on the minimum mean square error (MMSE) criterion can be used to perform the necessary ICAN.

The structure of the ICAN repeater is briefly described in Section II. In Section III, a feedback oscillation model of a radio repeater and an ICAN model for radio repeaters are presented. The validity of the proposed ICAN model is confirmed by a computer simulation in Section IV. Finally, conclusions are presented in Section V.

2. The structure of an ICAN repeater

The structure of the downlink path, which relays the signal from a base station to mobile stations, for a radio ICAN repeater is shown in Figure 1.

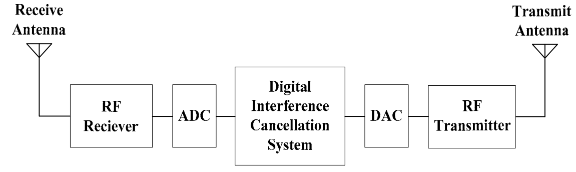

Figure 1. The structure of an ICAN repeater.

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It is composed of a radio frequency (RF) receiver, an ADC, a digital interference cancellation system (DICANS), a DAC, and a RF transmitter. The RF receiver executes pre-processing such as amplification, frequency downconversion to an intermediate (IF) frequency, and filtering for the incoming analog signal. The ADC converts the IF analog signal to a digital signal. The ICAN operation is performed by the DICANS in the digital domain. The DAC again transforms the interference cancelled digital signal to an analog signal. The RF transmitter performs post-processing such as filtering, frequency upconversion to RF frequency, and power amplification to radiate the RF signal into the air.

Parts of the output signal radiating from the repeater's transmit antenna toward mobile stations are reflected on reflectors around the repeater and enter the receive antenna of the repeater. This feedback signal, which interferes with the input signal coming from the base station to the receive antenna of the repeater, enters the RF receiver. In the case of a conventional radio repeater without the DICANS, if the repeater's gain is larger than the isolation between the transmit and receive antennas of the repeater, the amplitude of the feedback signal continues to increase every time the signal goes through a closed loop composed of the repeater and the feedback channel. Eventually, the repeater will go into feedback oscillation. However, implementation of a mechanism in the repeater that cancels the feedback signal every time it enters the repeater would prevent the repeater from oscillating. Therefore, a DICANS, which performs necessary ICAN, is needed to prevent feedback oscillation when the repeater's gain is larger than the isolation between the transmit and receive antennas of the repeater.

In general, the ICAN operation is performed at a low frequency range to obtain more accurate estimation and cancellation of signals. For this purpose, the first frequency conversion is executed in the RF receiver before the ADC and the second frequency conversion in the DICANS after the ADC. However, this frequency conversion process does not affect the feedback oscillation of the repeater, because it does not limit the increase of the signal level due to feedback oscillation.

3. The proposed ICAN model

A. Feedback oscillation model of a radio repeater

The analog signal, which propagates through a feedback channel and is processed in the RF receiver of a radio repeater, as shown in Figure 1, may be represented in the digital domain without any loss of information through an analog-to-digital conversion process. Hence, the feedback oscillation that occurs in a closed loop, which is composed of a radio repeater and a feedback channel, can be described in the digital domain by the simple model shown in Figure 2.

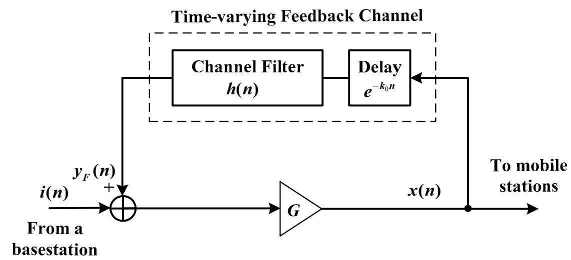

Figure 2. Feedback oscillation model of a radio repeater.

A normal radio repeater amplifies the small input signal that enters the input antenna, and transmits the amplified output signal via the transmit antenna. Therefore, the repeater can simply be represented by the repeater's gain G, as shown in Figure 2. Parts of the output signal radiating from the repeater's transmit antenna toward mobile stations are reflected on reflectors around the repeater and arrive at the receive antenna of the repeater via several feedback paths with different delays. Hence, the feedback channel can be modeled by a channel filter with a impulse response $h(n)$ and a delay block. The impulse response $h(n)$ is normalized to the dominant feedback component with maximum power so that $|h(n)| \le 1$ for any time n. The delay k_0 in the delay block indicates the delay of the dominant feedback component. If the reflectors around the repeater change over time, the impulse response $h(n)$ of the channel filter that models a time-varying feedback channel will change and the delay k_0 can be changed as well. However, in this work, for a succinct analysis of the feedback oscillation of a radio repeater, it is assumed that the impulse response $h(n)$ and the delay k_0 do not change.

The input signal $i(n)$ represents a signal that comes from a base station or the sum of a signal that comes from a base station, and noise that is generated in the repeater itself. The feedback signal $y_F(n)$ can be expressed by

$$y_F(n) = h(n) * x(n - k_0) \qquad (1)$$

where * denotes the convolution. In (1), the output signal $x(n)$ is

$$x(n) = G[i(n) + y_F(n)] \quad (2)$$

where G indicates the repeater's gain. If $y_F(n)$ in (1) is applied to (2), the output signal $x(n)$ becomes

$$x(n) = Gi(n) + Gh(n) * x(n - k_0). \quad (3)$$

Since it is assumed that the impulse response $h(n)$ and the delay k_0 do not change over time, after the output signal $x(n)$ in (3) is applied to itself twice, the output signal $x(n)$ at time $n = 3k_0$ can be expressed by

$$\begin{aligned} x(n) &= Gi(n) \\ &+ G^2 h(n) * i(n-k_0) \\ &+ G^3 h(n) * h(n-k_0) * i(n-2k_0) \\ &+ G^4 h(n) * h(n-k_0) * h(n-2k_0) * i(n-3k_0). \end{aligned} \quad (4)$$

In (4), it is assumed that $x(0) = G\ i(0)$.

Since the input signal that comes from a base station or a noise process can be assumed to be independent and identically distributed (i.i.d.), the mean and the variance of the input signal $i(n)$ become $E\{i(n)\} = 0$ and $E\{i^2(n)\} =$ constant, respectively. On the other hand, the feedback oscillation of the repeater occurs as a result of the increasing power of the input signal $i(n)$, which circulates in a closed loop composed of a repeater and a feedback channel, not by the type of information in the input signal $i(n)$. Therefore, the input signal $i(n)$ can be regarded as a time invariant signal from the viewpoint of feedback oscillation. The property of time invariance [8] for the input signal $i(n)$ and the impulse response $h(n)$ of the feedback channel results in

$$h(n) * i(n-k_0) = h(n-k_0) * i(n). \quad (5)$$

If (5) is applied to (4), the output signal $x(n)$ at time $n = 3k_0$ is

$$\begin{aligned} x(n) &= Gi(n) \\ &+ G^2 h(n-k_0) * i(n) \\ &+ G^3 h(n-k_0) * h(n-2k_0) * i(n) \\ &+ G^4 h(n-k_0) * h(n-2k_0) * h(n-3k_0) * i(n). \end{aligned} \quad (6)$$

Using the same logic, the output signal $x(n)$ at time $n = Mk_0$ can be represented by

$$x(n) = Gi(n) + \sum_{m=0}^{M} \left[G^{m+2} [\prod_{j=0}^{m} h(n-(j+1)k_0)] \right] * i(n) \quad (7)$$

where $x(0) = G\ i(0)$. In (7), the symbol Π denotes that a series of convolution operations is performed on delayed impulse responses. For example,

$$\prod_{j=0}^{2} h(n-(j+1)k_0) = h(n-k_0) * h(n-2k_0) * h(n-3k_0),$$
$$\prod_{j=0}^{0} h(n-(j+1)k_0) = h(n-k_0)$$
$$(8)$$

In (7), the first term after the equal sign indicates the normal output signal of the repeater and the remaining terms are generated by the feedback of the repeater's output signal via the feedback channel. If $G|h(n-k_0)| > 1$, which is equivalent to $G > 1$, because $h(n)$ is time invariant and the dominant component of $h(n)$ has an amplitude of 1, the output signal $x(n)$ in (7) will continue to increase over time. This causes the repeater to go into feedback oscillation. The condition $G > 1$ means that the repeater's gain is larger than the isolation between the transmit and receive antennas of the repeater. In addition, the larger the gain G is, the faster the repeater goes into feedback oscillation. Furthermore, even if there is no input signal coming from a base station, the repeater can go into feedback oscillation when G > 1 due to the noise that exists within the repeater.

B. ICAN model for a radio repeater

In order to prevent the repeater from going into feedback oscillation when the repeater's gain is larger than the isolation between the transmit and receive antennas of the repeater, the ICAN scheme illustrated in Figure 3 is used. To cancel the feedback signal $y_F(n)$ whenever it enters the repeater, the estimated feedback signal $y_E(n)$ is generated by an estimated channel filter with an impulse response $w(n)$ as follows:

$$y_E(n) = w(n) * x(n - l_0) \quad (9)$$

where l_0 is the estimated delay of the dominant feedback signal. The error signal $e(n)$ in Figure 3 is given by

$$e(n) = i(n) + y_F(n) - y_E(n) \quad (10)$$

If (1) and (9) are substituted in (10) and the estimated delay l_0 is assumed to be equal to the delay k_0,

$$e(n) = i(n) + [h(n) - w(n)] * x(n - k_0). \quad (11)$$

Therefore, the output signal $x(n)$ can be expressed by

$$x(n) = Gi(n) + G[h(n) - w(n)] * x(n - k_0) \quad (12)$$

where the relation $x(n) = G\,e(n)$ is used. By comparing (3) and (12), the output signal $x(n)$ at time $n = 3k_0$ can be obtained from (4) as follows:

$$\begin{aligned} x(n) &= Gi(n) \\ &+G^2[h(n-k_0) - w(n-k_0)] * i(n) \\ &+G^3[h(n-k_0) - w(n-k_0)] * [h(n-2k_0) - w(n-2k_0)] * i(n) \\ &+G^4[h(n-k_0) - w(n-k_0)] * [h(n-2k_0) - w(n-2k_0)] \\ &\quad * [h(n-3k_0) - w(n-3k_0)] * i(n). \end{aligned} \quad (13)$$

In the same manner, from (7), the output signal $x(n)$ at time $n = Mk_0$ can be represented by

$$x(n) = Gi(n) + \sum_{m=0}^{M} \left[G^{m+2} [\prod_{j=0}^{m} \{h(n-(j+1)k_0) - w(n-(j+1)k_0)\}] \right] * i(n). \quad (14)$$

According to (14), if $G\left|h(n-k_0) - w(n-k_0)\right| > 1$, which is equivalent to $G > 1$, the output signal $x(n)$ will continue to increase over time due to the terms that are generated by the feedback of the repeater's output signal. Therefore, to prevent the amplitude of the output signal $x(n)$ from continuing to increase when $G > 1$, the impulse response $w(n)$ of the estimated feedback channel should be equal to the impulse response $h(n)$ of the feedback channel. In other words, if $h(n) = w(n)$, then $y_F(n) = y_E(n)$. As a result, the error in (10) becomes $e(n) = i(n)$. This means there is no feedback oscillation of the repeater even though the repeater's gain is larger than the isolation between the transmit and receive antennas of the repeater.

However, it is almost impossible to always accurately estimate a time-varying feedback channel $h(n)$ and the delay k_0. Therefore, instead of trying to minimize the difference $y_F(n)$ - $y_E(n)$ by minimizing the difference $h(n)$ - $w(n)$ at every time n, it is more reasonable to minimize the difference $y_F(n)$ - $y_E(n)$ by minimizing the mean square difference $E\{[y_F(n) - y_E(n)]^2\}$. The minimum mean square of the error in (10) becomes

$$\begin{aligned} E\{e^2(n)\} &= E\{i(n)^2\} + E\{[y_F(n) - y_E(n)]^2\} \\ &\quad - 2E\{i(n)[y_F(n) - y_E(n)]\}. \end{aligned} \quad (15)$$

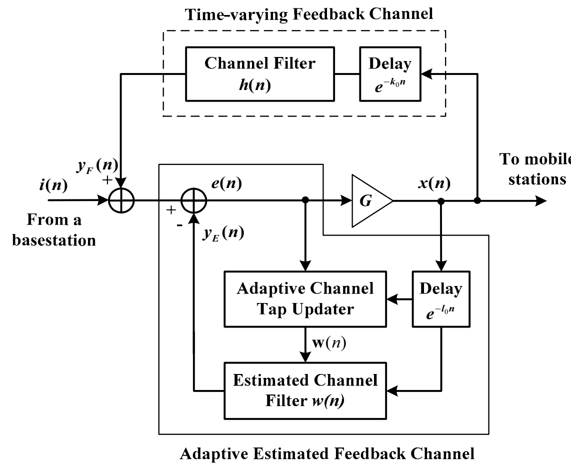

Figure 3. ICAN model for a radio repeater.

Since the input signal $i(n)$ is assumed to be i.i.d. and the feedback signal $y_F(n)$ is related to a series of the delayed input signal $i(n\text{-}mk_0)$ with m being an integer, the input signal $i(n)$ and the feedback signal $y_F(n)$ are uncorrelated. Therefore, $E\{i(n)y_F(n)\} = 0$. For the same reason, the input signal $i(n)$ and the estimated feedback signal $y_E(n)$ are uncorrelated. This means that $E\{i(n)y_E(n)\} = 0$. When these two results are applied to (15), the mean square error $E\{e^2(n)\}$ becomes

$$E\{e^2(n)\} = E\{i(n)^2\} + E\{[y_F(n) - y_E(n)]^2\}. \quad (16)$$

Since the input signal $i(n)$ is assumed to be i.i.d., $E\{i^2(n)\}$ is constant. Therefore, minimizing $E\{e^2(n)\}$ is equivalent to minimizing $E\{[y_F(n) - y_E(n)]^2\}$.

Numerous iterative algorithms that can minimize the mean square of the error $e(n)$ in Figure 3 are available, including the least mean square (LMS) algorithm, the normalized LMS algorithm, and the recursive least squares (RLS) algorithm [9]-[10]. In this work, the LMS algorithm is used owing to its low complexity. Its application to the ICAN of a radio repeater is briefly described below.

The ICAN algorithm in Figure 3 is based on an adaptive filter that consists of an adaptive channel tap updater (ACTU), an estimated channel filter, a delay block, and an adder block. The ACTU in the adaptive filter calculates the coefficient vector $\mathbf{w}(n+1)$ with a length of N using the error signal $e(n)$, the output signal vector $\mathbf{x}(n+l_0)$ and the previous coefficient vector $\mathbf{w}(n)$ such as,

$$\mathbf{w}(n+1) = \mathbf{w}(n) + \mu e(n)\mathbf{x}(n - l_0). \quad (17)$$

In (17), μ is a parameter to control the convergence rate and the excess mean square error of the LMS algorithm and l_0 is the delay of the dominant feedback signal component. The delay l_0 may be obtained by correlating the output signal $x(n)$ and the input signal $i(n) + y_F(n)$. The error $e(n)$ is

$$e(n) = i(n) + y_F(n) - y_E(n). \quad (18)$$

The estimated channel filter with the coefficient vector $\mathbf{w}(n)$ provided by the ACTU generates the estimated feedback signal $y_E(n)$, which is given by

$$y_E(n) = \mathbf{w}^T(n) \cdot \mathbf{x}(n - l_0). \quad (19)$$

In (19), $\mathbf{w}^T(n)$ indicates the transpose of the coefficient vector $\mathbf{w}(n)$ and the symbol · denotes the dot product. The feedback signal $y_F(n)$ in the input signal is cancelled by the estimated feedback signal $y_E(n)$ in the adder block. The LMS algorithm works so as to minimize the mean square of the error $e(n)$.

4. Computer simulation

To confirm the validity of the ICAN model for radio repeaters, a wideband code division multiple access (WCDMA) signal with one frequency assignment (FA) is used as an input signal [11]. Data sampling of 50 MHz is assumed in the ADC. The LMS algorithm with the control parameter μ = 100 is employed to update the coefficients of the estimated channel filter (LMS filter) to perform ICAN.

Two types of feedback channel models are used in this work. The simple delay feedback channel model emulates a 0.8 us delayed feedback path. The multipath feedback channel model is comprised of four multipaths with time delays of 0 us, 0.02 us, 0.10 us, and 0.14 us, and relative power levels of 0 dB, -3 dB, -10 dB, and -15 dB, respectively.

The amplitude of the output signal, which is normalized to the repeater's gain G, of a radio repeater without the DICANS as a function of G under a simple delay feedback channel is plotted in Figure 4. When the gain G = -10 dB, which is equivalent to the condition that $G < 1$, the repeater does not oscillate, as expected. With the gain G = 0 dB, the repeater shows some sign of oscillation but still does not oscillate. However, with the gain G = 5 dB and 10 dB, the repeater goes into feedback oscillation in a short period of time. Furthermore, Figure 4 shows that the larger the gain G is, the faster the repeater goes into feedback oscillation.

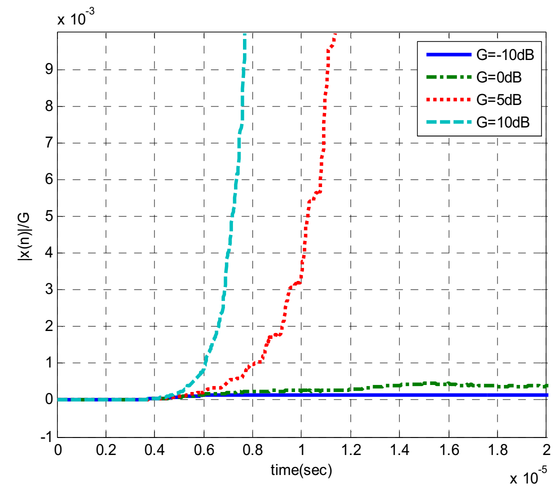

Figure 4. The normalized output signal *x(n)/G* of a radio repeater without the DICANS as a function of the repeater gain G under a simple delay feedback channel.

Figure 5 shows the amplitude of the output signal, which is normalized to the repeater's gain G, of a radio repeater with the DICANS as a function of the LMS filter length N and the repeater's gain G under a multipath feedback channel. It is assumed that the estimated delay l_0 is equal to the channel delay k_0. When N = 3 and G = 10 dB, the repeater oscillates, because the estimated channel filter does not cancel the 3rd and 4th feedback signals in the multipath feedback channel model. With N = 7, and G = 5 dB and 10 dB, the repeater does not oscillate, because the LMS filter cancels all the feedback signals in the multipath feedback channel model. However, in this case, there is some increase of the output signal at the initial period of time, because the LMS algorithm has a slow convergence rate. When G = 5 dB and N = 3, the repeater does not go into oscillation. The reason is that even though the 3rd and 4th feedback signals are not fully covered by the length of the LMS filter, they are cancelled by the three coefficients of the LMS filter due to their small power level.

Figure 6 shows the amplitude of the output signal, which is normalized to the repeater's gain G, of a radio repeater with the DICANS as a function of the estimated delay l_0 and the repeater's gain G under a multipath feedback channel. In this case, the LMS filter has the length N = 7. When $k_0 = l_0 + 2$ and G = 5 dB, the repeater does not oscillate, because the LMS filter covers the first two dominant feedback signals in the multipath feedback channel and the effect of the last two feedback signals is not so big. However, when $k_0 = l_0 + 2$ and G = 10 dB, it appears that the large gain causes the last two feedback signals which are not cancelled by the LMS filter to increase fast. In the case of $k_0 = l_0 - 2$, the repeater goes into feedback oscillation regardless of the repeater's gain, because the dominant two feedback signals are not cancelled by the LMS filter at all.

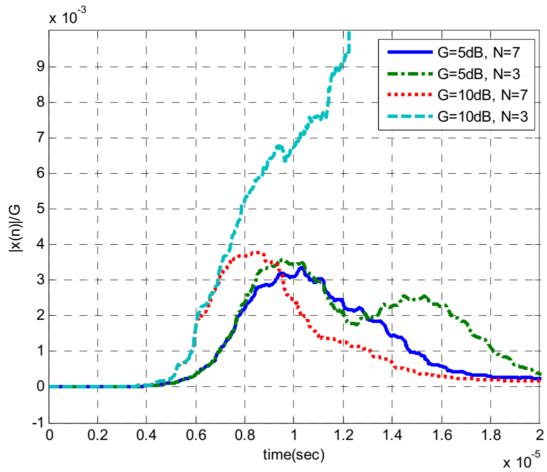

Figure 5. The normalized output signal $x(n)/G$ of a radio repeater with the DICANS as a function of the LMS filter length N and the repeater's gain G under a multipath feedback channel.

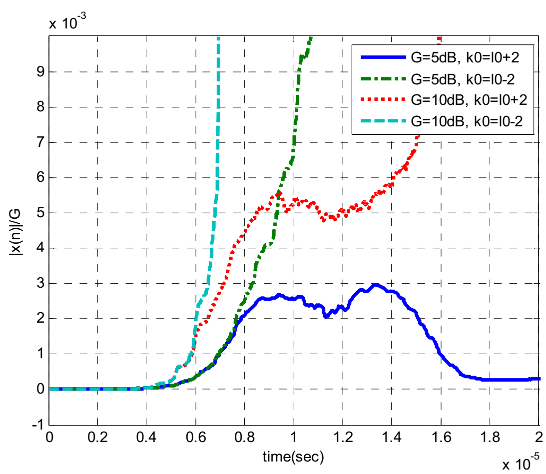

Figure 6. The normalized output signal $x(n)/G$ of a radio repeater with the DICANS as a function of the estimated delay l_0 and the repeater's gain G under a multipath feedback channel.

5. Conclusion

We proposed an ICAN model for a radio repeater that goes into feedback oscillation when the gain of the radio repeater is larger than the isolation between the transmit and receive antennas of the repeater. According to the ICAN model, which is derived from a feedback oscillation model of a radio repeater, it is found that minimizing the difference between the actual feedback signal and an estimated feedback signal using the MMSE criterion is a more reasonable to perform the necessary ICAN than trying to accurately estimate the feedback channel. The validity of the ICAN model is confirmed by simulations.

6. References

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