Performance of Decision Feedback Equalizers in Urban and Indoor Mobile Channels

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Abstract
This paper presents idealized computer simulation results of an equalizer using two-ray and measurement-based channel impulse response models. A decision feedback equalizer (DFE) with a recursive least squares (RLS) algorithm is used as the equalization scheme. The results show that adaptive equalization can significantly improve the bit-error-rate (BER) of a mobile system if the channel does not change too rapidly. The simulation shows that in a two-ray Rayleigh fading channel, if the delay of the second ray is too small, then adaptive equalization will degrade the BER performance. The value of the delay at which the adaptive equalizer can improve the BER depends on the normalized Doppler frequency. Also, a mobile channel simulator is used to show how much the equalizer can improve the BER in real world urban channels. The performance of adaptive equalization for indoor high data rate systems is also evaluated. Finally, an equalization structure for J/4 DQPSK modulation is developed and simulation results are presented.

1. Introduction
Adaptive equalizers are designed to mitigate intersymbol interference, which is one of the main factors affecting the performance of a mobile system. Several types of adaptive equalizers have been developed for mobile communication, such as the decision feedback equalizer, the lattice decision feedback equalizer, and the maximum likelihood sequence estimator. Since mobile channels are time-varying, the equalizer coefficients have to be adaptive to track the channel variation.

Several parameters are used to describe a mobile channel. First, \( E_b/N_0 \), which is defined as the ratio of the energy per bit, \( E_b \), to the noise power spectral density, \( N_0 \), measures the significance of the noise power. The smaller the \( E_b/N_0 \), the higher the BER [8].

Also, root-mean-square (rms) delay spread, \( \sigma_d \) [6], or normalized rms delay spread, \( \sigma_d/T_5 \), where \( T_5 \) is the symbol duration, indicates the significance of the ISI of the channel. Without equalization, a channel with larger \( \sigma_d/T_5 \) generally causes higher BER when other factors are the same.

The rate of the channel variation is another important channel parameter in adaptive equalization. The rate of the channel variation due to motion of a transmitter or receiver can be defined by the Doppler frequency [4]. The Doppler frequency \( f_d \) is

\[
   f_d = \frac{v}{\lambda}
\]

where \( v \) is the velocity of the mobile (m/s) and \( \lambda \) is the wavelength of the carrier (m). It makes more sense to define the channel variation by the normalized Doppler frequency \( f_N \),

\[
   f_N = \frac{f_d}{f_s}
\]

where \( f_s \) is the symbol rate in symbol per second, because a higher symbol rate results in a smaller spatial distance that the mobile moves between two consecutive symbols, and thus a smaller change between the channel impulse responses.

2. Equalization in Two-Ray Rayleigh Fading Channels
In the following equalization simulation, coherent QPSK is the modulation, and is simulated using the complex baseband model with perfect coherent detection before the equalizer. No clock recovery circuit is implemented and the clock in the receiver is exactly synchronized to the transmitter. The receiver is also synchronized to the first ray, which arrives at the receiver.

This equalization simulation uses the data rate done for U.S. Digital Cellular telephone (USDC) standard [5]. The data rate is 48.6 kbps, so the symbol duration is 41.15 \( \mu \)s. For our simulations, data are broken in 210 symbol blocks, in which the first 10 symbols are used for training. Raised cosine rolloff filters with \( \varepsilon = 0.35 \) rolloff factor are used at the transmitter.

The two rays in the channel have the same mean power, so the mean rms delay spread is \( \tau/2 \), where \( \tau \) is the delay of the second ray. The carrier frequency used was 850 MHz. Perfect decision feedback was assumed in simulation. This is not valid in the real world.

A DFE with an RLS algorithm is used as the equalizer. The weighting factor used was 0.9. To limit the simulation time requirement, only 10,000 bits were used to test the performance of each equalizer, so the results may lack accuracy at BER < 10\(^{-3} \).

Figure 2-1. BER vs. \( \tau \) of two-ray Rayleigh fading channel using DFE(3,2) at different speeds. Carrier frequency is 850MHz.
Figure 2-1 shows the irreducible BER using the DFE(3,2), where the DFE has 3 taps in the forward filter and 2 taps in the feedback filter, in the two-ray Rayleigh fading channels with different \( v \) and different vehicle speeds. One can see that the vehicle speed has a large influence on the BER, and the BER of 75 km/h is better than that of 100 km/h. The result of a speed of 20 km/h is superb; the BER is less than \( 2 \times 10^{-3} \) at all \( v/T_s \).

Compared with the performance of an unequalized system, an equalizer does not help a system when \( v/T_s \) is less than 0.15 at 75 km/h. This is because when \( v/T_s \) is small, the unequalized receiver has a good performance, but the adaptive equalizer still keeps a comparatively stable BER regardless the value of \( v/T_s \).

The result shows that adaptive equalization can improve the mobile system over a large range of rms delay spreads, and the rate a mobile channel changes is extremely important in terms of the degree to which an adaptive equalizer can improve system performance. When a mobile channel does not change very rapidly, adaptive equalization can improve the system significantly.

3. Equalization in SMRCIM Urban Channel Model

To evaluate the performance of adaptive equalization in real world channels, the Simulation of Mobile Radio Channel Impulse response Models (SMRCIM) was developed. SMRCIM is a statistical mobile channel impulse response model based on various wideband measurements.

Ten random SMRCIM channels at 1.3 GHz, which have \( \sigma_e \) ranging from 0.5 \( \mu s \) to 10 \( \mu s \), were used to determine if adaptive equalization improves the system performance. The mean BER performance for mobile speeds of 20 km/h and 75 km/h are shown in Figure 3-1. The results indicate that at 75 km/h, the adaptive equalization does not improve the BER for urban channels, and it has an overall error rate of more than 1% at 20 dB \( E_b/N_0 \), which is the same as unequalized receivers. At a lower speed, however, an adaptive equalizer can significantly reduce the BER as shown in Figure 3-1.

![Equalization on SMRCIM Channels](image)

Figure 3-1. Mean BER vs. \( E_b/N_0 \) at 10 channels randomly generated by SMRCIM using RLS-DFE(2,1) at 20 km/h and 75 km/h.

To transform the results of 1.3 GHz simulations to 850 MHz, which is the frequency band used for cellular telephones, the Doppler frequency is kept the same for the two frequencies. Let \( v_1, \lambda_1 \) represent the velocities and wavelengths at either 1.3 GHz (\( i = 1 \)) or 850 MHz (\( i = 2 \)), then, for fixed \( f_D \)

\[
f_D = \frac{v_1}{\lambda_1} = \frac{v_2}{\lambda_2} \quad (3)
\]

\[
v_2 = \frac{\lambda_2 \times v_1}{\lambda_1} = \frac{f_1 \times v_1}{f_2} = \frac{1300}{850} \times 75 = 115 \text{km/h} \quad (4)
\]

Therefore, at the 850 MHz band, the DFE cannot improve a USDC system BER at a receiver velocity faster than 115 km/h.

4. Equalization for SIRCIM Indoor Channel Model

The Simulation of Indoor Radio Channel Impulse response Model (SIRCIM) software package developed by MPRG at Virginia Tech is based on extensive wideband channel measurements of different indoor environments at different frequency bands [7].

An indoor channel is different from an urban channel in that it usually has a very small rms delay spread and small temporal variation [6]. Because of the small rms delay spread, the data rate of an indoor channel can be very high even without an equalizer. A small velocity of an indoor mobile causes slow variation in the channel and therefore a small Doppler frequency. The normalized Doppler frequency (2) is further reduced because of the high data rates of indoor systems.

In the following simulation, a DFE with an RLS algorithm is used and the weighting factor is 0.99. A SIRCIM channel HOBS2 for an open-plan building was generated. The channel has a large mean rms delay spread, \( \sigma_e = 138 \) ns, where the mean is taken as a spatial average of millions of closely spaced impulse responses across a 1 meter measurement track.

![BER vs. Eb/No at SIRCIM Indoor Channel HOBS2](image)

Figure 4-1. BER vs. \( E_b/N_0 \) at different data rates for SIRCIM Indoor channel HOBS2 using the RLS-DFE sizes obtained from the optimization of channel HOBS2. HOBS2 has a spatial mean RMS delay spread of 138 ns. The simulation uses QPSK modulation.

In the simulation, a 20 Mbps data rate was first selected and the speed of the receiver was set to 10 km/h. Coherent QPSK modulation is used but no clock recovery circuit is implemented. The symbol duration \( T_s \) is 100 ns and \( \sigma_e/T_s = 1.38 \). The normalized rms delay spread is excessively large, so adaptive equalization must be used to obtain an acceptable BER. DFE(6,5) was chosen to be the equalizer size for the channel HOBS2 at 20 Mbps. Compared to the
result without any equalization, which has a BER of about 30%, using a DFE gives a significant improvement in the performance (see Figure 4-1). The simulation shows that although an adaptive equalizer has a good performance in a frequency-selective fading indoor channel, it is still worse than a receiver working in an ideal additive white Gaussian noise (AWGN) channel.

Performance of the DFE for 10 Mbps, 4 Mbps and 2 Mbps are also shown in Figure 4-1. The simulation results show that at these data rates a DFE works very well. The BER is below $10^{-3}$ at 13 dB $E_b/N_0$ and decreases with increasing $E_b/N_0$. It is clear that adaptive equalization significantly increases the indoor system performance for these data rates. The BER results for different data rates shows that the data rate (or normalized Doppler frequency) has little effect on BER in the high data rate indoor systems.

Equalization performance in the channel HARDLOS2, which has a mean rms delay spread of 33.2 ns, is shown in Figure 4-2. Although, the mean $\sigma_c$ of HARDLOS2 is one third of LOS4, the DFE maintains good performance. The improvement over non-equalization is not as significant as in the channel HOBS2. At 2 Mbps data rate ($\sigma_c/T_s=0.03$), the results with and without equalization are very close.

![Figure 4-2. BER vs. $E_b/N_0$ at different data rates for SIRCIM indoor channel HARDLOS2 using the RLS-DFE sizes obtained from the optimization of channel HOBS2. HARDLOS2 has a spatial mean RMS delay spread of 33.2 ns. The system uses QPSK modulation.](image)

Comparing the equalization results for the two indoor channels, it is apparent that the equalizers have very similar performance in different channels and at different data rates. Therefore, indoor equalization systems have very consistent performance regardless of $\sigma_c$ and data rate. Also, the simulation results show that adaptive equalization can improve the BER by a large margin as long as there exists some ISI. Equalization can even improve the BER performance at $\sigma_c/T_s$ as small as 0.03. The reason for the superior performance of adaptive equalization for indoor channels is its small normalized Doppler frequency.

5. Equalization for Differential Modulations

All of the previous equalization simulations done in this research were for coherent modulations; however, differential modulation techniques such as $\pi/4$ DQPSK are widely used because their receivers do not require a coherent detector, so the receivers are easy and inexpensive to build.

The differential phase shift keying technique sends information by the difference in the phase shift between consecutive symbols. By detecting the phase difference of the two consecutive symbols, the value of the second symbol can be identified. Using noncoherent techniques, the original carrier phase does not have to be recovered, and only the instantaneous phase difference. Thus, the receiver is simpler to build [8].

Figures 5-1 (a) and (b) show the block diagram for the implementation of adaptive equalization for $\pi/4$ DQPSK. The equalizer is located before the differential decoder. The differential decoder is located between the equalizer and the decision maker. The input of the forward filter is the output of the channel, which is denoted by A in the figures. The output of the equalizer after the decision maker is denoted by D, and D is recoded using the same differential coder as the transmitter. Therefore, B is the recoded signal, which is used as the input of the feedback filter. The error used to update the equalizer is between B and the output of the equalizer before the differential decoder, C.

![Figure 5-1(a). Structure for Implementing adaptive equalization of differential modulations.](image)

![Figure 5-1(b). Structure of a decision feedback equalizer in a differential modulation system.](image)

All types of adaptive equalizers can be used in this structure, and both the LMS and RLS algorithms can be applied to update the equalizer.

This structure works well when perfect decision-making is assumed, which means using E instead of D as the input to the differential coder at the receiver. However, if detected data at D is fed
in, once an error appears, error propagation appears. One of the methods to solve the error propagation problem is to retrain the equalizer at the beginning of each data block. Also, coding and diversity can be used to reduce chance of error propagation.

A DFE with an RLS algorithm using the structure in Figure 5-1 was used in the simulations. To test how well this structure works, several mobile channels were used in the evaluation of the adaptive equalization for π/4 DQPSK. The two-ray Rayleigh fading channel was the first to be implemented. Perfect decision feedback was assumed.

Figure 5-2 shows how a differential π/4 DQPSK DFE with an RLS algorithm works in a two-ray Rayleigh fading channel. The performance pattern is similar to that of the QPSK in Figure 2-1. However, as can be expected, equalization results for π/4 DQPSK are not as good as for QPSK except at τ/Tx = 0. This can be seen by comparing Figure 5-2 with Figure 2-1.

Figure 5-2. BER vs. τ of two-ray Rayleigh fading channel using RLS-DFE(3,2) and π/4-DQPSK at different speeds. Carrier frequency is 850 MHz.

Differential Equalization in SIRCIM indoor Channel HOB2S
π/4-DQPSK

Figure 5-3. BER vs. Eb/N0 of SIRCIM channel HOB2S using RLS-DFE using π/4-DQPSK at different speeds, and the sizes of the DFE are obtained from QPSK modulation. Carrier frequency is 1.3GHz.

The indoor SIRCIM channel HOB2S was also used to evaluate the adaptive equalization for π/4 DQPSK. The DFE sizes chosen for QPSK were used here, and the simulation results are shown in Figure 5-3. The results show the BER can be maintained around 10^-3 or less at 20 dB Eb/N0. However, compared to the results for QPSK in Figure 4-1, the BER for π/4 DQPSK is still higher

6. Conclusion

The performance of adaptive equalizers in urban mobile channels was evaluated. The urban channels were simulated by two-ray Rayleigh fading models and a real world channel impulse response simulator, SIRCIM. The simulation results show that in urban mobile channels, the performance of an equalizer is highly dependent on the rate of the channel variation, or the normalized Doppler frequency. More rapid channel variation results in a higher bit-error-rate.

From the results presented, an adaptive equalizer does not necessarily improve the performance of a system. The conditions for an adaptive equalizer to improve BER are that the channel has some delay spread and the channel has a slow variation. The σc value at which the equalizer can improve the system performance is dependent on the variation of the channel; the slower the variation, the smaller the σc can be. A DFE for a USDC system will not improve BER at 1.3 GHz, unless the receiver speed is slower than 75 km/h, and for 850 MHz, the receiver speed should be less than 115 km/h.

SIRCIM indoor channel models were used to simulate indoor mobile channels. Indoor channels have small rms delay spreads, so the data rates for indoor systems can be very high compared to urban systems, and the variation of an indoor channel is much slower than an urban channel. The slow channel variation and high data rate result in good performance of the adaptive equalization.

Finally, an equalizer structure for differential modulations was developed. It coherently detects the differential signals. The simulation results show that, although the structure has the similar properties of an equalizer in coherent modulation, the performance is not as good as coherent modulation.

References