Adaptive Antenna Arrays and Equalization for Indoor Digital Radio

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Abstract

Adaptive antenna arrays and equalizers for use in transceivers for peer-to-peer wireless communications in local area networks are examined. A new adaptive transmission algorithm which uses receiver diversity combiner weights for transmission is developed. This method provides large gain with a simple design suited for a distributed network. The effects of network topology and channelization on convergence are discussed.

1 Introduction

The large cost and difficulty of rewiring offices for computer networks has spurred research interest in wireless networks. Our target application is the design of a peer-to-peer communication system for notebook computers. In such a system users communicate directly between themselves, not with a central basestation. Consequently, network control operations and adaptive algorithms, which support high capacity communications, must all be distributed.

The system design issues of adaptive, high bit-rate, wireless transceivers for an indoor local area network are significantly different from those of mobile communications. We are not as limited so much by power consumption and size, but require much higher performance. Therefore we have access to a richer and more complicated set of communications techniques to deliver this performance.

Such a high-speed wireless transceiver is under development at UCLA. The system design will include many new algorithms to maximize data rates [7]. In this paper we explore the adaptive antenna arrays and adaptive equalizers for the transceiver. These two areas must be investigated jointly due to the interaction between diversity combining and equalization. The performance of the antenna array and equalizer is affected by the interference level in the system. Several other techniques reduce the interference level in the system and are thus included in our simulation of the transceiver. These include power control and orthogonal signaling in cells.

Our primary concern will be the reduction of co-channel interference (CCI) caused by multiple competing users on the same frequency. We will reduce the CCI by partitioning the office building into cells. We implement orthogonal signaling in each cell. By increasing the frequency reuse distance we better isolate and decouple users in the system. Decoupling the users reduces the adaptive interaction between users, thus decreasing training sequence lengths and permitting joint adaptation of several adaptive algorithms.

To properly simulate the performance of our transceiver designs, we require a channel model that captures the main dynamics and interactions. First, the model must include multipath and co-channel interference. Second, the gain, phase, and delay of the channel impulse response must be a function of the precise position of the transmitting antenna element and receiving antenna element. If this is not the case we cannot accurately simulate the performance of the adaptive antenna arrays. Therefore we have opted not to use statistical channel models and instead have implemented a ray tracing algorithm to generate channel impulse responses [5].

Using this model, we have simulated several different receiver structures with diversity combining and equalization to examine their performance in the indoor radio channel. Most of the literature in this area originates from the investigation of portable phones which are restricted in size and power consumption, and thus limited to lower diversity orders, usually dual diversity, or no diversity. Since a portable PC does not have the size and power restrictions of a telephone, we analyze in depth the performance of the receiver structures with larger antenna arrays.

In a cellular environment, central basestations may use transmitter structures such as sectorized antennas, whereby the basestation transmits with a narrow beam in the direction of the receiving user with a predetermined set of beampatterns [9]. This method eliminates CCI from other users. However, this method requires hundreds of elements to create directional beampatterns with wide scan angles [2]. With our platform we are limited to nine antenna elements, an order of magnitude too small to create directional beam patterns. In addition, in a peer-to-peer communication system, with the adaptive transmitters on the platforms of the individual users, we cannot isolate the antenna array from human contact. Unfortunately, any contact would corrupt pre-determined beampatterns via electromagnetic coupling. Our design must adapt to this situation.

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In another adaptive transmitter scheme for the cellular environment, channel information is sent from the mobile receivers to the central basestation [3]. In order to adapt all the adaptive transmitters in a peer-to-peer network we would need feedback information between every user to every other user in the network. This is not feasible due to the tremendous added network complexity.

We will describe a novel adaptive transmitter algorithm suited for an indoor peer-to-peer communication system that uses the diversity combiner receiver weights for transmission. Large system performance gain is attained with this algorithm. Since this method does not require feedback of channel information between users, there is no added network complexity. Also, this method results in a very simple transmitter hardware implementation.

Our initial analysis of system performance was based on analytical expressions which assume perfect knowledge of the channel. A real implementation of the transceiver structure requires a low-complexity, iterative adaptation. We have simulated a least-mean-squared (LMS) adaptation of our transceiver structure. We have also investigated convergence rates and the effects of network topology and channelization on adaptation rates. These issues are especially important given that adaptation of transmitter patterns causes a response by other adaptive transmitters, potentially leading to instability. We illustrate a simple structure which ensures convergence.

In Section 2, we investigate the performance of an adaptive receiver array and equalization. We compare the performance of a multitap diversity combiner (MC) and a single-tap diversity combiner (DC) followed by either a linear equalizer (DC/LE) or a decision-feedback equalizer (DC/DFE). In Section 3 we introduce our new algorithm for adaptive transmission. We illustrate the system performance in comparison to other methods. The best tradeoff between performance and hardware complexity appears to be a DC receiver and receiver weights for transmission. In Section 4, we describe an LMS implementation of our transceiver. We examine the interaction between several users in a system and the effect on training sequence lengths. In order to ensure robust performance in occasionally bad ISI conditions, in Section 5 we add an equalizer following the DC. We examine the convergence behavior.

2 Adaptive Reception

To simulate the performance of the receivers we created a floor of an office building, divided into three cells with a pair of users randomly placed in each cell. The receivers were composed of a nine element antenna array for reception, with omnidirectional transmission. The channel from every user to every antenna element of every other user was determined, yielding the received signal and the co-channel interference. For each receiver the optimal receiver weights for the minimum MSE of the system were calculated for a range of signal-to-noise ratios (SNR), based on 4-QAM modulation. The symbol rate was $16MHz$. To reduce the length of the simulation, the receiver weights were analytically calculated to determine the MSE and an upperbound on the P_e. This was repeated for many different user placements to produce averaged results. The results are given in Figure 3.

We see from Figure 3 that at a P_e of 10^{-3}, the MC yields a reduction in the required received SNR of almost $5dB$ as compared to the DC. We see that the DC/LE and DC/DFE are both less than $1dB$ better than the DC alone.

The performance of the DC with a large number of antennas limits the effectiveness of equalization. The DC reduces the ISI caused by delayed responses in the indoor radio environment by placing a null in the beampattern of the antenna array in the direction of the ISI. In addition the indoor radio environment is dominated by CCI and the ISI is minimal as compared to the mobile radio environment. Therefore the effect of an equalizer following a DC on the MSE is small. In addition, the equalizers have no effect on co-channel interference. On the other hand, with the MC, the multiple taps for each antenna branch allows for joint adaption in time and space. This results in the optimal reduction of both the ISI and CCI yielding a large performance gain.

3 Adaptive Transmission

With the LMS algorithm the receiver weights are adaptively calculated based on minimizing the measured error. In this manner, the receiver can adapt to changes in the channel. However, on transmission there is no error information with which to adapt our antenna weights, and in a distributed system the transmitter has no knowledge of the signaling environment.

To deal with these difficulties we have developed a new algorithm in which the DC receiver antenna weights are used for transmission. The receiver calculates the optimal antenna weights to null interfering signals and minimize the MSE. Therefore, if we use the same weights on transmission, we will be transmitting through nulls in the beampattern in the direction of the interfering users, thereby reducing co-channel interference in the system (assuming time-division duplex transmission.) In addition, with a DC receiver, there is minimal additional hardware complexity in implementing the adaptive transmitter. For other receiver structures, it would be necessary to calculate DC receiver antenna weights for use on transmission. A significant benefit of this scheme is that no feedback is required between users.

To measure the performance of the transceivers, we use the same simulation as in Section 2, adding now the transmitter array. In Figure 4, we illustrate the optimal analytical simulation results. These are calculated by solving for the receiver weights which minimize the MSE for the given channel. Then the DC receiver weights are used for transmission. The receiver weights are then recalculated. This procedure is repeated until the MSE of system converges to a stable solution. In the figure, the solid lines indicate omnidirectional transmission. This is used as a comparison with the adaptive transmitter algorithms. The dashed lines indicate using receiver weights for transmission (RW).

For comparison, we will also simulate the system in which we feed back channel information between all the users in the network and adapt the transmitters by a zero-forcing (ZF) solution. Dotted lines in the figure indicate a ZF transmitter. For each transmitter we examine two different receivers, a single-tap diversity combiner, noted as DC in the figure, and a multitap diversity combiner with three taps per antenna, noted as MC in the figure.

As in Section 2, we achieve a $5dB$ gain, at a P_e of 10^{-3}, with the MC receiver over the DC receiver, with omnidirectional transmission. Comparing the transmitter structures, we achieve the best performance with the ZF transmitter and an MC receiver. This structure yields a $3dB$ gain over the RW transmitter and an MC receiver. In addition, the ZF transmitter results in more than a $8dB$ gain over omnidirectional transmission. But this performance gain is at the cost of a tremendous increase in system and hardware complexity. On the other hand, using the RW transmitter attains a $5dB$ performance gain over omnidirectional transmission with a small increase in system and hardware complexity.

An important result is that we see that with the RW transmitter, we only achieve a $1dB$ gain by using an MC receiver instead of a DC receiver. However in Section 2 we saw a $5dB$ gain using the MC receiver as opposed to the DC receiver. Since the adaptive transmitter greatly reduces the CCI, the benefits of the MC receiver are now greatly diminished. Therefore, for a minimal loss in performance, we can significantly simplify our transceiver design by only implementing a DC receiver. For transmission we can then use the receiver weights directly without having to calculate a separate set of weights for the transmitter.

4 LMS Adaptation of the Transceiver Structure

4.1 General Performance

We now examine the performance of a realistic implementation of the adaptive transceiver. Instead of calculating the antenna weights based on analytical expressions, we converted our simulation to an LMS adaptation. Simulations have shown that the performance is close to optimal when allowing 1000 samples to train the transceiver.

4.2 Convergence Rates

We now examine the convergence behavior of the LMS adaptation of the transceiver. First we will explore the effects of network topology on adaptation rates. We compare the adaptation rates of a multiple cell system versus a single cell system. In the latter, the interfering users could be spaced much closer together. This illustrates the effects of the proximity of the interfering users to each other on the adaptation rates.

From simulations we found that for the multiple cell system there is almost no loss in performance with as few as 300 training symbols. For the single cell environment, the overall performance is significantly reduced, but the adaptation rate has not changed. We again found that with as few as 300 training symbols, there is little loss in performance.

However, in some cases the single cell system did not converge. When there is a strong interaction between the users in the network it sometimes occurs that when one user adapts its transmitter, all other users adapt their transmitters in reaction. This again causes a strong reaction by all the users and they all adapt again, and so forth. The network oscillates with no convergence, or diverges. In addition, there are cases where an interferer is in much closer proximity to a user than its partner. The interference strongly dominates the received signal and causes the adaptation of the transceiver to diverge.

Distributed operation requires that such events be very rare. We must ensure that the primary factor governing adaptation should be the users own link. When we implement a multicell system with orthogonal signaling to reduce CCI, we are also decoupling the users in the network. By reducing the interaction between users we ensure system convergence. In addition, our complete system design will include line-probing and power control algorithms which will only allow users to enter the system in a high SNR environment. With these algorithms we are further ensuring that the interaction between interfering users will be limited.

We now consider two different operating scenarios. Suppose first that the users are active for only a short period of time, as for example in bursty data transmission. In addition, if we implement a frequency-hopped system, the users will also only transmit at a given frequency for a short time. These situations result in the users constantly retraining their transceivers. Therefore we may have many users entering the system and training simultaneously. We compare this system to one in which users are active for long periods of time, such as voice communication. Therefore a new user would enter a stable system.

We have simulated six users training simultaneously. As before using a training sequence length of 300 symbols results in little loss in performance. When a new pair of users enters a system where four other users have already trained and are fully adapted, 200 symbols for training suffice.

5 A More Robust System

Our simulations of the indoor environment have shown that on average small delay spreads result in little benefit from equalization. This is especially true when utilizing a large antenna array for diversity combining. In addition, we have shown that the dominant interference is CCI, which is not reduced by equalization. However, occasionally ISI will limit performance, particularly when we wish to employ large constellations.

In Figure 5 we illustrate the analytical results of adding an LE or a DFE following the DC. The signaling environment is comprised of significant ISI and no CCI. We still see that the DC/LE with 9 equalizer taps provides almost no gain over the DC alone. Therefore the adaptive transmitter and the

DC receiver must still be able to place nulls in the beampattern in the directions of the significant ISI and also smooth out channel spectrum nulls. We do see a $1.5dB$ gain in performance at a P_e of 10^{-3} when implementing the DC/DFE with 5 feedforward taps and 4 feedback taps. However, all the performance gain is due to the feedback filter; the same system performance is achieved with no feedforward taps. The DC/DFE with 0 feedforward taps and 8 feedback taps provides a system performance gain of almost $2.5dB$ over a DC alone.

Adding the DFE may reduce the speed of adaptation. We simulate the performance of the adaptive transceiver with a DFE following the DC with 5 feedforward taps and 4 feedback taps, with a repeat of the simulation from Section 4.2 for a multicell system. We now find that we require 400 training samples instead of 300 as before. We repeated the experiment with no feedforward taps and 4 feedback taps. For the same system performance, we see that the required number of training symbols is again reduced to 300. We saw that we achieved greater performance in an ISI environment with no feedforward taps and 8 feedback taps. Simulations show that we still only require 300 training symbols. Therefore we can add a feedback filter following the DC with no reduction in the adaptation rate. In addition, since the feedback filter is adapted separately from the DC, we can still use the receiver DC weights for transmission.

6 Conclusion

In a distributed indoor system, feedback of channel information to adapt transmitters, or fixed beampatterns, is not feasible. We have developed a practical scheme of adapting the transmitters that leads to large performance gains without such interaction. The algorithm converges with mild restrictions on system coupling.

To ensure robust performance in ISI, we include a short feedback section of the DFE after the DC for reception. We adapt the DC and the DFE separately, so as to not reduce the rate of convergence. In addition, separate adaptation of the DC and the DFE allows the DC weights to be resuded for transmission, minimizing hardware complexity.

The complete system will include other adaptive algorithms. Future research will include a detailed investigation of the interaction among the adaptive antenna, adaptive power control, and line probing algorithms.

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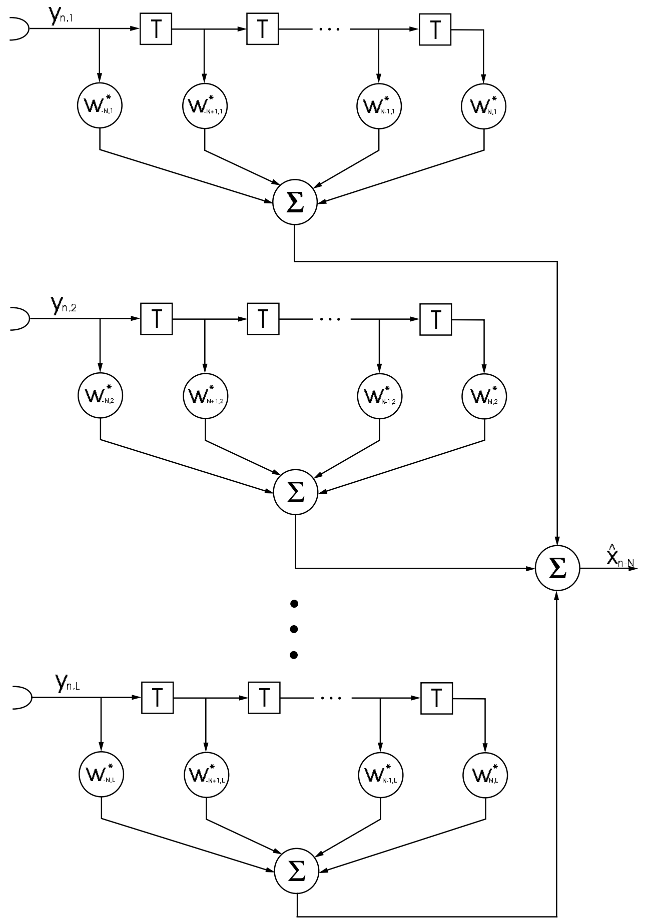

Figure 1: Multitap diversity combiner.

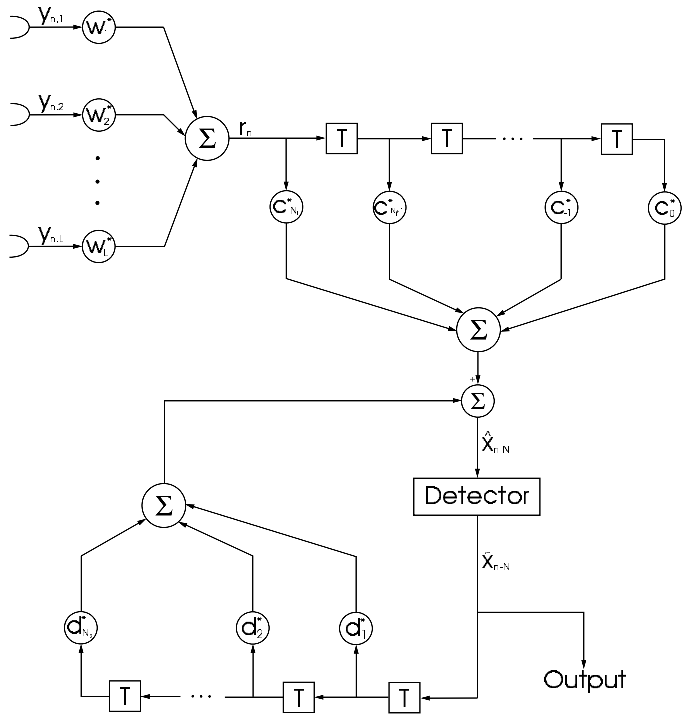

Figure 2: Diversity combiner followed by a decision feedback equalizer.

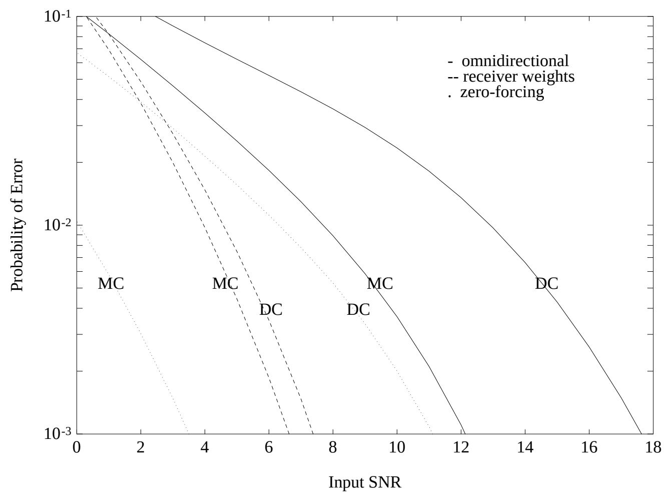

Figure 4: Probability of error vs. received SNR for adaptive transmitter/receiver simulation.

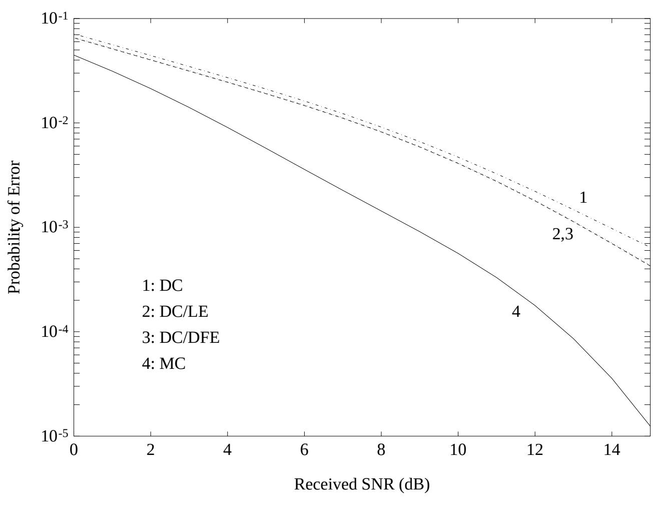

Figure 3: Probability of error vs. received SNR for adaptive receiver simulation.

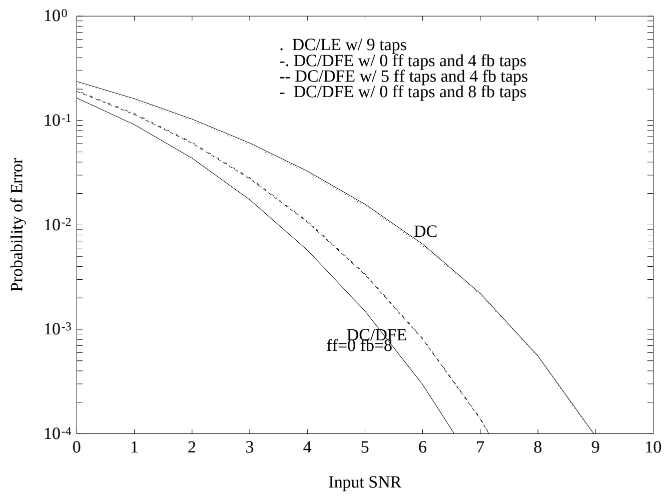

Figure 5: Analytical simulation results for the adaptive transceiver with equalization in an ISI signaling environment.