Forward Link Antenna Diversity Using Feedback for Indoor Communication Systems

JEN-WEI LIANG AND AROGYASWAMI J. PAULRAJ
Information Systems Laboratory, Stanford University
Stanford, CA 94305

Abstract

An approach to mitigate forward link signal fading in a FDD communication system by using an adaptive transmit antenna array and feedback on the reverse link is presented. In a personal communication system environment, multipath propagations can lead to severe space selective fading. Cordless phones and similar devices which can not conveniently provide multiple antennas at the receiver can suffer from long term fading and therefore have unacceptable quality. Using multiple adaptive transmit antennas, we can adjust the transmission weights to ensure the user is kept out of deep fades. This is achieved by using feedback of the received signal level on the reverse link and adapting the transmission weights. Simulation shows the significant gain against the fading characteristics can be achieved.

I Introduction

Multipath signals arising from scattering and reflections cause space selective fading. When signals combine destructively, the signal level may drop 10 to 20 dB. With a single transmit antenna, the system has no control over the positions of nulls and sweetspots in the coverage area. As a user moves in the coverage area, there will be large variations in the received signal power as shown in Fig. 1. However, using multiple transmit antennas, we can adjust the weight of each antenna and make the multipath signals constructively combine at the receiver. In a TDD (Time Division Duplex) system, the channels in both directions are identical and the optimal transmit vector is a conjugation of the received vector [1]. In a FDD (Frequency Division Duplex) system, this is no longer true. Therefore, information about the received signal level needs to be fed back to the transmit antennas in order to allow them to adjust the weight. Using this closed loop adjustment, we constantly track the user and maintain the received signal power by constructively combining the multipath signals. In this paper, we assume narrow band signal sources, which implies the delay spread is much less than the symbol period. This leads to a flat fading channel.

II Problem Formulation

We consider a widely separated array of M narrow band transmit antennas and a single receiver as shown in Fig. 2. A unit power digitally modulated signal $s(k)$ is weighted by a complex weight w_i at the i^{th} antenna and the signals from all M antennas along with multipath bounces arrive at the receiver. Define the weight vector $\mathbf{w}(k) \triangleq [w_1(k), w_2(k), \cdots, w_M(k)]^T$. Let the response at the receiver due to the unit CW signal applied at the i^{th} transmit antenna be a_i. Then $\mathbf{a}(k) \triangleq [a_1(k), a_2(k), \cdots, a_M(k)]^T$ is the channel vector from the transmit antennas to the receiver. This narrow band channel model, *i.e.*, when the delay spread is much smaller than the symbol period, implies that all the paths are coherent. Such a model is realistic for many indoor applications. The receiver output is therefore given by

$$y(k) = s(k)\mathbf{w}^*(k)\mathbf{a}(k) + n(k) \tag{1}$$

where $n(k)$ is a zero mean white Gaussian noise and uncorrelated with the signal $s(k)$. The received power $E|y(k)|^2$ is

$$\begin{aligned} E|y(k)|^2 &= |\mathbf{w}^*(k)\mathbf{a}(k)|^2 + E|n(k)|^2 \\ &= \sigma_s^2 + \sigma_n^2 \end{aligned} \tag{2}$$

where $\sigma_s^2 = |\mathbf{w}^*(k)\mathbf{a}(k)|^2$ and σ_n^2 are the received signal and noise power, respectively.

Our goal is to keep σ_s^2 as close to unity as possible to guarantee good SNR at the receiver. If $\mathbf{w}(k)$ is constant, the received signal power σ_s^2 can drop due to space selective fading. Therefore, $\mathbf{w}(k)$ needs to be adjusted adaptively to ensure $\sigma_s^2 = 1$. A simple choice of $\mathbf{w}(k)$ is

$$\mathbf{w}(k) = \frac{\mathbf{a}(k)}{\| \mathbf{a}(k) \|^2} \tag{3}$$

To derive $\mathbf{w}(k)$, $\mathbf{a}(k)$ needs to be estimated. We should note that since the paths from each antenna to the receiver fade independently, all components of $\mathbf{a}(k)$ will rarely be in a fade simultaneously. Therefore, $\| \mathbf{a}(k) \|$ and consequently $\| \mathbf{w}(k) \|$ will not show large variation. The total transmitted power needs only small adjustment but can deliver constant received signal level.

III Estimating Channel Response Using Feedback

The general approach of estimating channel response $\mathbf{a}$ is as follows. Assume we have a good estimate of $\mathbf{a}$ and our job is to track its variation in time. We do so by perturbing the transmitter weight vector $\mathbf{w}$ by a small $\Delta\mathbf{w}$ and observing the resultant perturbation $\Delta\mathbf{z}$ at the receiver. M orthogonal perturbations are performed in an interval T_p. Using these M snapshots of $\Delta\mathbf{z}$ and $\Delta\mathbf{w}$ as a single observation and repeating the same perturbation procedure in an interval T_l, $T_l \gg T_p$, we set up a Kalman filter to track $\mathbf{a}$. Note that $\Delta\mathbf{z}$ is available only at the receiver and has to be sent to the transmitter through a reverse channel which is available in a duplex communication system. We propose a perturbation approach to identify $\mathbf{a}$ since it does not interrupt the transmission and the desired signal is constantly delivered to the receiver. Small perturbations in $\mathbf{w}$ do not impact the delivered signal but allow update of $\mathbf{a}$ and $\mathbf{w}$.

The algorithm requires an initial estimate $\mathbf{a}(0)$. This estimate can be obtained in several ways. For example, we can excite each antenna element in turn by a CW signal and measure the receiver response. Note that the intrinsic receiver gain and phase response $\mathbf{z} = \mathbf{w}^*\mathbf{a}$ in the presence of a digitally modulated signal $s(k)$ can be obtained from $y(k)$ by a decision directed approach, *i.e.*, decide on the received bit and then compensate for it. These estimates are further averaged over time to smooth out the estimation error. For indoor environment, channel vector $\mathbf{a}(k)$ is slowly varying and hence the transmitters do not need to perturb the channel too often and the feedback rate is low compared to the forward link data channel. The feedback delay is tolerable because the channel moves slowly in comparison. Several estimation techniques can be used to estimate the channel vector $\mathbf{a}$. In this paper, we model the problem as a discrete time Kalman filter with sampling rate $\frac{1}{T_l}$ and the perturbation rate $\frac{1}{T_p}$,

$$\mathbf{a}(l+1) = \mathbf{a}(l) + \mathbf{u}(l) \tag{4}$$

$$\begin{aligned}
\Delta\mathbf{z}(l) &= \begin{pmatrix} \Delta z(l,1) \\ \Delta z(l,2) \\ \vdots \\ \Delta z(l,M) \end{pmatrix} \\
&= \begin{pmatrix} \Delta\mathbf{w}^*(l,1) \\ \Delta\mathbf{w}^*(l,2) \\ \vdots \\ \Delta\mathbf{w}^*(l,M) \end{pmatrix} \mathbf{a}(l) + \begin{pmatrix} v(l,1) \\ v(l,2) \\ \vdots \\ v(l,M) \end{pmatrix} \\
&= \Delta\mathbf{W}^*(l)\mathbf{a}(l) + \mathbf{v}(l) \qquad (5)
\end{aligned}$$

where $\Delta\mathbf{z} = \mathbf{z_p} - \mathbf{z_o} = (\mathbf{w_{opt}} + \Delta\mathbf{w})^*\mathbf{a} - \mathbf{w_{opt}}^*\mathbf{a}$, a $M \times 1$ vector which is a collection of M snapshots of observations. $\mathbf{z_p}$ and $\mathbf{z_o}$ are the compensated receiver output when using the perturbed weight $\mathbf{w_{opt}} + \Delta\mathbf{w}$ and the nominal weight $\mathbf{w_{opt}}$, respectively. $\Delta\mathbf{W}$ is the perturbation weight matrix, which is a set of the perturbation weight vectors and $\mathbf{v}(l)$ is the error introduced at the receiver when measuring and estimating $\Delta z(l)$. From the assumption that the channel vector $\mathbf{a}(l)$ is slowly varying, we can collect M snapshots of data at time l and perform block processing if the perturbation is rapid enough. $\mathbf{u}(l)$ and $\mathbf{v}(l)$ are white Gaussian noise sources with zero mean and covariance matrix $\mathbf{Q}(l)=E(\mathbf{u}(l)\mathbf{u}^*(l)) = \sigma_u^2\,\mathbf{I}$ and $\mathbf{R}(l) = E(\mathbf{v}(l)\mathbf{v}^*(l)) = \sigma_v^2\,\mathbf{I}$, respectively. The propagation of the error covariance matrix $\mathbf{P}(l)$ is [2, 3]

$$\begin{aligned}
\mathbf{P}(l+1) &= (\mathbf{P}(l)^{-1} + \Delta\mathbf{W}(l)\mathbf{R}^{-1}(l)\Delta\mathbf{W}^*(l))^{-1} \\
&\quad + \mathbf{Q}(l) \qquad (6)
\end{aligned}$$

and

$$\begin{aligned}
\hat{\mathbf{a}}(l+1) &= \hat{\mathbf{a}}(l) + \mathbf{P}(l)\Delta\mathbf{W}(l)(\Delta\mathbf{W}^*(l)\mathbf{P}(l)\Delta\mathbf{W}(l) \\
&\quad + \mathbf{R}^{-1}(l))^{-1}(\Delta\mathbf{z}(l) - \Delta\mathbf{W}^*(l)\hat{\mathbf{a}}(l)) \qquad (7)
\end{aligned}$$

which is a prediction of the channel vector $\mathbf{a}$. It can use $\mathbf{a}(0)$ to initialize the Kalman filter. The optimal choice of the perturbation matrix $\Delta\mathbf{W}$ is given in a separate paper. Here we perturb the channel by equal power, orthogonal perturbation to obtain channel information. Therefore, we choose $\Delta\mathbf{W}$ as

$$\Delta\mathbf{W} = \sqrt{\frac{Ep}{M}}\,\mathbf{I} \tag{8}$$

IV Simulation Result

As shown in Fig. 2, four transmit antennas are located at the corners of a 10m $\times$ 10m square room.

We simplify the scattering and reflection phenomena into 4 scattering sources placed at (4.5,7), (7,4.5) and (9,6) and (4,3.5) without loss of generality. An omni-directional receiver moves in a straight line from (2,5.5) to (9,5.5). Signals are narrow band at frequency 900 MHz. In Fig. 1, only the antenna located at (0,0) is used. The received signal power varies in a range of 10dB to 15 dB. In Fig. 3, all antennas are used but the total transmit power remains the same. We perturb the channel by orthogonal perturbation which has equal energy in each direction and adjust the antenna weights according to the estimate of the channel vector $\hat{\mathbf{a}}$. We find that using multiple adaptive antennas raises the received signal power level and increasing the number of antennas can improve the performance.

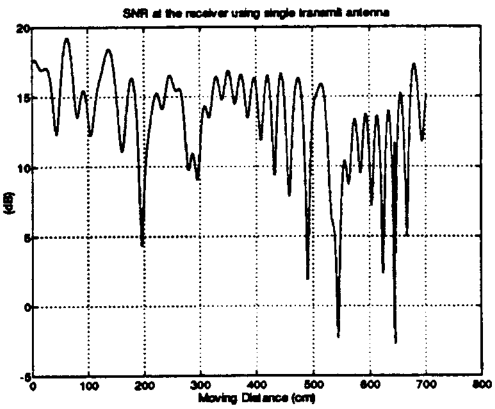

Figure 1: Receiver SNR with a single transmit antenna

V Conclusion

In this paper, we present an approach to alleviate the forward link fading effect in an indoor multipath environment using an adaptive transmit antenna array. The results show that by adaptively adjusting the antenna weights, fading can be substantially reduced.

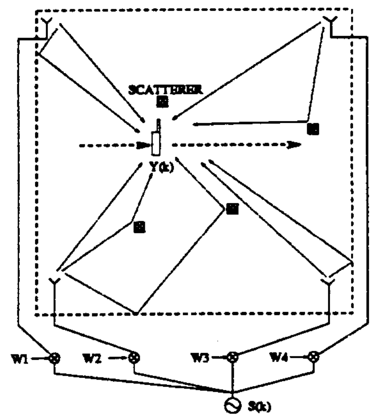

Figure 2: Multiple antennas structure, M=4

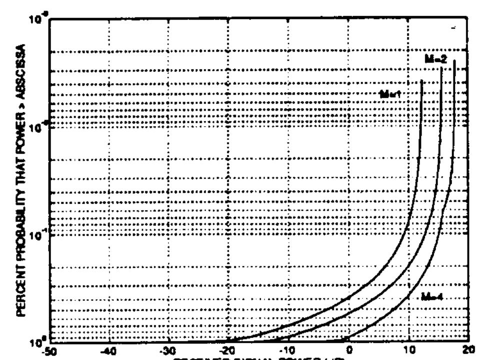

Figure 3: Probability distribution of received signal power

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