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Interference cancellation in a multiuser, spaced transmit antenna diversity system

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**Interference Cancellation
in a Multiuser, Spaced
Transmit Antenna Diversity
System**

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INTERFERENCE CANCELLATION
IN A MULTIUSER, SPACED
TRANSMIT ANTENNA DIVERSITY
SYSTEM

by
Hussein K. Mecklai

A Thesis
Presented to the Graduate Committee
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Abstract

Increased demand for wireless communications in the workplace and for cellular communications has revitalized the concept of spaced antenna diversity. Both transmit and receive diversity are being explored to increase the capacity and improve the performance of wireless communication systems. Transmit diversity is the focus of this paper. Multiple antennas transmit amplitude and phase weighted signals to a single antenna for each user. Fading coefficients were assumed to vary at a slow enough rate so that reliable estimates can be obtained at the transmitter. It is further assumed that all the user's signals are known at the transmitter (base station). This information is exploited in derivation of transmitter weights that maximize the Signal to Interference Noise Ratio (SINR) at the output of the matched filter based receiver for each user.

Chapter 1

Introduction

The derogatory effects of multipath fading in a wireless communication system can be mitigated by employing antenna diversity. Most commonly, receiver diversity has been used. A fairly general receiver diversity scheme has been studied in [1] by Wu and Haimovich. However, in some cases receiver diversity may be impractical or too expensive. In either case transmitter diversity may offer a more viable solution [2,3,4]. Both amplitude and phase weighting are used to enhance the performance of the system by offsetting the effects of fading and interference.

Transmitter diversity has received a great deal of attention recently. Weerackody [2] studied transmission diversity for wideband signals. An M antenna transmitter array was used in conjunction with an L -branch RAKE receiver to achieve an effective diversity of the order of LM for spread spectrum signals. Naguib, Paulraj and Kailath [3] have also reported a many-fold increase in system capacity for CDMA mobile cellular systems using multiple antennas. For narrowband signals, Winters [4] determined that the diversity gain achieved by an M antenna transmitter array was within 0.1 dB of that achieved by an M antenna receiver array.

Some recent investigations have attempted to exploit knowledge of the channel model. The techniques used by Paulraj [3,5] and Winters [6,7], for example, rely on being able to accurately estimate the fading coefficients which are assumed to vary slowly. There are a number of interesting cases where the fading coefficients do vary slowly [8] and so these techniques appear to be promising. In this paper this

concept was taken one step further by attempting to also exploit our knowledge of other users' communications.

In the case of multi-user systems, such as cellular systems employing DS-CDMA, a large part of the interference between users is the result of correlation between the signals being transmitted from the base station to the various users. In these cases, all the signals transmitted to the various users are known at the base station. This information, along with an estimate of a channel model, can be used to reduce the interference between the different signals transmitted by the base station. Here we consider the design of transmitter diversity schemes to minimize this interference for such cases.

Several schemes for interference cancelation using multiple antennas employ a statistical approach. These schemes typically assume that all the fading coefficients are independent. The amount of fading experienced by a signal from a particular transmitter to a particular receiver is described by a complex number called the fading coefficient. Sayeed and Kassam [9] recently reported that the benefits due to diversity are actually increased if the fading coefficients are not independent for some cases. This would affect the performance of the statistically based schemes. However, the scheme proposed here, for nulling out interference, does not rely on statistics.

The goal of this paper is to demonstrate how knowledge of the user signals might be employed to reduce interference and a number of simplifying assumptions are made to promote clarity. In practice, each user will be exposed to noise and interference which are not caused by signals transmitted from the base station in question. In order to focus on reducing the interference which comes from other signals emanating from the same base station, the suppression of noise or interference from other sources is not addressed here. It should be possible to combine existing techniques with the one presented in this paper to suppress noise or interference from other sources and this will be investigated in future efforts.

To simplify the analysis and explanation, a relatively simple channel model is assumed. In the assumed model, for example, the magnitude of the fading does not vary with frequency. Further, it is assumed that the parameters (fading coefficients)

of this model vary at a slow enough rate so that reliable estimates of these parameters can be obtained at the transmitter, possibly by probing the channel. We believe that the analysis given here can be extended to many cases with more complicated channel models, provided that accurate estimates of the parameters of these models can be maintained. A particular receiver structure, a coherent detector with a matched filter, is assumed. The analysis is expected to hold, with some modification, for some other interesting receiver designs. We consider explicitly only the case of binary communications where a polar amplitude shift keying signaling scheme is employed, but it appears that the analysis can be extended to many other cases, including some non-binary cases, in a relatively straight forward manner. Only noise added after transmission is considered in the analysis. Noise added to signals prior to their transmission is ignored since its effects are largely overshadowed by the noise added at each receiver. Our analysis assumes discrete-time processing at the base station, although an extension to continuous time appears possible.

Chapter II defines the system under consideration. Chapter III presents the performance criterion used for design purposes and outlines the optimization procedure used. Chapter IV considers power constraints which may exist and how they affect the optimization. Conclusions are given in Chapter V.

Chapter 2

The Model

Consider the case where an array of M antennas is used to transmit to each of the K users. A weighted version of each of the users signals is transmitted from each antenna. Complex envelope notation is employed in this section to simplify presentation. Let $w_{mk}[n]$ denote the complex transmission weight multiplying the signal of the k^{th} user, which is transmitted from the m^{th} antenna. $u_k[n]$ denotes the k^{th} users signal. The m^{th} antenna transmits

$$B_m[n] = \sum_{k=1}^K w_{mk}[n] u_k[n], \quad m = 1, \dots, M. \quad (2.1)$$

Now focus on the signal received by the i^{th} user and consider the case where the transmission from each antenna arrives at each receiver multiplied by a single complex fading coefficient which is frequency independent. Since receiver diversity is not considered here, each user is assumed to have a single antenna. Let $G_{mi}[n]$ denote the complex fading coefficient for the signal transmitted by the m^{th} antenna to the i^{th} user. The $G_{mi}[n]$, $i = 1, \dots, K$, $m = 1, \dots, M$, are assumed to be known. The signal received by the i^{th} ($i = 1, \dots, K$) user's antenna is given by

$$\sum_{m=1}^M G_{mi}[n] B_m[n] + \epsilon_i[n] = x_{di}[n] + x_{Ii}[n] + \epsilon_i[n], \quad (2.2)$$

where $x_{di}[n]$ is the desired signal of the i^{th} user, $x_{Ii}[n]$ is the interference due to the other users at the i^{th} receiver and $\epsilon_i[n]$ is the additive noise component at the i^{th}

receiver. In (2.2)

$$x_{di}[n] = \sum_{m=1}^M G_{mi}[n] w_{mi}[n] u_i[n] \quad (2.3)$$

and

$$x_{Ii}[n] = \sum_{m=1}^M G_{mi}[n] \sum_{k=1, k \neq i}^K w_{mk}[n] u_k[n]. \quad (2.4)$$

Assume that the i^{th} user transmits one of two possible waveforms, $u_i[n] = p[n]$ or $u_i[n] = -p[n]$ during an interval including $N + 1$ discrete-time instants. One of the waveforms corresponds to a binary zero and the other a binary one. Now consider the case where the waveform corresponding to a given binary digit is received during the time interval $0 \leq n \leq N$. Assume that a matched filter with an impulse response, $h_i[n] = p[N - n], n = 0, \dots, N$ will be used to process the signal in (2.2). Let $s_{di}[N]$, $s_{Ii}[N]$, and $\gamma_i[N]$ be the outputs of the matched filter due to $x_{di}[n]$, $x_{Ii}[n]$ and $\epsilon_i[n]$ respectively. Assuming that a decision will be made based on the output of the matched filter at discrete time N , we define the received signal power, interference power and noise power as

$$|s_{di}[N]|^2 = \left| \sum_{n=0}^N h_i[N - n] x_{di}[n] \right|^2, \quad (2.5)$$

$$|s_{Ii}[N]|^2 = \left| \sum_{n=0}^N h_i[N - n] x_{Ii}[n] \right|^2, \quad (2.6)$$

and

$$|\gamma_i[N]|^2 = E \left[\left| \sum_{n=0}^N h_i[N - n] \epsilon_i[n] \right|^2 \right] \quad (2.7)$$

where $|\cdot|^2$ denotes magnitude squared and $E[\cdot]$ denotes the expected value.

Chapter 3

Optimum Weights

The transmission weights are picked to maximize the signal-to-interference-plus-noise ratio (SINR) at each receiver as measured at the output of the corresponding matched filter. The SINR of the i^{th} user is

$$SINR_i = \frac{|s_{di}[N]|^2}{|s_{Ii}[N]|^2 + |\gamma_i[N]|^2}. \quad (3.1)$$

Since the only noise considered is that which is added after the signals are multiplied by the weights, the weights cannot be employed to reduce $|\gamma_i[N]|^2$. Thus, $SINR_i$ can be maximized by simultaneously maximizing the desired signal power, $|s_{di}[N]|^2$, and minimizing the interference power, $|s_{Ii}[N]|^2$, provided this is possible. The analysis given here shows that this is indeed possible for many cases of interest.

First consider the conditions needed to maximize $|s_{di}[N]|^2$. The output power of a matched filter is maximized if the input signal is a scalar multiple (denoted by P_i here) of the desired signal (the signal the matched filter is matched to), that is,

$$\begin{aligned} x_{di}[n] &= P_i u_i[n] = \sum_{m=1}^M w_{mi}[n] G_{mi}[n] u_i[n], \\ \text{for } i &= 1, \dots, K, \quad n = 0, \dots, N \end{aligned} \quad (3.2)$$

Note that the condition in (3.2) is actually independent of $u_i[n]$ since it cancels out of both sides. Further, the scalar multiple P_i in (3.2) determines the power in

the desired component received by user i since from (2.5) this power is

$$|s_{di}[N]|^2 = P_i^2 \left| \sum_{n=0}^N p^2[n] \right|^2.$$

regardless of whether $u_i[n] = p[n]$ or $-p[n]$. Here we assume that the power of the desired component in the signal received by the i^{th} user, hence P_i , is specified for all the users, $i = 1, \dots, K$. These parameters will be quoted to each user as performance guarantees. In fact, in the case of known noise statistics and zero interference, it is possible to directly relate P_i to $SINR_i$. Of course, such statements assume that the system is designed to have enough transmit power to meet these specifications. We will address cases where these specifications cannot be met in Section IV.

Our next goal is to find conditions on the weights to minimize $|s_{Ii}[N]|^2$, assuming the conditions in (3.2) are satisfied. Note that (3.2) requires that the product of two time-varying terms, the fading coefficients and the weights, equal a constant that is time-invariant. Hence, both the time-dependent terms must vary at the same rate. Thus, in general, the weights must be updated at the rate at which the fading coefficients change. In order to provide a general treatment, $|s_{Ii}[N]|^2$ is initially minimized for the case where the fading changes every sample. If the fading varies more slowly, the weights can be updated at a slower rate. This will be discussed in more detail later in this chapter.

$|s_{Ii}[N]|^2$ can be written as a function of the weights by substituting (2.4) in (2.6). Necessary conditions to minimize each $|s_{Ii}[N]|^2$ for $i = 1, \dots, K$ can be developed by taking partial derivatives of $|s_{Ii}[N]|^2$ for $i = 1, \dots, K$ with respect to the real and imaginary parts of $w_{\ell j}[q]$ for $q = 0, \dots, N, \ell = 1, \dots, M, j = 1, \dots, K, j \neq i$ and setting the results equal to zero to obtain

$$\begin{aligned} \left[h_i[N - q] G_{\ell i}[q] u_j[q] \right]^* s_{Ii}[N] &= 0 \quad \text{for } i = 1, \dots, K, \\ q = 0, \dots, N, \ell = 1, \dots, M, j = 1, \dots, K, j &\neq i \end{aligned} \quad (3.3)$$

where $[\cdot]^*$ is the complex conjugate of $[\cdot]$ in (3.3). The quantity $[h_i[N - q] G_{\ell i}[q] u_j[q]]^*$ in (3.3) is independent of the weights so only $s_{Ii}[N]$ can be forced to zero. If it happens that $[h_i[N - q] G_{\ell i}[q] u_j[q]]^* = 0$ then the corresponding equation in (3.3) is

automatically satisfied for any weights. Now consider the set of equations in (3.3) for which $[h_i[N - q]G_{ik}[q]u_j[q]]^* \neq 0$ and call the set of i indices for which this is true \mathcal{I} . The conditions in (3.3) become

$$s_{ii}[N] = 0 \text{ for } i = 1, \dots, K \text{ and } i \in \mathcal{I} \quad (3.4)$$

Note that (3.4) can correspond to at most K equations. To simplify our discussion, in the sequel we assume that all K equations are listed in (11) and so each must be satisfied. In addition to these K equations, (3.2) gives rise to $K(N + 1)$ more equations for a total of $K(N + 2)$ equations. These equations can be written in matrix form as

$$A\bar{w} = \bar{P} \quad (3.5)$$

where \bar{w} , the weight vector, is of size $MK(N + 1)$. A , \bar{w} and \bar{P} are described in Table 1 and Table 2. If the rank of A is equal to the number of rows of A (the number of equations used to compose A), $K(N + 2)$ in this case, then a solution exists. This requires that the number of unknowns, $MK(N + 1)$, be equal to or greater than the rank of A or that $M \geq (N + 2)/(N + 1)$. This condition is satisfied for any $M \geq 2$. Interestingly enough this condition is independent of the number of users. Assuming $M \geq 2$, the number of degrees of freedom in the solution is the difference between the number of unknowns and the rank of A . Furthermore, any solution reduces the interference power at the output of the matched filter to zero, for every user. Clearly, the necessary conditions for minimizing interference are also sufficient since they zero out the interference power. Any degrees of freedom in the solution could be exploited to reduce system cost.

Now consider the case where the fading remains approximately constant during a signaling interval, when a single bit is sent. From (3.2) this would mean that the transmission weights would only have to be updated once every bit, reducing (3.2) to K equations. There is still at most K different equations from the conditions in (3.3). Hence, the total number of equations would reduce to $2K$ (at most) while the number of variables would reduce to MK . An equation of the form (3.5) still applies with the A , \bar{w} and \bar{P} described in Table 3 and Table 4. A specific example

will be given later. If the rank of A is equal to the number of rows in A , then a solution exists. Again this requires $M \geq 2$.

It is possible that the rank of A may not be equal to the number of rows in A . For this to occur there must be a linear relationship between the rows of A such that

$$\sum_{i=1}^Q \gamma_i a_i = 0 \quad (3.6)$$

where γ_i is a scalar constant, a_i is the i^{th} row of A and Q is the number of rows in A . If the random vector of fading coefficients is a continuous random vector, the usual model, then any set of random vectors satisfying (3.6) occurs with zero probability. Thus, these cases do not effect any statistical performance measure. These ideas are best illustrated through an example.

Consider a case where the weights are to be updated once per bit since the fading coefficients are constant over each bit. Here we drop the dependence of the weights and the fading coefficients on n . Assume two transmission antennas and two users. In this case the weight vector \bar{w} consists of four variables

$$\bar{w} = (w_{11} \ w_{12} \ w_{21} \ w_{22})^T \quad (3.7)$$

A is the 4 by 4 matrix given in Table 5, while \bar{P} is

$$\bar{P} = (0 \ 0 \ P_1 \ P_2)^T \quad (3.8)$$

If A has rank 4, then the solution for \bar{w} is given in Table 6.

Now consider the case where the rank of A is less than 4. The rank of A will be less than 4 if any row of A is a linear combination of any of the other rows. This would be the case if

$$G_{12} = CG_{11} \quad (3.9)$$

and if

$$G_{22} = CG_{21} \quad (3.10)$$

at the same time, where C is some arbitrary constant. In this event the constraints on \bar{w} would be conflicting (assuming $P_1, P_2 \neq 0$) and could not be satisfied simultaneously. Hence, there would be no solution for this case. If C is equal to one, for

example, it implies that the signal experiences the same fading from the transmitter to both the receivers. If this were the case, zeroing out the interference for user 1 at receiver 2 would zero out the signal of user 1 at receiver 1. The conditions we developed require that the same quantity equal P_i and zero at the same time. Clearly, this is impossible. However, if the random variables G_{12}/G_{11} and G_{22}/G_{21} have a joint probability density functions with no point masses of probability then the event described by (3.9) and (3.10) would occur with probability zero.

In practice, one must specify what should be done for cases where no solution for the weights exists. One approach is to just assign a reasonable set of weights and to live with the interference that results. For example, in the case we described, we could transmit user 1 from antenna 1 only and user 2 from antenna 2 only. More elaborate schemes could also be considered.

Since the interference can be nulled by updating the weights once a bit, one might consider updating the weights at an even slower rate and ask how much degradation in performance would result, if any. To answer this question it is necessary to re-examine the equations that determine the weights that minimize the interference. As stated before, (3.2) requires the weights be updated as often as the fading changes. If the fading were to change only once every B bits, not an altogether unreasonable assumption, then the weights need only be updated once every B bits to satisfy (3.2). Using similar arguments as used to develop (3.4), conditions similar to those in (3.4) would result for each bit. Hence, it would be necessary to update the weights once every bit in order to satisfy (3.4) for each bit. A slower update rate for the weights could be used to minimize the mean squared interference over B bits but the interference could not be zeroed out altogether.

The scheme proposed here can be easily extended to deal with DS-CDMA. If the PN sequence of the i^{th} user is given by $c_i[n]$ then equation (2.1) becomes

$$B_m[n] = \sum_{k=1}^K w_{mk}[n]c_k[n]u_k[n], \quad m = 1, \dots, M. \quad (3.11)$$

which changes equation (2.3) and (2.4) to

$$x_{di}[n] = \sum_{m=1}^M G_{mi}[n]w_{mi}[n]u_i[n] \quad (3.12)$$

and

$$x_{I_i}[n] = \sum_{m=1}^M G_{mi}[n] \sum_{k=1, k \neq i}^K w_{mk}[n] u_k[n]. \quad (3.13)$$

respectively. If $s_{d_i}[N]$ and $s_{I_i}[N]$ are considered to be despread output of the matched filter due to $x_{d_i}[n]$ and $x_{I_i}[n]$ then (2.5) remains unchanged while (2.6) changes to

$$|s_{I_i}[N]|^2 = \left| \sum_{n=0}^N c_i[N-n] h_i[N-n] x_{I_i}[n] \right|^2, \quad (3.14)$$

Consequently (3.2) remains unchanged as does (3.3) and (3.4). Only (3.4) has an additional scale factor that is the convolution of the desired users PN sequence and the interferer's PN sequence as defined in (3.14). Equations (3.2) and (3.4) are used to find the zero interference solution to the problem. If DS-CDMA is used then (3.2) and (3.14) should be used to find the zero interference solution.

Chapter 4

Power Constraints

The physical assumption made in (3.2) is that there is enough power available at the transmitter to meet the specifications, $P_i, i = 1, \dots, K$, on the power of the desired users' signal at the corresponding receivers. Since only a finite amount of power, ρ_T , is available at the transmitter, the weights are constrained by

$$\rho_T \geq \sum_{m=1}^M \sum_{k=1}^K |w_{mk}[n]|^2, \quad (4.1)$$

If the set $\{P_i, i = 1, \dots, K\}$, is such that the solution vector \bar{w} , obtained from (3.2) and (3.4) does not satisfy the power constraint in (4.1) then a new solution vector \bar{w}' may be defined by

$$\bar{w}' = \delta \bar{w} \quad (4.2)$$

where

$$\delta = \sqrt{\frac{\rho_T}{\sum_{m=1}^M \sum_{k=1}^K |w_{mk}[n]|^2}} \quad (4.3)$$

The new solution vector \bar{w}' would zero out interference from other users, exactly meet the overall power constraint in (4.1) and would result in a performance criteria that would be a scaled version of the original specification. Specifically, each new P_i would be a fraction, δ , of the originally specified P_i . Clearly this would reduce the power of the desired signal at the i^{th} receiver, but the relative sizes of the various P_i 's would remain unchanged relative to the original specification.

Chapter 5

Conclusions

In this thesis an approach was discussed for reducing the interference at each receiver for a multi-user system. This was accomplished by weighting the transmitted signals. Various update rates for the transmission weights and their effects on reducing interference were discussed. The interference could be set equal to zero for all users for a number of interesting cases. This technique relies on the fading coefficients and all the users' transmitted signals being known at the transmitter. The constraints on obtaining a solution and the degrees of freedom in the system were indicated. Extensions of this work could include techniques for exploiting the degrees of freedom in this system to incorporate methods for combating other problems that plague wireless communication systems.

Appendix A

$$\begin{bmatrix}
 0 & h_1[N]G_{11}[0]u_2[0] & \dots & 0 & h_1[N-1]G_{11}[1]u_2[1] & \dots & h_1[0]G_{M1}[N]u_K[N] \\
 h_2[N]G_{12}[0]u_1[0] & 0 & \dots & h_2[N-1]G_{12}[1]u_1[1] & 0 & \dots & h_2[0]G_{M2}[N]u_K[N] \\
 \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
 h_K[N]G_{1K}[0]u_1[0] & h_K[N]G_{1K}[0]u_2[0] & \dots & h_K[N-1]G_{1K}[1]u_1[1] & h_K[N-1]G_{1K}[1]u_2[1] & \dots & 0 \\
 G_{11}[0] & 0 & \dots & 0 & 0 & \dots & 0 \\
 0 & G_{12}[0] & \dots & 0 & 0 & \dots & 0 \\
 \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
 0 & 0 & \dots & 0 & 0 & \dots & G_{MK}[N]
 \end{bmatrix}$$

Table 1: A matrix for M transmission antennas and K users and update each sample.

$$\begin{aligned}
 \bar{w} &= (w_{11}[0] \ w_{12}[0] \ \dots \ w_{1K}[0] \ w_{21}[0] \ \dots \ w_{MK}[0] \ w_{11}[1] \ \dots \ w_{MK}[N])^T \\
 \bar{P} &= (0 \ 0 \ \dots \ 0 \ P_1 \ P_2 \ \dots \ P_K \ \dots \ P_1 \ \dots \ P_K)^T
 \end{aligned}$$

Table 2: \bar{P} and \bar{w} for M transmission antennas and K users and update each sample.

$$\begin{bmatrix}
 0 & \sum h_1[N-n]G_{11}u_2[n] & \dots & \sum h_1[N-n]G_{11}u_K[n] & 0 & \dots \\
 \sum h_2[N-n]G_{12}u_1[n] & 0 & \dots & \sum h_2[N-n]G_{12}u_K[n] & \sum h_2[N-n]G_{22}u_1[n] & \dots \\
 \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
 \sum h_K[N-n]G_{1K}u_1[n] & \sum h_K[N-n]G_{1K}u_2[n] & \dots & 0 & \sum h_K[N-n]G_{2K}u_1[n] & \dots \\
 G_{11} & 0 & \dots & 0 & G_{21} & \dots \\
 0 & G_{12} & \dots & 0 & 0 & \dots \\
 \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
 0 & 0 & \dots & G_{1K} & 0 & \dots
 \end{bmatrix}$$

Table 3: A matrix for M transmission antennas and K users and single update per bit ($\sum = \sum_{n=0}^N$).

$$\begin{aligned} \bar{w} &= (w_{11} \quad w_{12} \quad w_{13} \quad \cdots \quad w_{1K} \quad w_{21} \quad \cdots \quad w_{MK})^T \\ \bar{P} &= (0 \quad 0 \quad \cdots \quad 0 \quad P_1 \quad P_2 \quad \cdots \quad P_K)^T \end{aligned}$$

Table 4: \bar{P} and \bar{w} for M transmission antennas and K users and single update per bit.

$$\begin{bmatrix} 0 & G_{11} \sum_{n=0}^N h_1[N-n]u_2[n] & 0 & G_{21} \sum_{n=0}^N h_1[N-n]u_2[n] \\ G_{12} \sum_{n=0}^N h_2[N-n]u_1[n] & 0 & G_{22} \sum_{n=0}^N h_2[N-n]u_1[n] & 0 \\ G_{11} & 0 & G_{21} & 0 \\ 0 & G_{12} & 0 & G_{22} \end{bmatrix}$$

Table 5: A matrix for the two transmission antennas and two users example.

$$\begin{aligned} w_{11} &= \frac{(G_{22}P_1)}{(G_{11}G_{22} - G_{12}G_{21})} & w_{12} &= \frac{(G_{21}P_2)}{(G_{12}G_{21} - G_{11}G_{22})} \\ w_{21} &= \frac{(G_{12}P_1)}{(G_{12}G_{21} - G_{11}G_{22})} & w_{22} &= \frac{(G_{11}P_2)}{(G_{11}G_{22} - G_{12}G_{21})} \end{aligned}$$

Table 6: \bar{w} for the two transmission antennas and two users example.

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