QUASI-STATIC ANTENNA ARRAY PROCESSING FOR RAPIDLY TIME-VARYING CHANNELS

Timothy A. Thomas and Frederick W. Vook

Motorola Labs - Communication Systems Research Laboratory
1301 E. Algonquin Road, IL02-2912
Schaumburg, IL 60196
T.Thomas@motorola.com

ABSTRACT

This paper explores the use of quasi-static frequency-domain antenna combining weights for multi-user (e.g., SDMA) or multi-stream (e.g., MIMO) communication systems operating in rapidly time-varying frequency-selective channels. By implementing combining weights that are constant across a time slot but are updated from slot-to-slot (i.e., "quasi-static"), great computational complexity savings can be realized compared to calculating new weights at each data block within a time slot. The quasi-static weights are computed by first modeling the time-varying channel for each user as the superposition of multiple time-invariant channels, called Doppler channels. The weights are then calculated based on all users' Doppler channels. These new weights work by using some of the degrees of freedom of the antenna array to suppress time variations as well as multiple access interference. Despite being fixed across a time slot, these weights can equalize and suppress SDMA interference even when the channel varies significantly over the slot. Simulation results show the effectiveness of these weights for equalization and interference suppression.

1. INTRODUCTION

In a broadband mobile communication system, high levels of Inter-Symbol Interference (ISI) and rapid time variations can severely distort the transmitted signal. Mobile broadband systems operating at carrier frequencies above 2 GHz can experience ISI levels greater than 50 symbols and maximum Doppler rates exceeding 300 Hz. Furthermore, in rapidly-varying frequency-selective channels, the presence of multipath angular spread causes the vector channel response of a signal arriving at an antenna array to change rapidly in both time and frequency, which complicates the problem of using antenna arrays to exploit spatial diversity and suppress interference. Traditional time-domain equalization and interference suppression techniques [1][2] are highly complex and difficult to implement in such channels. As an alternative, Orthogonal Frequency Division Multiplexing (OFDM) and frequency-domain equalization [3] have been proposed for broadband systems. However, these systems have difficulty recovering the transmitted symbols when the channel varies significantly within a data block (a block of symbols that are FFT'd into the frequency domain).

To assist the frequency-domain equalization process in single carrier systems, [3] proposes to attach OFDM-style cyclic prefixes before each block of single-carrier data symbols. The cyclic prefix at the beginning of a data block is simply a repetition of the symbols that are at the end of the data block. One benefit of the cyclic prefix is that it creates the appearance of a circular channel response, which greatly simplifies the receiver design by eliminating the need for frequency-domain filtering techniques like overlap and save. However, channel variations over a data block will destroy the appearance of a circular channel and cause Inter-Carrier Interference (ICI) in the frequency domain.

To deal with the problems associated with ICI, [4] proposes the use of cyclic prefixes composed of zero symbols, called "null cyclic prefixes." These null cyclic prefixes restore the appearance of a circular channel thereby eliminating the ICI in the frequency domain when the time-varying channel is modeled similarly to [4]. This model characterizes the time-varying channel between a single transmit and single receive antenna as the sum of multiple time-invariant "Doppler" channels. [4] also proposes equalization and interference suppression methods that counteract the Doppler-induced ICI. Unfortunately, the frequency-domain combining weights of [4] need to be updated at every data block within a time slot in order to effectively equalize and suppress interference in rapidly time-varying channels.

This paper presents new quasi-static frequency-domain adaptive array processing algorithms for equalization and interference suppression in broadband channels having severe ISI and high Doppler rates. We consider a pilot-assisted high-speed single-carrier system which uses the null cyclic prefixes of [4]. We use the term "quasi-static" to indicate that the array combining weights are fixed within a time-slot and are updated at each new time slot. In other words, rather than computing a new frequency-domain weight vector at each data block as in [4], the same frequency-domain weights are applied at every data block within a time slot. These quasi-static weights are computed based on the Doppler channel model of [4] and can be applied to a time slot during which the Doppler channel model adequately represents the channel. Despite being fixed across a time slot, these weights can equalize and suppress SDMA interference even when the channel varies significantly over a large number of data blocks. As a result, the computational complexity of calculating the combining weights can be dramatically reduced.

After describing the system in Section 2, Section 3 reviews the combining weights presented in [4] that are updated at each data block within a time slot. Then, Section 4 presents the quasi-static adaptive antenna combining weights which exploit the Doppler channel model and the null cyclic prefixes described in [4]. Finally, Section 5 presents simulation results that verify the ability of these quasi-static weights to combat severe time and frequency variations for a null cyclic prefix single-carrier communication system.

2. BACKGROUND

Figure 1 shows a diagram of the Doppler channel model from [4] that will be used in this paper to approximate a time-varying ISI channel. This channel is similar to the one proposed in [5]. According to this model, the transmitted signal is multiplied by V_T=(2V+1) Doppler sinusoids to produce V_T Doppler signals. Each Doppler signal is then convolved with its respective time-invariant Doppler channel, and the results are summed to produce the received signal. In [4], it was shown that when a single carrier system uses null cyclic prefixes (i.e., L_{CP} zero symbols) rather than OFDM-style cyclic prefixes [3], the received frequency-domain Doppler signals have no ICI.

Figure 2 shows an example of the pilot/data block structure for the single carrier communication system under consideration. Each pilot block of length L_p (denoted P in the figure) and each data block of length K are surrounded by L_{CP} zero symbols that are the null cyclic prefixes/postfixes (denoted CP in the figure). For a data block, the N=(K+L_{CP}) symbols that are FFT'd into the frequency domain consist of the data symbols plus their corresponding null cyclic postfix.

With M receive antennas, the received M×1 frequency-domain signal vector is modeled as (see [4]):

$$\mathbf{Y}(k,b)=\sum_{u=1}^{U}\sum_{v=-V}^{+V}\mathbf{H}_{u,v}(k)Z_{u,v}(k,b)+\mathbf{N}(k,b) \quad (1)$$

where k is the subcarrier number (0≤k≤N-1), U is the number of known users, $\mathbf{N}(k,b)$ is the FFT of the noise on block b, $\mathbf{H}_{u,v}(k)$ is the v^{th} frequency-domain Doppler channel for user u and is given as:

$$\mathbf{H}_{u,v}(k)=\sum_{\ell=0}^{L-1}\mathbf{h}_{u,v}(\ell)e^{-j2\pi k\ell/N} \quad (2)$$

For data block b, the frequency-domain v^{th} Doppler signal, $Z_{u,v}(k,b)$, is given as:

$$Z_{u,v}(k,b)=\sum_{n=0}^{K-1}z_{u,v}(n,b)e^{-j2\pi kn/N} \quad (3)$$

and the time-domain v^{th} Doppler signal is:

$$z_{u,v}(n,b)=x_u(n,b)e^{j2\pi v(n+n_b)/N_k} \quad (4)$$

where $x_u(n,b)$ is user u's symbol at time n on data block b, N_k is the "DFT" size of the Doppler channel model and is typically chosen to be twice the length of the time slot, and n_b is defined to be the time that a particular block starts. For the format in Figure 2, b=1 is a pilot block and n_1=0, b=2 is a data block and n_2=N_P, b=3 is also a data block and n_3=N_P+N, and so forth (N_P=L_P+L_{CP}).

3. MMSE DOPPLER COMBINING WEIGHTS

Using the Doppler channel estimates from the estimator of [4], MMSE combining weights, referred to as MMSE Doppler combining weights, can be found. These weights were originally presented in [4] and are updated at each data block within a time slot. These weights are included in this paper because we use these weights as a baseline comparison for the quasi-static weights presented in the next section. Because there are V_T Doppler channels, a different set of combining weights can be found to minimize the mean squared error between the combined output and user u's v^{th} frequency-domain Doppler signal as follows:

$$\min_{\mathbf{w}_{u,v}(k,b)} E\left|\mathbf{w}_{u,v}^H(k,b)\mathbf{Y}(k,b)-Z_{u,v}(k,b)\right|^2 \quad (5)$$

The solution can be shown to be:

$$\mathbf{w}_{u,v}(k,b)=\left(\mathbf{R}(k,b)+\sigma_n^2\mathbf{I}\right)^{-1}\mathbf{p}_{u,v}(k,b) \quad (6)$$

where σ_n^2 is the frequency-domain noise power and:

$$\mathbf{R}(k,b)=\sum_{u=1}^{U}\sum_{v=-V}^{V}\sum_{w=-V}^{V}\mathbf{H}_{u,v}(k)\mathbf{H}_{u,w}^H(k)\alpha_b(v-w) \quad (7)$$

$$\mathbf{p}_{u,v}(k,b)=\sum_{w=-V}^{V}\mathbf{H}_{u,w}(k)\alpha_b(w-v) \quad (8)$$

$$\alpha_b(v)=e^{j\pi v(K-1+2n_b)/N_k}\frac{\sin(\pi vK/N_k)}{\sin(\pi v/N_k)} \quad (9)$$

The time-domain symbol estimates for user u on Doppler channel v are given as (recall that the last L_{CP} symbols are the null cyclic postfix):

$$\hat{x}_{u,v}(n,b)=\left(\frac{1}{N}\sum_{k=0}^{N-1}\mathbf{w}_{u,v}^H(k,b)\mathbf{Y}(k,b)e^{j2\pi kn/N}\right)\bullet e^{-j2\pi v(n+n_b)/N_k} \quad (10)$$

Now these symbol estimates for each Doppler channel can be combined to get the symbol estimates which we call the Combined MMSE Doppler symbol estimates. One way to combine the estimates is to weight each output based on the power in their respective Doppler channels (which is what is done in the simulations). An alternative set of weights only decode the DC (i.e., v=0) Doppler channel and are called the DC MMSE Doppler weights.

4. QUASI-STATIC WEIGHTS

The MMSE Doppler weights have one drawback in that different weights need to be calculated at each data block. If good quasi-static weights can be found, the number of computations required to compute the weights can be greatly reduced. For example in the simulation runs, the MMSE Doppler weights have to be re-calculated 24 times (i.e., at each data block) as opposed to the quasi-static weights that only need to be calculated once.

4.1 Null Doppler Weights

The idea behind these quasi-static combining weights is to treat the v^{th} Doppler signal for user u as the desired signal and all other signals as SDMA-type interference. In equation form, the v^{th} null Doppler combining weight for user u is (assuming the MMSE criteria):

$$\mathbf{w}_{u,v}(k)=\left(\sum_{w=-V}^{+V}\sum_{p=1}^{U}\mathbf{H}_{p,w}(k)\mathbf{H}_{p,w}^H(k)+\sigma_n^2\mathbf{I}\right)^{-1}\mathbf{H}_{u,v}(k) \quad (11)$$

The problem with the Null Doppler weights is that they null some of the desired user's signal power by treating the V_T-1 other Doppler signals for the desired user as unwanted interference. One way to recover some of this desired power is to find a symbol estimate for each Doppler channel for user u and then combine these V_T symbols similar to the procedure described at the end of Section 3.

4.2 Quasi-Static MMSE Doppler Weights

The Quasi-Static MMSE Doppler weights use an average MMSE criteria to try to find better quasi-static weights than the Null Doppler weights. Basically, these weights are the quasi-static versions of the MMSE Doppler weights of Section 3. The Quasi-Static MMSE Doppler weight for the v^{th} Doppler channel and user u is the argument that solves the following equation:

$$\min_{\mathbf{w}_{u,v}(k)} \sum_{b\in\Gamma_d} E\left|\mathbf{w}_{u,v}^H(k)\mathbf{Y}(k,b) - Z_{u,v}(k,b)\right|^2 \tag{12}$$

where Γ_d is the set of data blocks. The solution is:

$$\mathbf{w}_{u,v}(k) = \left(\mathbf{R}(k) + \sigma_n^2\mathbf{I}\right)^{-1}\mathbf{p}_{u,v}(k) \tag{13}$$

where
$$\mathbf{p}_{u,v}(k) = \sum_{w=-V}^{V}\mathbf{H}_{u,w}(k)\gamma(w-v) \tag{14}$$

$$\mathbf{R}(k) = \sum_{u=1}^{U}\sum_{v=-V}^{V}\sum_{w=-V}^{V}\mathbf{H}_{u,v}(k)\mathbf{H}_{u,w}^H(k)\gamma(v-w) \tag{15}$$

$$\gamma(v) = \sum_{b\in\Gamma_d} e^{j\pi v(K-1+2n_b)/N_k}\frac{\sin(\pi vK/N_k)}{\sin(\pi v/N_k)} \tag{16}$$

Again an improvement to the Quasi-Static MMSE Doppler weights is to find a symbol estimate for each Doppler channel for user u and then combine these V_T symbols similar to the procedure described at the end of Section 3.

5. SIMULATION RESULTS

The parameters for the simulated null cyclic prefix single-carrier communication system are given in Table 1. Each user's simulated channel was generated as 12 rays, each with an arrival angle uniformly distributed on [0,2π] where the array manifold vector for each ray assumes a uniform linear array. The first ray arrives with zero delay, and the last ray arrives with 8.0 μsec delay. The other 10 rays arrive randomly distributed between 0.0 and 8.0 μsec in increments of 0.018333 μsec (the symbol rate divided by 10). Each ray is faded according to Jake's model [6] for a Doppler frequency of 330 Hz.

Figure 3 shows an example channel for the given simulation parameters and how well three Doppler channels per user match this particular channel. Note that the Quasi-Static (QS) weights have to work over 24 data blocks where the channel potentially changes drastically over that time interval. On the other hand, the MMSE Doppler weights, which are updated on each block of $N=K+L_{cp}=256$ frequency-domain symbols, do not need to compensate for much variation. Thus the QS weights will need to use more degrees of freedom of the array to be able to compensate for the severe time variations.

Figure 4 shows a BER comparison of the algorithms for $M=8$ receive elements. The MMSE-Ave. Chan. weights find an average channel estimate between each pair of pilot blocks and then finds one set of MMSE combining weights for the 8 data blocks between the two pilot blocks. (Note that these weights are updated 3 times.) For the rest of the algorithms, any algorithm without a DC in the figure legend indicates that a time-domain symbol estimate is found for each Doppler channel for a particular user and then these are combined to find an improved symbol estimate as described at the end of Section 3. In the legend, the algorithms labeled with a DC are the symbols estimates for the $v=0$ Doppler channel only.

Note that the weights found by averaging the channel do not work well because the channel is changing too rapidly. Of all of the QS weights, the QS MMSE Doppler weights perform the best when the symbol estimates associated with each Doppler channel are combined after detection. However, there is a significant gap between the QS MMSE Doppler weights and the MMSE Doppler weights due to the QS MMSE Doppler weights needing to suppress some of the time variations and thus some of the desired user's signal energy is lost. However, the QS weights are only calculated once versus 24 times for the MMSE Doppler weights.

Figure 5 and Figure 6 show the effect of varying the number of receive elements on the MMSE Doppler weights and the QS MMSE Doppler weights where the symbols estimates associated with each Doppler channel are combined after detection. Because of the number of degrees of freedom needed for the QS weights, the QS MMSE Doppler weights work well (i.e., without a BER floor) only for $M>6$. On the other hand because the data block sizes are small, the MMSE Doppler weights work well for $M\geq3$. Note that as more receive elements are added, the performance gap between the QS MMSE Doppler weights and the MMSE Doppler weights decreases.

One last thing to note is that for the QS weights to work, the Doppler channels for each user have to be sufficiently different spatially. This condition occurs when the multipath rays arriving at the array are adequately separated in angle. For a linear array spaced at 3 wavelengths, simulations have shown just a few degrees of angular spread are sufficient for the QS weights to work.

Table 1. Simulation Parameters for the Single-Carrier System

Parameter	Value
M (# of antennas)	Varies
Raised cosine pulse rolloff factor	0.1
Symbol rate	0.18333 μsec
Null to null bandwidth	6.0 MHz
L_{cp} (Null cyclic prefix length)	64
L_P (# of symbols in a pilot block)	192
# of pilot blocks	4
K (number of symbols in a data block)	192
# of data blocks between any two adjacent pilot blocks	8
U (# of SDMA users)	2
Modulation type	64-QAM
Data rate	21.0 Mbit/sec/user
V_T (# of Doppler channels)	3
L (# of assumed time-taps)	64
N_k (the Doppler DFT size)	20,000

6. CONCLUSION

This paper proposed quasi-static frequency-domain antenna combining weights to combat severe frequency and time variations in multi-user/MIMO communications. Through the use of quasi-static weights, the number of computations needed to compute combining weights can be dramatically reduced. The effectiveness of the quasi-static combining weights was demonstrated for a null cyclic prefix single carrier communication system operating in rapidly time-varying frequency-selective channels.

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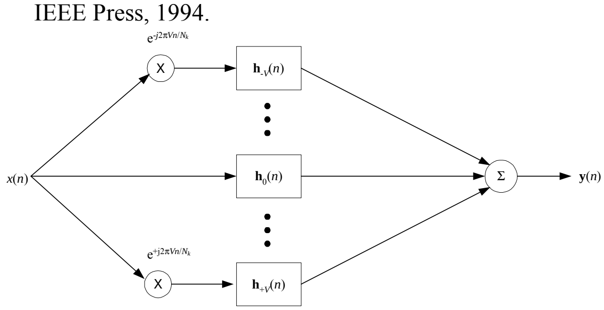

Figure 1. Time varying channel model

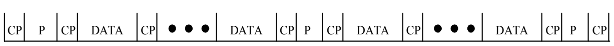

Figure 2. Example time slot format

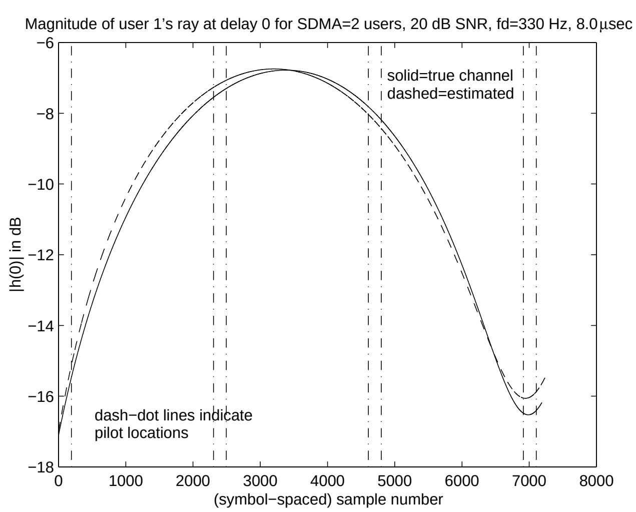

Figure 3. Estimated channel versus true channel

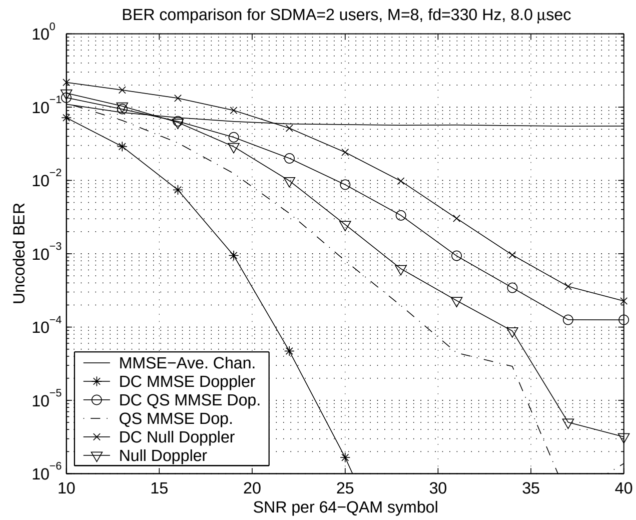

Figure 4. BER comparison for *M*=8 receive antennas

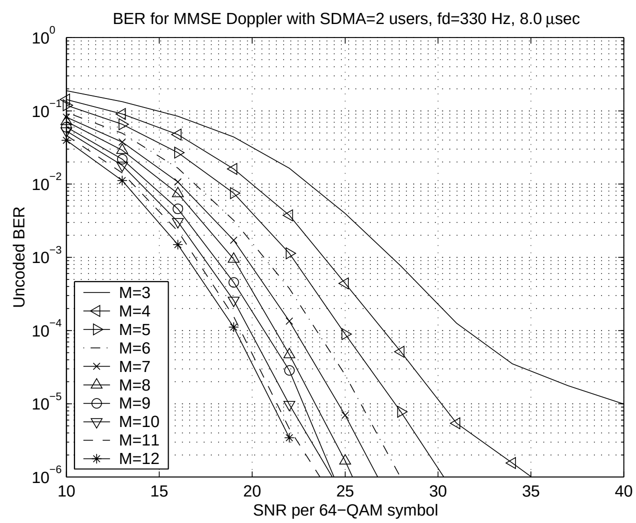

Figure 5. MMSE Doppler BER for varying *M*

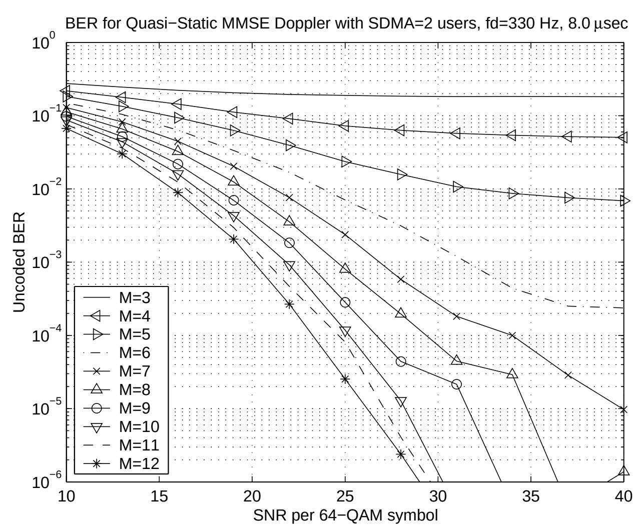

Figure 6. Quasi-Static MMSE Doppler BER for varying *M*