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# Wireless Communication Systems with Transmitter Diversity Signal Design for Rayleigh Fading Channels

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***Abstract***— In this paper, transmitter diversity wireless communication systems over Rayleigh fading channels using pilot symbol assisted modulation (PSAM) are studied. Unlike conventional transmitter diversity systems with PSAM that estimate the superimposed fading process, we are able to estimate each individual fading process corresponding to the multiple transmitters by using appropriately designed pilot symbol sequences. With such sequences, special coded modulation schemes can thenbe designed to access the diversity provided by the multiple transmitters without having to use an interleaver or expand the signal bandwidth. The notion of code matrix is introduced forthe coded modulation scheme, and its design criteria are also established. In addition to the reduction in receiver complexity, simulation results are compared to, and shown to be superior to, that of an intentional frequency offset system over a wide rangeof system parameters.

***Index Terms***— Channel coding, diversity methods, Rayleigh channels.

## I. INTRODUCTION

PROVIDING an architecture with diversity is importantfor maintaining high performance in wireless mobile communications. Diversity can be achieved by using multipleantennas, using interleaved coded modulation, resolving propagation paths in time or spatially, and using multicarrier trans-mission [1], [2]. Perhaps the most commonly used technique is interleaved coded modulation. The coding adds the redundancyto provide diversity and the interleaving separates the code symbols to (hopefully) provide independent fading distortionfor each of the code symbols. The problem with standard interleaved coded modulation is that a tradeoff must be madebetween decoding delay (a function of the interleaver depth)and demodulation performance. This is especially importantin applications where performance is decoding delay sensitive(e.g., voice transmission). For situations with small Dopplerspread (e.g., pedestrian or stopped vehicle), either a very long interleaver is needed to achieve quasi-independent distortion on code symbols or else interleaving is not effective.

An effective technique in wireless communications is trans-mission diversity. The advantage of transmission diversity is that by transmitting from multiple spatially separated antennas (e.g., a base station) diversity can be achieved without greatly increasing the complexity of the receiver (e.g., a portable unit).The simplest idea is to switch between the transmitters atdifferent time instants and allow only one transmitter to be on at a time. Because the transmitters are operated intermittently, their peak power is considerably higher than their average power, which complicates the design of their output amplifiers. Other transmission diversity techniques that do not switch off the transmitter are ones using an intentional time offset [3] or frequency offset [4], phase sweeping [5], frequency hopping [6], and modulation diversity [7]. Most of these techniquesuse phase or frequency modulation of each transmitter carrier to induce intentional time-varying fading at the receiver.[1] The advantage of these techniques is that the modulation level of the carrier and the interleaving depth can be chosen to achieve near ideal interleaving. In these applications, a shorter inter- leaver depth is usually only achieved with an expanded signal bandwidth. The focus of this paper is the exposition of a fairlysimple alternate system architecture which can provide the diversity inherent in multiple transmissions without requiring interleaving even with low mobility.

In this paper we consider linear modulation on frequency nonselective fading channels. Consequently, applications of this work are in modems using narrowband or multicarrier modulation. Decoding of error control codes in frequency non-selective fading channels requires an estimate of the channel state (or multiplicative distortion), and transmitted reference techniques usually provide the simplest method for channel state estimation. Common transmitted reference techniquesare tone-calibration techniques (TCT) [8] and pilot symbol assisted modulation (PSAM) [9]. PSAM is preferred in prac- tice because it typically provides a better peak to average transmitted power ratio without the need to redesign the modulation pulse. Both TCT and PSAM are amenable to a performance analysis for ideal interleaved coded modulation
[1] and for correlated fading [10]. In fact, the work in [11] designed and analyzed the performance of a system usinginterleaved coded modulation and frequency offset diversity

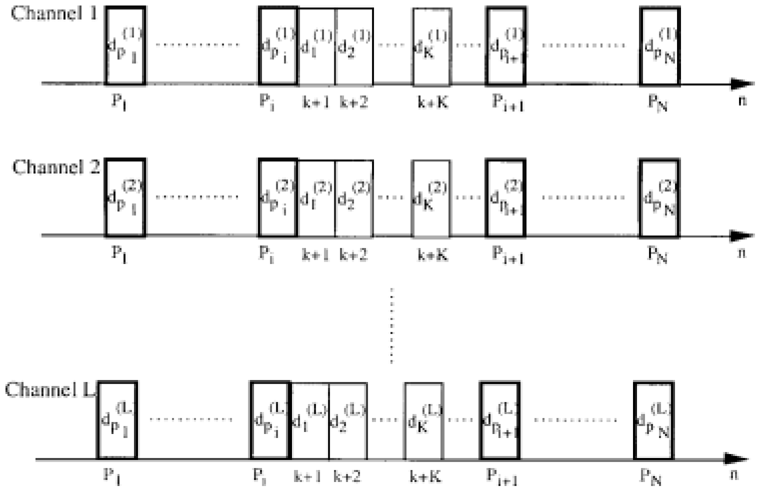

Fig. 1. The transmitted signals.

transmission using PSAM. At the time of our study [12],the system of [11] was the highest performing complete transmitter diversity system and will be used as a benchmark for comparison to our proposed system.

In this paper, we propose a new coded modulation scheme to access the diversity of a multiple transmitters system without having to use interleaving. This method is similar to the modulation diversity method proposed by [7], but does not require an equalizer for decoding. The relationship between the system's error performance and the design of the coded modulation scheme is also thoroughly examined from a more general point of view. Since the proposed coded modulation scheme requires the knowledge of the states on all channels, not just the single state of the superimposed process, pilot symbol sequences need to be appropriately designed. This important issue that has been missing in [7] will be addressed in a solid mathematical framework.

The rest of this paper is organized as follows. The next section formulates the problem and introduces the notation used throughout this paper. A receiver architecture is devel- oped and its error performance is analyzed in Section III. The information provided by this analysis is then used as design criteria in Sections IV and V, where code matrix and pilot symbol matrix designs are considered, respectively. In Section VI, an example is shown and compared to the result of an intentional frequency offset system. Section VII concludes.

## II. PROBLEM DESCRIPTION

In the sequel, bold lowercase italic denotes vectors, bolduppercase italic denotes matrices; , and $\boldsymbol{x}^H$ will denotethe complex conjugate, transpose, $\boldsymbol{x}^*$, $\boldsymbol{x}^T$ and Hermitian transpose ofrespectively; denotes the inner product between two vectors and denotes the determinant of $C$, and $I_K$ denotes an identity matrix of dimension $K$. $\boldsymbol{x}$, $\langle \boldsymbol{x}, \boldsymbol{y} \rangle$

Assuming that bits per baud are transmitted, a repre- sentation of the transmitted signals for a transmitter diversity system is given in Fig. 1 where each channel represents the signal on a different antenna. When a linearly modulated information bearing signal, $\sum_n$ , where $\boldsymbol{x}$, $\boldsymbol{y}$, $|C|$

$u(t)$ is the unit energy pulse shape and is the symbol time, is transmitted over a frequency nonselective, time-varying, isotropic scattering, Rayleigh fading channel, the signal at the receive end is modeled by $s(t) = d_n u(t - nT)$

$$y(t) = c(t)s(t) + n(t) \qquad (1)$$

where $c(t)$ is a zero mean complex Gaussian multiplicative distortion (MD) random process and $n(t)$ is a zero mean AWGN process with one-sided spectral density $N_0$. The processes $c(t)$ and $n(t)$ are assumed independent and the isotropic Rayleigh scattering assumption implies that $c(t)$ is a wide sense stationary random process with autocorrelation function [2]

$$R_c(\tau) \triangleq E[c(t)c^*(t-\tau)] = E_s J_0(2\pi f_D \tau) \qquad (2)$$

where $f_D$ is the Doppler spread of the channel, $E_s$ is the average energy per transmitted symbol, and is the Besselfunction of zeroth order. Using superscript to index the transmitter, the multiple transmitter case can be described as $J_0(\cdot)$ $(l)$

$$+ n(t)$$

$$\sum^{L} c^{(l)}(t)s^{(l)}(t)$$

$$y(t) - \qquad (3)$$

where $\{c^{(1)}(t), c^{(2)}(t), \cdots, c^{(L)}(t)\}$ are assumed i.i.d. with
an autocorrelation function given in (2). The assumption of independent multiplicative distortions for each antenna implies the antennas are separated appropriately. For indoor network topologies this separation can be a small number of wavelengths. For elevated outdoor antennas, greater care in placement of antennas is important [2].

By assuming the fading is slow enough to be roughly con- stant over the support of the pulse and that $u(t)$ is appropriately shaped so that intersymbol interference can be ignored, the matched filter outputs are approximate sufficient statistics and given as

$$x_k - \int_{-\infty}^{\infty} y(t)u^*(t-kT)\,dt \qquad - \sum_{l=1}^{L} d_k^{(l)} c_k^{(l)} + n_k \tag{4}$$

depth is about 57. Both
Fig. 5 for both $f_DT - 0$ and $f_DT - 0.01$ against $E_b/N_0$.
Optimal Wiener filter coefficients and the decoding algorithm derived in Section III are used for both fading rates. That is, we assume an adaptive system exists that can keep updating the channel statistics and control the filter coefficients when channel statistics change. Both union bound results derived in Section III-C and simulation results are shown. The number ofMonte Carlo simulations ranged from $10^{5}$ to $10^{6}$ depending on the error rate. Simulated Rayleigh fading is generated by the Jakes model [2]. Consequently, this figure demonstrates that the union bound is a very accurate performance estimator, and the remainder of the discussion will focus on the union bound analytical results.

The best performance occurred when the fading is station- ary. Since there is no variation in the channel states with time, the channel state estimation is very accurate, and thereforewe have lower error rates. As the fading rate increases, the channel state estimation becomes less accurate (due to a largerinterpolation filter bandwidth) and error rates get higher. The results of and are given. The former are shown in solid lines, while the latter are indicated by dashed lines.

The comparison between the herein proposed scheme andthe intentional frequency offset scheme analyzed in [11] demonstrates several interesting characteristics. Comparedto the intentional frequency offset method, our worst case $0.01)$ performance is approximately the same as its performance at stationary fading. The reason is as follows.For our method, since there are three channels that needto be estimated, the sampling period for each individualchannel is in effect instead of 7 as with theintentional $f_DT -$ frequency offset system. This is a critical value for $0.01$, and the channel state estimation is expected to be less accurate than that of the intentional frequency offset system. However, as discussed in Section V, the estimation errors of our method are nearly independent, whereas for the intentional frequency offset method, the estimation errors are highly correlated, especially when fading is slow, since the $3P_{ms} - 21$

$f_DT -$

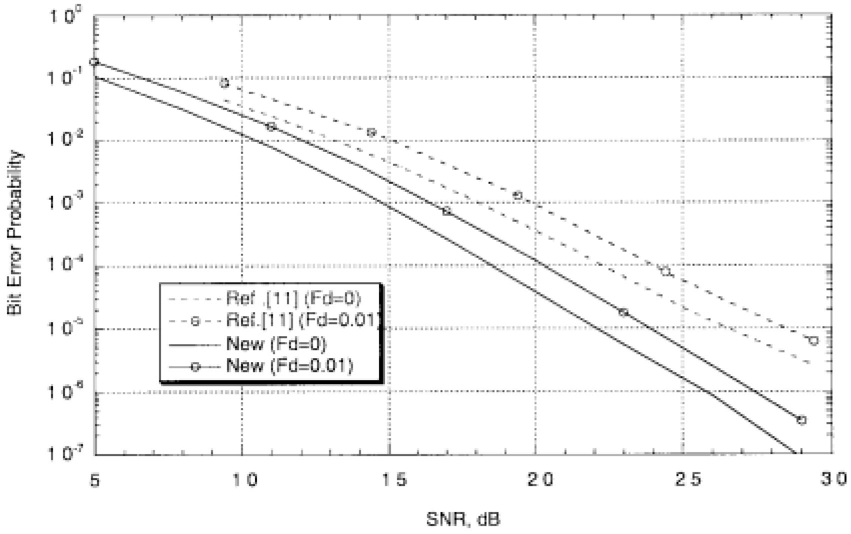

Fig. 6. Conditional BEP (only union bound results are shown) curves of the information block {1, 1, 1, 1} for the proposed scheme and the intentional frequency offset system.

pilot symbol observations are drawn from overlapped samples. This gives a little edge to our method and roughly cancels the degradation caused by the less accurate channel estimation.

One disadvantage of our scheme is, however, that it cannot operate at as high a Doppler spread as the frequency offset scheme, since the equivalent fading rate is times the fading rate of an individual channel. In an intentional frequency offset system, on the other hand, this equivalent fading rateis approximately the larger one of and

$f_D T$ $f_0 T$.

## III. CONCLUSION

We have considered transmitter diversity in wireless communication systems over Rayleigh fading channels using coded modulation with pilot symbol assisted channel state estimation. A new method of accessing diversity provided by multiple transmit antenna systems is proposed. Unlike the conventional phase-sweeping or frequency offset methods, the diversity is gained at the level of coded modulation instead of carrier phase or frequency, which most often will require some bandwidth expansion. Furthermore, this new method does not require an interleaver to separate symbols of a code to obtain independent fading effects or an equalizer. This significantly reduces the receiver complexity and avoids possible decoding delay.

Because of the special structure of the coded modulation scheme considered, the channel state estimator is required to estimate all individual channel states of the multiple trans- mitters, unlike the conventional methods where only a single channel is to be estimated. The design of such sequences is carefully studied, and their general constructions are de- rived. A detailed optimal receiver design and its performance analysis are also presented. Simulation results have shownthat our method is superior to the conventional intentional frequency offset system with similar normalized parameters. Improvement is even more significant when the simplification of our system is taken into account.

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