

Transmitter Diversity for OFDM Systems and Its Impact on High-Rate Data Wireless Networks

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Abstract—Transmitter diversity and down-link beamforming can be used in high-rate data wireless networks with orthogonal frequency division multiplexing (OFDM) for capacity improvement. In this paper, we compare the performance of delay, permutation and space-time coding transmitter diversity for high-rate packet data wireless networks using OFDM modulation. For these systems, relatively high block error rates, such as 10%, are acceptable assuming the use of effective automatic retransmission request (ARQ). As an alternative, we also consider using the same number of transmitter antennas for down-link beamforming as we consider for transmitter diversity. Our investigation indicates that delay transmitter diversity with quaternary phase-shift keying (QPSK) modulation and adaptive antenna arrays provides good quality of service (QoS) with low retransmission probability, while space-time coding transmitter diversity provides high peak data rates. Down-link beamforming together with adaptive antenna arrays, however, provides higher capacity than transmitter diversity for typical mobile environments.

Index Terms—High-rate wireless networks, interference suppression, orthogonal frequency division multiplexing (OFDM), parameter estimation, transmitter diversity.

I. INTRODUCTION

CELLULAR radio services have been extremely successful in providing untethered voice communications. Wireless data services, however, have captured only a limited market share so far. One obstacle for wireless data services is their limited capability in both technology and applications. A combination of wireless, computer and Internet technologies has been proposed to provide advanced cellular Internet service (ACIS) [1], [2] using a wide-area cellular network for ubiquitous information access. Existing wireless data rates, up to several tens of kbits/s, may be over one order of magnitude short of what is required to make popular applications user-friendly [3]. There are existing wireless Ethernet modems providing several Mbits/s or higher peak rates for local environments [4]. Peak transmission rates at several Mbits/s, however, have not generally been demonstrated in wide-area cellular networks due to significant path loss, delay spread, and fading, as well as limited spectrum availability. Transmitter diversity is a highly effective technique for combating fading in mobile wireless communications and improving the capacity of wireless networks. In this paper, we investigate the radio link performance of different transmitter diversity approaches

for orthogonal frequency division multiplexing (OFDM) systems providing high-rate data transmission and their impact on the capacity, packet delay, and retransmission probability of packets for wireless networks.

Many researchers have studied transmitter diversity for single-carrier wireless systems. As indicated in [5] and the references therein, transmitter diversity can be based on linear transforms. The performance gain and asymptotic properties of linear transform-based transmitter diversity have been investigated in [6] and [7].

Transmitter diversity combined with Reed–Solomon (R-S) codes has been studied for clustered OFDM systems in [8]. Space-time codes [9] can also be used to provide transmitter diversity for OFDM systems [10]–[12]. Channel state information is desirable at the receiver for decoding of space-time coding transmitter diversity. A channel parameter estimator [10], [11] can be used to provide the channel state information for the decoding of space-time codes.

Delay transmitter diversity is one of the linear transform-based diversity approaches [5] for single-carrier systems. It can also be used for OFDM systems in a modified form, where the delay is only a small fraction of an OFDM symbol. This causes the fading to become more randomized between OFDM tones than without the delay diversity. The required channel state information for coherent detection and maximal ratio combining can be obtained by a robust estimator [13]. Space-time coding transmitter diversity impairs the system's interference suppression ability because it generates multiple signals that appear independent to adaptive antenna arrays. Hence, adaptive antenna arrays [14], [15] are more effective for cochannel interference suppression for delay diversity than for space-time coding transmitter diversity.

Permutation transmitter diversity, initially proposed for single-carrier systems [16], [17], can also be used for OFDM systems. A channel parameter estimator designed for space-time coding transmitter diversity [10], [11] can be applied to provide the desirable channel state information for permutation transmitter diversity.

In this paper, we first compare the radio link performance of the three transmitter diversity approaches we have discussed. Then we study the impact of transmitter diversity on the capacity of high-rate data wireless networks, the transmission delay of packets, and the retransmission probability of data blocks.

The rest of this paper is organized as follows. In Section II, we briefly describe three transmitter diversity approaches for OFDM systems. In Section III, we study the radio link

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performance of these different approaches through extensive computer simulations. Finally in Section IV, we investigate the impact of these transmitter diversity techniques on high-rate data wireless networks using a simulation of a wireless network with many base stations and terminals communicating packet data.

II. TRANSMITTER DIVERSITY

In this section, we introduce three transmitter diversity approaches: delay, permutation, and space-time coding approaches.

A. Delay Approach

Fig. 1(a) shows an OFDM system with delay transmitter diversity. The signal from the second transmitter antenna is a delayed version of the signal from the first transmitter antenna. Hence, if multiple receiver antennas are used in the system, the received signal at the i th antenna is

$$\begin{aligned} r_i[n, k] &= \frac{1}{\sqrt{2}} (H_{1i}[n, k] + H_{2i}[n, k]e^{-j2\pi k\Delta f T}) \\ &\quad \cdot t[n, k] + w_i[n, k] \\ &= H_i[n, k]t[n, k] + w_i[n, k]. \end{aligned} \quad (1)$$

In the above expression, T is a delay which should be no less than $1/K\Delta f$ to generate sufficient fading decorrelation among different tones, where Δf and K are the tone spacing and total number of tones of the OFDM system, respectively. $w_i[n, k]$ in (2) is additive Gaussian noise from the i th antenna at the k th tone of the n th block, which has zero-mean and variance σ_n^2 .

$H_{ji}[n, k]$ in the above expressions is the frequency response for the k th tone of the n th OFDM block corresponding to the j th transmitter and the i -receiver antenna, which are assumed to be independent for different i 's or j 's. $H_i[n, k]$ is the compound frequency response defined as

$$H_i[n, k] \triangleq \frac{1}{\sqrt{2}} (H_{1i}[n, k] + H_{2i}[n, k]e^{-j2\pi k\Delta f T}). \quad (2)$$

Direct calculation yields that the frequency-domain correlation of $H_i[n, k]$ at any time n will be

$$\begin{aligned} \tilde{r}_f[m] &\triangleq E\{H_i[n, k+m]H_i^*[n, k]\} \\ &= r_f[m] \frac{1 + e^{-j2\pi m\Delta f T}}{2} \end{aligned} \quad (3)$$

where $r_f[m]$ is the frequency-domain correlation of $H_{ji}[n, k]$ defined as

$$r_f[m] \triangleq E\{H_{ji}[n, k+m]H_{ji}^*[n, k]\}. \quad (4)$$

Since $|1 + e^{-j2\pi m\Delta f T}/2| \leq 1$

$$\tilde{r}_f[m] \leq r_f[m] \quad (5)$$

which implies that the $H_i[n, k]$'s for different k are more diverse than $H_{ji}[n, k]$. The R-S code across the tones of each OFDM block make use of the diversity to improve the system performance. As demonstrated by the simulation results in the

next section, this transmitter diversity approach is especially useful for channels with flat or small delay spread.

From (2), the received signal at each antenna $r_i[n, k]$ can be regarded as the transmitted signal $t[n, k]$ passed through a fading channel $H_i[n, k]$. Hence, both a robust channel estimator [13] and adaptive antenna arrays [14], [15] can be used here for minimum mean-square-error diversity combining (MMSE-DC) and coherent detection.

B. Permutation Approach

Permutation transmitter diversity for an OFDM system is shown in Fig. 1(b). The modulated signal and its permutation are transmitted through two transmitter antennas. Hence, the received signal from the i th antenna at the k th tone of the n th block is

$$r_i[n, k] = H_{1i}[n, k]t[n, k] + H_{2i}[n, k]t_1[n, k] + w_i[n, k] \quad (6)$$

where

$$\begin{pmatrix} t_1[n, 1] \\ t_1[n, 2] \\ \vdots \\ t_1[n, K] \end{pmatrix} = \mathbf{P} \begin{pmatrix} t[n, 1] \\ t[n, 2] \\ \vdots \\ t[n, K] \end{pmatrix} \quad (7)$$

and $\mathbf{P}$ is a permutation matrix. To simplify the receiver, we chose

$$\mathbf{P} = \begin{pmatrix} \mathbf{0} & \mathbf{I} \\ \mathbf{I} & \mathbf{0} \end{pmatrix} \quad (8)$$

where $\mathbf{I}$ is a $K/2 \times K/2$ identity matrix and $\mathbf{0}$ is a $K/2 \times K/2$ matrix with all zero elements. Hence

$$t_1[n, k] = \begin{cases} t[n, k + K/2], & \text{if } 1 \leq k \leq K/2, \\ t[n, k - K/2], & \text{if } K/2 + 1 \leq k \leq K. \end{cases} \quad (9)$$

Using (6) and (9), we have

$$\mathbf{r}[n, k] = \mathbf{H}[n, k]\mathbf{t}[n, k] + \mathbf{w}[n, k] \quad (10)$$

for $1 \leq k \leq K/2$, where

$$\begin{aligned} \mathbf{r}[n, k] &\triangleq \begin{pmatrix} r_1[n, k] \\ r_2[n, k] \\ r_1[n, k + K/2] \\ r_2[n, k + K/2] \end{pmatrix} \\ \mathbf{t}[n, k] &\triangleq \begin{pmatrix} t[n, k] \\ t[n, k + K/2] \end{pmatrix} \\ \mathbf{w}[n, k] &\triangleq \begin{pmatrix} w_1[n, k] \\ w_2[n, k] \\ w_1[n, k + K/2] \\ w_2[n, k + K/2] \end{pmatrix} \end{aligned}$$

and

$$\mathbf{H}[n, k] \triangleq \begin{pmatrix} H_{11}[n, k] & H_{21}[n, k] \\ H_{12}[n, k] & H_{22}[n, k] \\ H_{21}[n, k + K/2] & H_{11}[n, k + K/2] \\ H_{22}[n, k + K/2] & H_{12}[n, k + K/2] \end{pmatrix}.$$

From (10), the system can be regarded as a two-user system with four receiver antennas.

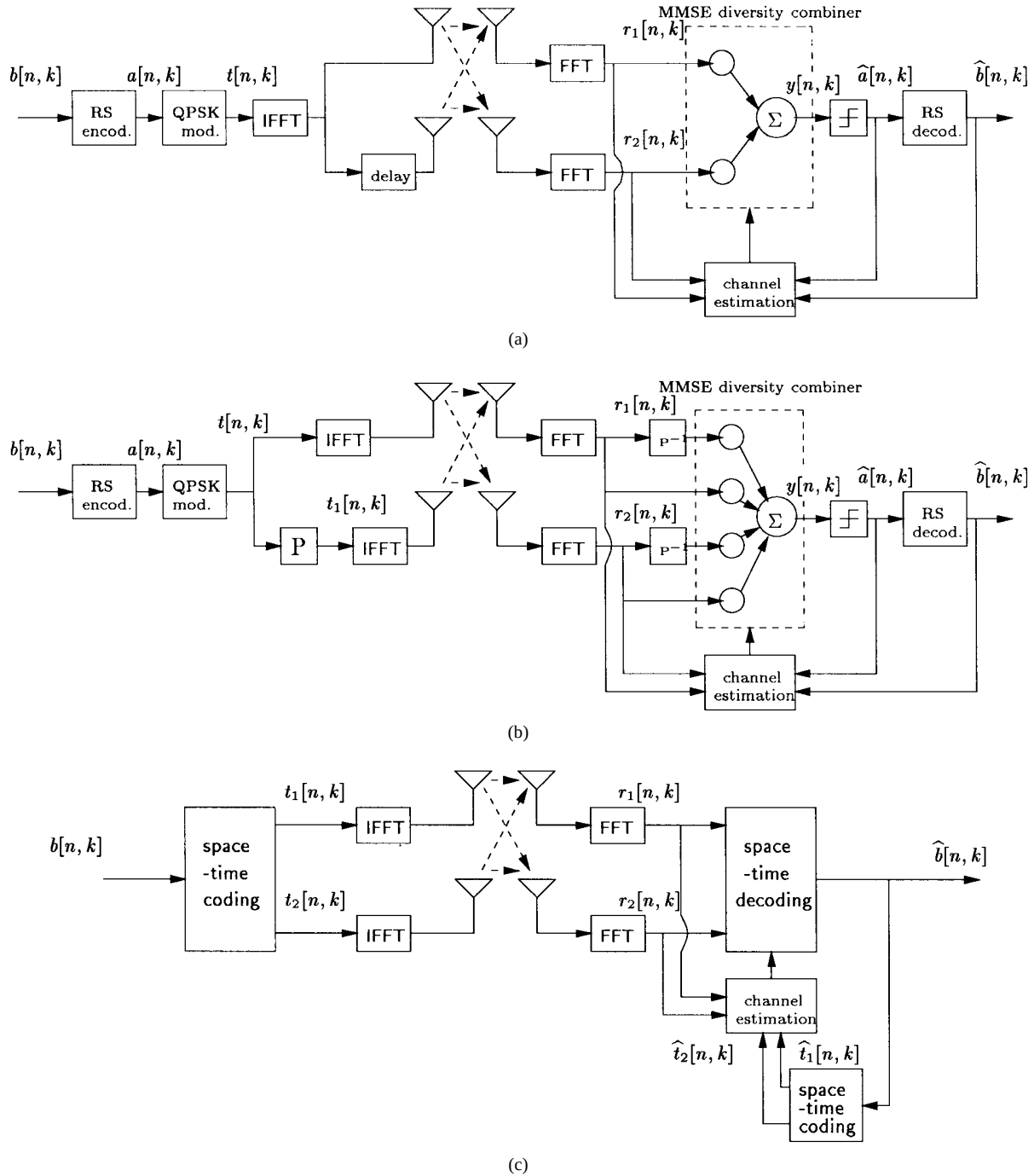


Fig. 1. Three different transmitter diversity approaches. (a) Delay transmitter diversity, (b) permutation transmitter diversity, and (c) space-time coding transmitter diversity.

An MMSE combiner is used at the receiver to recover the transmitted signal. To obtain the parameters required by the MMSE combiner, the channel estimator developed in [10] and [11] can be used. With the estimated parameters, the transmitted signal $\hat{t}[n, k]$ can be estimated by

$$\hat{t}[n, k] = C^\dagger[n, k]r[n, k] \quad (11)$$

where

$$C \triangleq \left(H[n, k]H^\dagger[n, k] + \rho^{-1}I \right)^{-1} H[n, k] \quad (12)$$

ρ denotes the signal-to-noise ratio (SNR) of the system, and † denotes the matrix Hermitian.

If the MMSE combiner is used for diversity reception in the system without error correction coding, then the system is equivalent to a single user system with three receiver antennas when the channel delay spread is so large that $H_{ij}[n, k]$ and $H_{ij}[n, k + K/2]$ are independent for all $i, j = 1, 2$ [18]. For a system with coding, however, the performance of permutation transmitter diversity may not be as good as delay transmitter diversity.

C. Space-Time Coding Approach

An OFDM system with transmitter diversity using space-time coding [10], [11] is shown in Fig. 1(c). At each time n , a binary data block $\{b[n, k]: k = 1, 2, \dots\}$ is encoded into two different signals, $\{t_i[n, k]: k = 1, 2, \dots, K\}$ for $i = 1, 2$. Each of these signals forms an OFDM block. The two transmitter antennas simultaneously transmit the OFDM signals modulated by $t_1[n, k]$ and $t_2[n, k]$, respectively. Hence, the signal at each receiver antenna is the superposition of two transmitted signals, which can be expressed as

$$r_i[n, k] = H_{1i}[n, k]t_1[n, k] + H_{2i}[n, k]t_2[n, k] + w_i[n, k]. \quad (13)$$

The decoding of space-time codes [9] uses the Viterbi decoding algorithm with the metrics

$$\|\mathbf{r}[n, k] - \hat{\mathbf{H}}[n, k]\hat{\mathbf{t}}[n, k]\|^2 \quad (14)$$

where $\|\cdot\|$ denotes the Euclidean norm; $\mathbf{r}[n, k]$, $\hat{\mathbf{H}}[n, k]$, and $\hat{\mathbf{t}}[n, k]$ are defined as

$$\mathbf{r}[n, k] \triangleq \begin{pmatrix} r_1[n, k] \\ r_2[n, k] \end{pmatrix}$$

$$\hat{\mathbf{H}}[n, k] \triangleq \begin{pmatrix} \hat{H}_{11}[n, k] & \hat{H}_{21}[n, k] \\ \hat{H}_{12}[n, k] & \hat{H}_{22}[n, k] \end{pmatrix}$$

and

$$\hat{\mathbf{t}}[n, k] \triangleq \begin{pmatrix} \hat{t}_1[n, k] \\ \hat{t}_2[n, k] \end{pmatrix}$$

respectively.

The channel parameters required by the decoding can be obtained by using the estimator proposed in [10] and [11]. The estimator also exploits the correlations of channel parameters at times and frequencies that are close to each other to improve performance. Compared with the estimators in [13]–[15], this estimator requires a $2K_o \times 2K_o$ matrix inversion and more fast Fourier transforms (FFT's) and IFFT's. Consequently, heavier computational complexity is required for the parameter estimator. Furthermore, it is more sensitive to delay leakage [10], [11].

As indicated in [10] and [11], for OFDM systems with space-time coding transmitter diversity, each cochannel interference source will produce two interference signals. Hence, this transmitter diversity approach will reduce a system's cochannel interference suppression ability. The space-time codes, however, are highly efficient. Transmitter diversity based on these codes can transmit higher data rates than the delay or permutation approaches described in Section II-A and II-B.

In summary, compared with the previous two approaches, the space-time coding approach supports higher data transmission rates; however, it requires a more complicated parameter estimator and decoder, and it reduces a system's interference suppression ability. But for slow fading environments, the complexity of the estimator for space-time coding could be significantly reduced by removing tracking.

TABLE I
THE AVERAGE POWER AND DELAY OF EACH PATH FOR THE TU CHANNEL

path number		1	2	3	4	5	6
TU channel	delay in (μsec)	0.0	0.2	0.5	1.6	2.3	5.0
	average power	0.1897	0.3785	0.2388	0.0951	0.0600	0.0379

TABLE II
MODULATION AND CODING FOR THE DELAYED TRANSMITTER DIVERSITY

parameter set	I	II	III
modulation	QPSK	8-PSK	16-QAM
RS code	parameters (40,20)	(60,40)	(60,45)
	field GF(2 ⁶)	GF(2 ⁶)	GF(2 ⁸)
RS code	symbols erased 10	10	5
decoder	errors corrected 5	5	5
data rate (Mbits/sec)	0.6	1.2	1.8

III. RADIO LINK PERFORMANCE

We show the radio link performance of delay and permutation transmitter diversity and compare it with space-time coding transmitter diversity. First, we briefly describe the parameters of the simulated OFDM system.

A. System Parameters

In our simulation, we use the two-ray (TR) and typical-urban (TU) channel models [10], [11], [19], respectively. For the TR channel model, each ray has the same average power, and the delay between the two rays is determined by the delay spread, which is assumed to be equal to that of the TU channels. The delay profile of the TU channel is shown in Table I. Each ray in the TR and TU profiles is characterized by Jakes' fading spectrum. We assume that the channels corresponding to different transmitters or receivers for both the interferer and the desired signals are independent, but have the same statistics. The level of additive channel noise is determined by the average SNR, which is defined as

$$\text{SNR} = \frac{E\{|H_{1i}[n, k]|^2 + |H_{2i}[n, k]|^2\}}{\sigma_n^2} \quad (15)$$

where $E\{\cdot\}$ denotes the ensemble average.

The system has two receiver antennas and one or two transmitter antennas, unless otherwise specified. To construct an OFDM signal, assume a channel bandwidth of 800 kHz is divided into 128 subchannels. The four subchannels on each end are used as guard tones, and the rest (120 tones) are used to transmit data. To make the tones orthogonal to each other, the symbol duration is 160 μs . An additional 40 μs guard interval, which is longer than the channel delay span, is used to provide protection from intersymbol interference due to the multipath delay spread of wireless channels. This results in a total block length $T_f = 200 \mu\text{s}$ and a subchannel symbol rate $r_b = 5$ kbaud.

As shown in Table II, for the system with delay transmitter diversity, three sets of different modulations and R-S codes are used to study the performance of the system under different data transmission rates. In all cases, each OFDM block forms an R-S code word. The first set has the same modulation and code as those in [13]–[15].

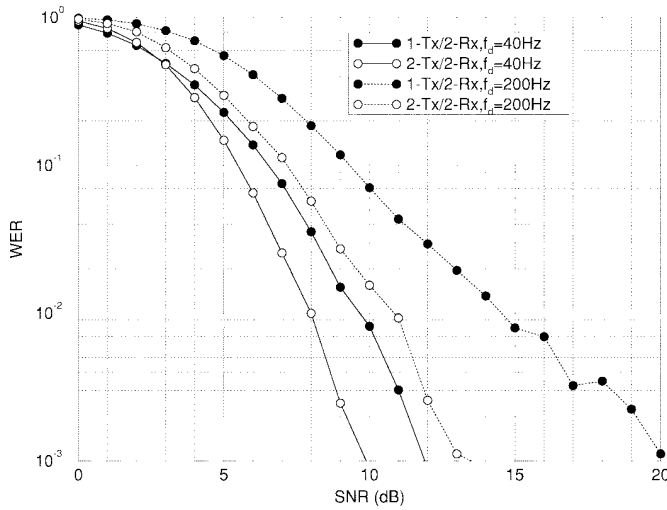


Fig. 2. Performance comparison for a system with and without the delay diversity for the TU channel.

The permutation transmitter diversity described in Section II-B is used in the simulation. The same parameters of coding and modulation as the first set in Table II are used for the permutation diversity.

The system with transmitter diversity using space-time codes has the same code and modulation as those in [10] and [11]. A 16-state space-time code with quaternary phase-shift keying (QPSK) is used in the system. Each data block, containing 236 bits, is coded into two different blocks, each of which has exactly 120 symbols to form an OFDM block. Hence, the described system transmits data at a rate of 1.18 Mbits/s over an 800 kHz channel.

In our simulation, each packet consists of ten OFDM blocks. The first OFDM block of each packet is a synchronization block, which is used for time and frequency synchronization as well as initial channel estimation. To gain insights into the average behavior of OFDM systems with different transmitter diversity approaches, we have averaged the performance over 10 000 OFDM blocks, or 1000 packets.

B. Performance

Figs. 2 and 3 demonstrate the performance of delay transmitter diversity for OFDM systems. Fig. 2 compares the word-error rate (WER) of OFDM systems with and without delay transmitter diversity for the TU channels without cochannel interference when the robust channel estimator [13] is used for coherent detection and maximal ratio diversity combining (MC-DC). From the figure, compared to a conventional single transmitter case, the use of delay transmitter diversity reduces the required SNR for a 10% WER by 1.2 dB when $f_d = 40$ Hz, and by about 2 dB when $f_d = 200$ Hz.

Fig. 3 shows the WER contours of a system with delay transmitter diversity using the MMSE-DC [14], [15] for the TU channel with $f_d = 40$ Hz. From Fig. 3(a), for system with QPSK modulation and a (40, 20) R-S code, the required SNR and signal-to-interference ratio (SIR) for a 10% WER are 20 and 2.8 dB, respectively, or 5.6 and 20 dB, respectively. Hence, the performance of the delay transmitter diversity

system is improved by using adaptive antenna approaches for cochannel interference suppression. Fig. 3(b) and (c) shows the WER contours for a system with 8-PSK and a (60, 40) R-S code and 16-QAM and a (60, 45) R-S code, respectively. From Fig. 3(b), for the system with 8-PSK modulation and a (60, 40) RS code, the required SNR and SIR for a 10% WER are 30 and 11 dB, respectively, or 12.5 and 30 dB, respectively, which shows that adaptive antenna arrays can improve the system's noise-plus-interference performance by about 1.5 dB. For an OFDM system with 16-QAM, however, the estimation error of instantaneous correlation [14], [15] results in adaptive antenna array performance that shows no interference suppression ability, as shown by Fig. 3(c).

Fig. 4 compares the performance of delay and permutation transmitter diversity approaches for systems with and without error correction codes. Fig. 4(a) shows the bit error rates (BER's) for systems without error-correction codes. It demonstrates that for the TR channel, the system without transmitter diversity and with delay transmitter diversity has the same BER, while the system with permutation transmitter diversity has better BER performance. Since a delay approach only creates frequency ripples, there is no performance improvement for the system without error-correction codes. On the other hand, as indicated in [18], permutation transmitter diversity averages the frequency ripples caused by multipath; therefore, it has better BER performance. For a system with delay transmitter diversity and an R-S code, however, if the decoder at the receiver erases those tones with small energy and corrects errors for the remaining tones, then the performance of the system can be improved and it is about equal to the performance of the permutation case, as shown in Fig. 4(b) for the TR channel.

Fig. 5 compares the performance of the delay and space-time coding transmitter diversity approaches for a system with the same data transmission rate. From the figure, for a system with two transmitter and two receiver antennas, the required SNR's for a 10% WER are 12.7 and 9 dB, respectively. Even though adaptive antenna arrays can be used for a delay transmitter diversity system to provide about 1.5-dB improvement for systems with cochannel interference, space-time coding transmitter diversity still has better performance than delay transmitter diversity. The parameter estimator and decoder for delay transmitter diversity, however, are less complicated than for space-time coding transmitter diversity. Fig. 5 also shows WER versus SNR for delay and space-time coding transmitter diversity approaches when there is only one receiver antenna. From the figure, it is clear that delay transmitter diversity is not as good as space-time coding transmitter diversity for lower SNR's. It is better, however, for higher SNR's. Also, the performance of delay transmitter diversity can be improved with convolutional coding, and the performance of space-time coding transmitter diversity can be improved by stronger codes.

IV. IMPACT ON HIGH RATE DATA NETWORKS

In this section, the radio link results obtained earlier are used in large scale wireless system simulations to determine

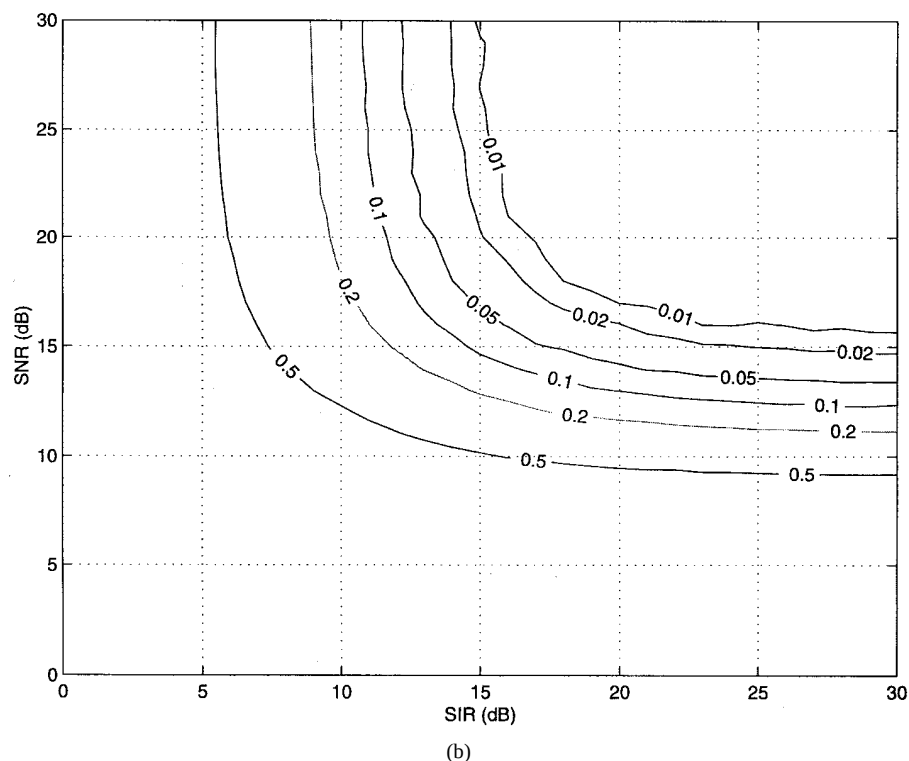
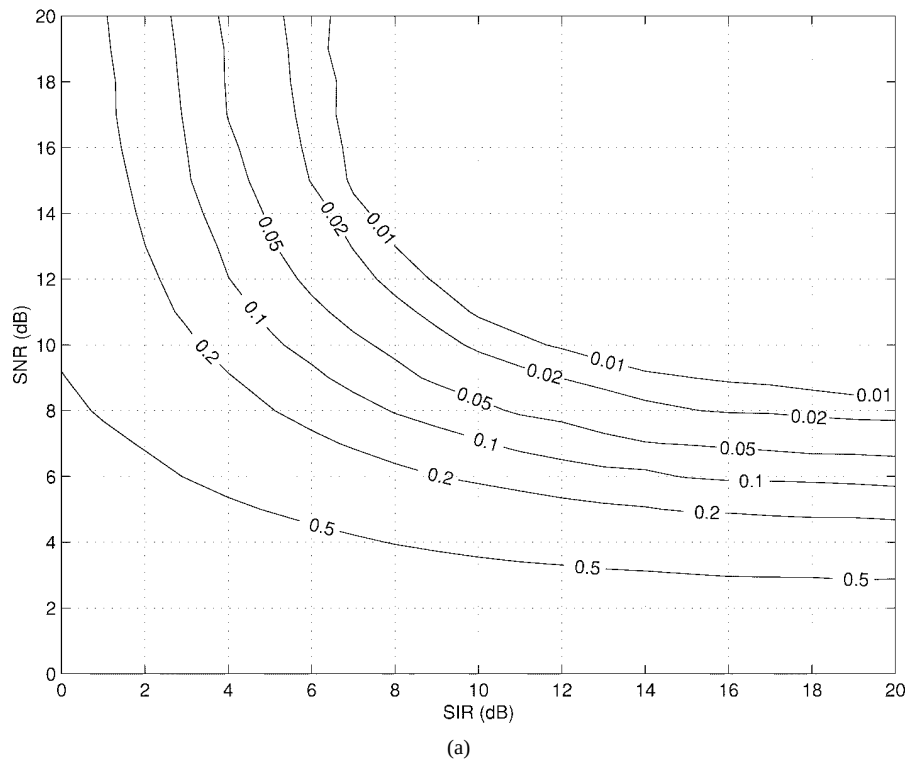


Fig. 3. WER contours of delay transmitter diversity with 2-Rx for systems with (a) QPSK and (b) 8-PSK, respectively, and for a typical urban channel with $f_d = 40$ Hz and with cochannel interference.

the impact of different transmitter diversity techniques on wireless network capacity as well as packet transmission delay and retransmission probability for the downlink. A traffic model based on measurements of World Wide Web traffic is used for these simulations. A medium access control (MAC) protocol based on dynamic packet assignment (DPA)

[2], which reuses the same radio resource in every base station, is used to obtain high spectrum efficiency. The DPA protocol enables dynamic slot assignment for user packets by using interference avoidance. Interference avoidance is achieved by 1) designating a subset of OFDM subcarriers as “pilots” to indicate slots being used and 2) using a time

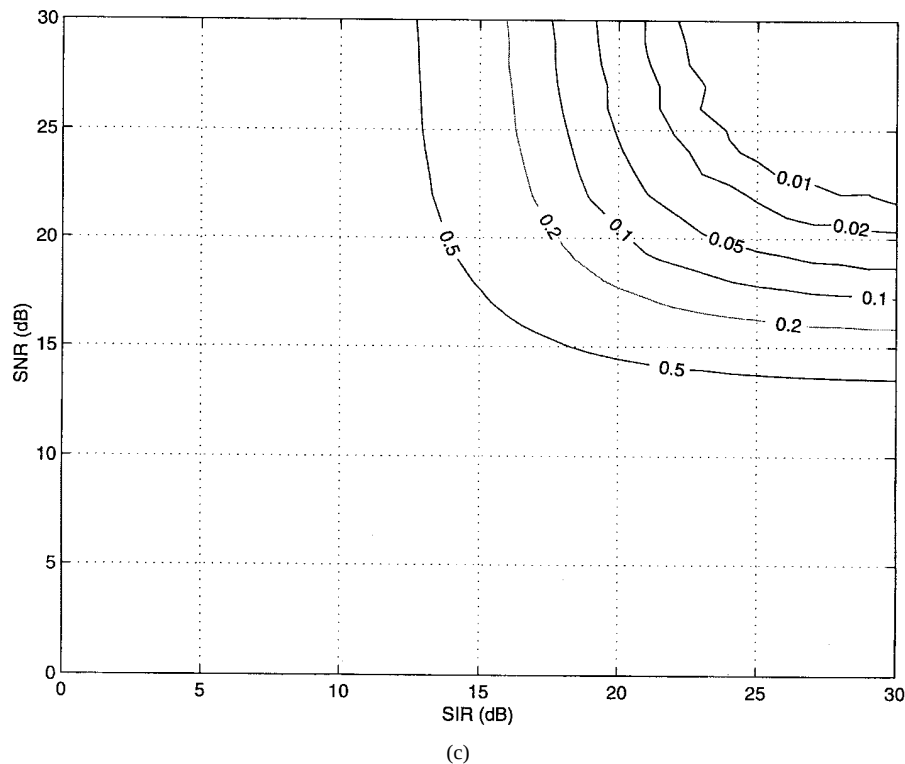


Fig. 3. (Continued.) WER contours of delay transmitter diversity with 2-Rx for systems with (c) 16-QAM modulation and for a typical urban channel with $f_d = 40$ Hz and with cochannel interference.

division multiple access (TDMA) frame structure described in [2] to schedule paging by base stations and measurements and feedback by mobiles at different cell sites to avoid intercell contention. The DPA protocol requires base station synchronization and additional TDMA overhead. While this increases system complexity, it also permits a significant increase in the overall spectrum efficiency.

For the system described in Section III-A, assuming 80% of the information is used to carry traffic while the remaining 20% is used to facilitate control functions for dynamic packet assignment, this air interface can support 480 kbits/s after decoding. Furthermore, if a 10% overhead is used for synchronization and channel estimation as indicated in the previous section, and an additional 10% is used for guard time to separate adjacent traffic slots in the frame structure described in [2], then the usable traffic rate per carrier is 384 kbits/s for QPSK signaling. For systems that adapt to a second set of modulation and coding parameters, however, the peak traffic rate is 768 kbits/s per RF carrier. Since transmitter diversity based on space-time (ST) coding gives approximately twice the bit rate compared to that based on the delay diversity (DD) for QPSK, it is instructive to compare the DD with 8PSK and ST with QPSK, both providing 768 kbits/s per carrier.

A. Simulation Model

To characterize the DPA performance, a system of 36 base stations arranged in a hexagonal pattern is assumed, each having three sectors using idealized antennas with 120° beamwidths and a 20-dB front-to-back ratio. The mobile antennas are assumed to be omni-directional. In each sector,

one radio provides eight traffic slots to deliver downlink traffic packets. The same channel can be used in different sectors of the same base station as long as the SIR at the DPA admission process exceeds 10 dB. Four neighboring base stations in each reuse area take turns to perform the DPA procedure, and the assignment cycle is reused in a fixed pattern [2]. Since a wrap-around algorithm for the base station locations is included to remove the boundary effect, the results obtained are insensitive to edge effects in the system and represent the case of a large frequency reuse system.

The cochannel interference limited case is considered, that is, noise is ignored in the simulation. In the propagation model, the average received power decreases with distance d as d^{-4} , and the large-scale shadow-fading distribution is log-normal with a standard deviation of 10 dB. Rayleigh fading is ignored in the channel assignment, which approximates the case where antenna diversity is employed and sufficient averaging in both time and frequency domains is achieved in signal and interference estimations.

Uniformly distributed mobiles receive packets, which are generated from the network and arrive at different base stations. Mobiles are assumed to be stationary during simulated sessions.¹ Therefore, handovers are not simulated. Since channels are reassigned every four frames (as discussed below), the channel reassignment during handover can be performed through reassignment at the new base station. A handover

¹We employed more conservative $f_d = 40$ Hz WER curves for the link performance. Stationary users can achieve better performance due to better channel estimation and tracking.

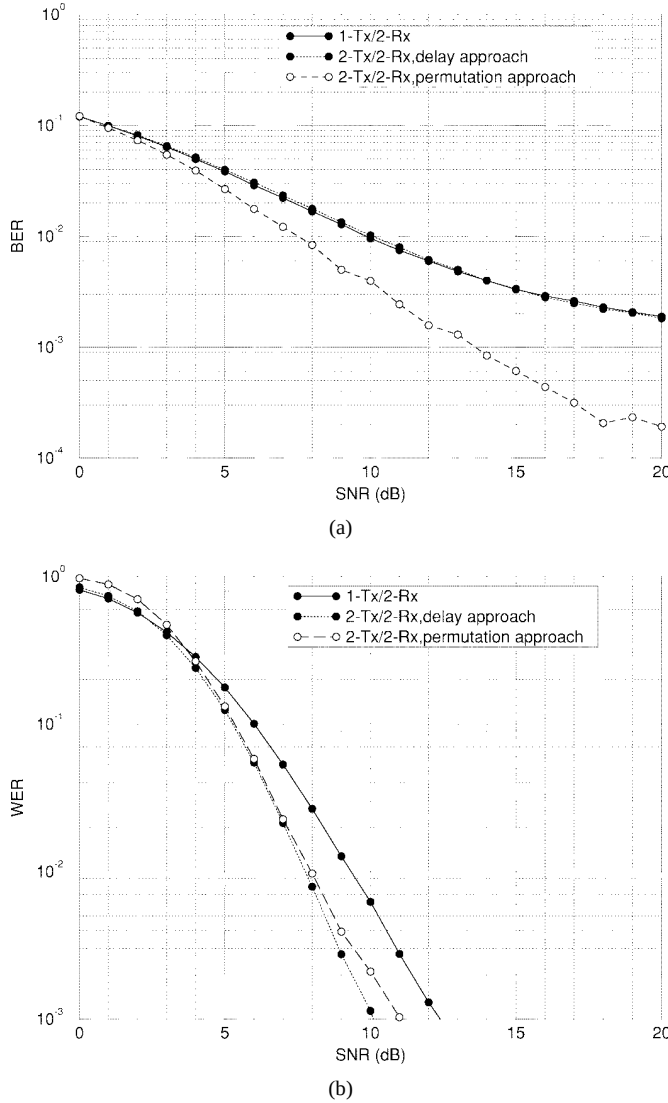


Fig. 4. Comparison of the delay and permutation transmitter diversities for the two-ray channel with $f_d = 40$ Hz: (a) BER for system without coding and (b) WER for system with RS code.

margin similar to what is used for voice services can be applied to select the new base station.

A data-service traffic model, described in [2], based on wide-area network traffic statistics [20] which exhibit a self-similar property when aggregating multiple sources [21], was used to generate packets. The same radio server (a time slot in a given radio) is statistically multiplexed to deliver packets for different mobiles. Mobiles are allocated as many radio channels as possible so long as they are available and meet the SIR requirement. When the number of pending packets exceeds the number of channels assigned, they are queued for later delivery. The assigned channels are reserved for the same mobile until all packets are delivered or the DPA process reassigns radio channels in the next superframe. A superframe consists of four frames, each of which consists of eight traffic slots and two control slots. Four neighboring base stations take turns performing DPA in each of the four frames in a superframe. A detailed description is shown in

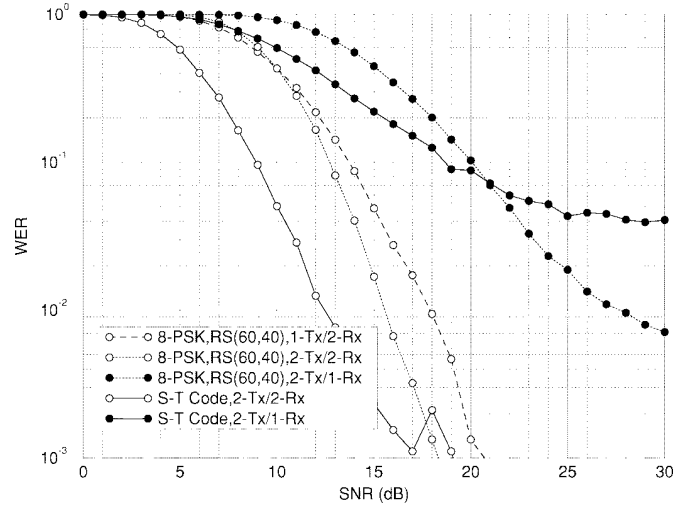


Fig. 5. Performance comparison of delayed and space-time coding transmitter diversities for the TU channel model with $f_d = 40$ Hz and without cochannel interference.

[2]. No downlink collisions occur in the same cell since the base station schedules packet delivery for all of its mobiles. A selective repeat automatic retransmission request (ARQ) protocol is employed, assuming ideal feedback, to request base stations for retransmission when a packet (word) is received in error. This is simulated based on the WER curves obtained in the previous section for the TU channel and $f_d = 40$ Hz with different diversity schemes. If a packet cannot be successfully delivered in 3 s, which may be the result of traffic overload or excessive interference, it is dropped from the queue.² Table III summarizes the simulation parameters for the numerical results. The control messages are assumed to be error free in the designated control slots.

We consider two radio-link enhancement techniques to study DPA performance: 1) beamforming and 2) interference suppression. For beamforming, each 120° -sector is divided into four 30° beams (with the same 20-dB front-to-back ratio and idealized antenna pattern) or two 60° beams. We assume that a packet is delivered using the beam that covers the desired mobile station. To simulate interference suppression, we find the strongest interferer and combine the remaining interference and then treat these two components as the cochannel interference and noise components, respectively, in the link simulation model (MMSE adaptive antenna arrays described in Section III).

B. Performance Results

In the following, downlink performance is studied by large-scale computer simulations. The uplink protocol and performance are currently under investigation. Only the downlink simulation results are shown here since the downlink transmission information bandwidth demands in popular applications (such as Web browsing) is higher. Although the uplink

²In practice, this condition should be modified based on the service requirements. We included this to bound the simulation buffer size. In the active region of our performance comparison, the number of packets dropped is negligibly small.

TABLE III
SIMULATION PARAMETERS

PARAMETERS		NOMINAL VALUES
# base stations		36
# sectors/base		3
# radios/sector		1
# traffic slots/frame		8
# frequencies		1
antenna front to back ratio		20 dB
SIR threshold for admission / power control		10 dB
frame duration		20 msec
control overhead per frame		4 msec
allowable delay per packet		3 sec
traffic model (as described in [2])	session arrival	Poisson
	session duration	Pareto
	intra-session burst ON/OFF duration	Pareto
	intra-burst data-rate	constant, once per frame
	path loss	40 dB/decade
shadow fading standard deviation		10 dB

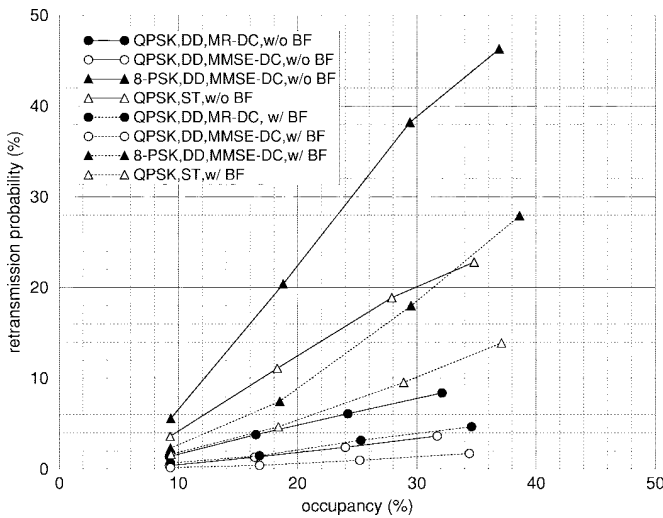


Fig. 6. Average retransmission probability as a function of occupancy for systems with 2-Tx/2-Rx and without beamforming and with four beams per sector.

efficiency could be reduced by random access collisions, the downlink spectrum efficiency is the crucial factor in determining the spectrum requirement for early deployment.

Fig. 6 shows the overall average probability of packet retransmission as a function of occupancy, defined as the percentage of traffic slots used, with and without beamforming. Clearly, QPSK modulation with interference suppression is the most robust and provides the best quality of service (QoS) with a lower retransmission probability. Space-time coding results in a higher retransmission probability because 1) no interference suppression is performed and 2) it attempts to deliver twice the information with two transmit antennas and with the same power limitation as QPSK modulation. On the other hand, the delay versus throughput curves in Fig. 7 clearly indicate that the higher peak-rates provided by ST-QPSK and DD-8PSK result in better throughput performance. In all cases, DPA algorithms and different diversity schemes enable a spectrally efficient air interface. In particular, interference suppression and delay diversity with 8PSK appears to be a low-complexity option for high-throughput services, but

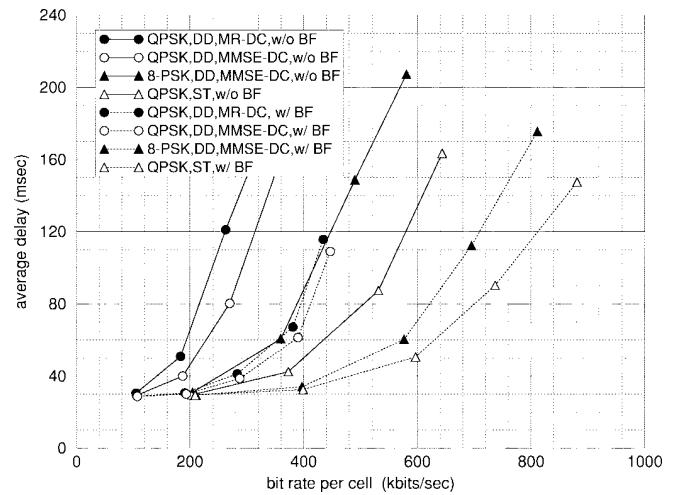


Fig. 7. Average delay of the delivered packets as a function of the throughput per base station for systems with 2-Tx/2-Rx and without beamforming and with four beams per sector.

space-time coding provides the highest throughput. If QoS is of higher importance, interference suppression and delay diversity with QPSK appears to be desirable.

It is also clear that downlink beamforming is an effective method for increasing both QoS and throughput. Since beamforming also requires multiple transmit antennas, a tradeoff study between beamforming and transmit antenna diversity is of interest. To do this, we first examine the performance achieved by 8PSK using a single transmit antenna (but no beamforming) in Fig. 8. Comparing the performance of the single transmitter antenna case with the case of DD, a single transmit antenna with 8PSK performs only slightly worse, if interference suppression is employed.

Based on this observation and the effectiveness of beamforming observed previously, a good choice is to use multiple transmit antennas for beamforming³ instead of delay diversity. Also note that for the case of two beams transmit power can be boosted by 3 dB against noise by using only one

³Here we assume beamforming can be achieved by using multiple narrow-beam antennas. Alternatively, adaptive antenna arrays can be used. In both cases, more transmit antennas must be used.

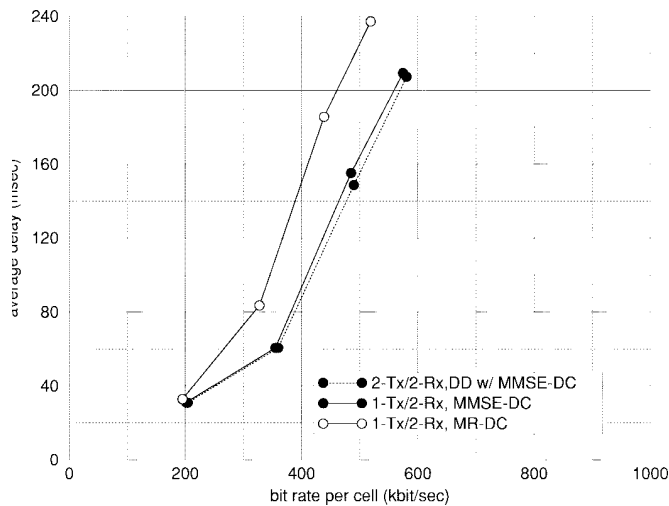


Fig. 8. Comparison of delay versus throughput with and without multiple transmit antennas for a system using 8PSK without beamforming.

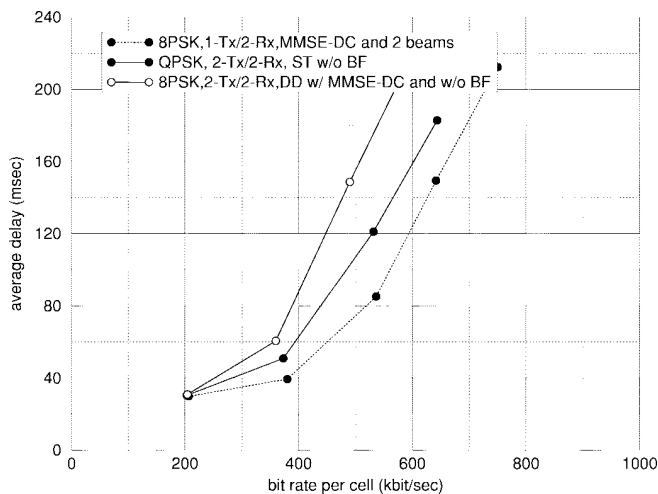


Fig. 9. Comparison of DD-8PSK, ST-QPSK transmit diversity and, 8PSK with beamforming (two transmitter antennas in each 120° sector for each case).

beam at a time. Fig. 9 compares the delay versus throughput performance for ST-QPSK, DD-8PSK transmit diversity and no beamforming with that of a single transmit antenna 8PSK with two beams per sector. Interference suppression is employed for the cases of 8PSK. All three schemes have the same peak rate. It is found that, given the same number of transmit antennas, a combination of interference suppression and beamforming appears to result in the best performance enhancement. In environments with large angular spread of radio signals, however, beam switching does not provide good performance. Thus, space-time coding may be preferred in environments with large angular spread or when it may be desirable for 3–4 bits/s/Hz coding.

V. CONCLUSIONS

We have studied delay, permutation, and space-time coding transmitter diversity combined with two branch receiver diversity for OFDM used in high-rate data wireless networks.

Space-time coding transmitter diversity is the best approach for providing high peak data rates. Compared with the permutation and space-time coding approaches, however, the delay approach requires a simpler parameter estimator. For a delay transmitter diversity system with a 800 kHz channel transmitting data at a rate of 600 kbits/s, or a 384 kbits/s user rate considering control overhead, from the computer simulation the required SNR for a 10% WER is about 5.5 dB for the TU channel with a 40-Hz Doppler frequency. But at a rate of 1.2 Mbits/s, it is as large as 12.7 dB, while it is only about 9 dB for a space-time coding transmitter diversity system at the same data transmission rate.

The physical layer performance difference of each approach has a different impact on the networks' performance. The delay transmitter diversity system using QPSK modulation with interference suppression is the most robust and provides QoS with a low retransmission probability. Downlink beamforming is also shown to be an effective method for increasing both QoS and throughput when the environment permits this technique. Wireless networks using downlink beamforming together with adaptive antenna arrays can provide higher capacity than those employing delay or space-time coding transmitter diversity systems with two transmitter and two receiver antennas. Space-time coding will perform well in environments with large angular spread, such as microcells, and can support higher peak-rate data transmission in those environments.

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