Spread-Spectrum Multiple-Access Performance of Orthogonal Codes for Indoor Radio Communications

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Abstract—**Direct sequence spread spectrum with its inherent resistance to multipath is a promising technique for indoor wireless communication. To allow multiple users within a limited bandwidth, code division multiple access (CDMA) is needed. This correspondence analyzes the bandwidth efficiency of M-ary CDMA systems in fading multipath indoor radio channels. It is shown that M-ary signaling improves the bandwidth efficiency significantly as compared to binary signaling.**

I. Introduction

THE modern workplace requires data communications between a variety of data processing equipment. Such interconnections are achieved through local area networks (LAN's). To provide portability to the terminals and to avoid installation and relocations costs, a wireless LAN (WLLAN) is a possible solution. One such WLLAN is based on direct-sequence spread-spectrum (DSSS) techniques [1]–[7].

DSSS provides resistance to multipath caused by walls, ceilings and other objects between the transmitter and the receiver and can overlay existing systems because of the low spectral density level. Recently, FCC has assigned three bands for nongovernmental applications of spread spectrum which makes this alternative more attractive for indoor channels [8]. The only reservation concerning DSSS communications is the efficiency of the bandwidth utilization in fading multipath indoor channels [7]. Coding and diversity combining can improve the bandwidth efficiency of DSSS communications [3], [4].

Another method for improving the bandwidth efficiency is the use of M-ary signaling. The bandwidth efficiency of M-ary orthogonal codes over nonfading channels is discussed in [9]. This correspondence analyzes such a system over fading multipath channels. The goal is to determine the bandwidth efficiency of M-ary spread spectrum signals over fading multipath channels for an allocated bandwidth. The particular example uses multipath characteristics of the indoor radio channel and the bandwidth assigned by the FCC.

II. System Model

The system [9] consists of K users, each assigned a set of sequences $V^{(k)}$ consisting of M-orthogonal sequences, each of length N;

$$V^{(k)} = \{V_1^{(k)}, V_2^{(k)}, \cdots V_M^{(k)}\} \tag{1}$$

where

$$V_\mu^{(k)} = \{V_{\mu,0}^{(k)}, V_{\mu,1}^{(k)}, \cdots, V_{\mu,N-1}^{(k)}\}$$

and $V_{\mu,n}^{(k)} = \exp(j\theta_{\mu,n}^{(k)})$ is a complex rth root of unity (r-phase modulation). There is no specific relationship between r and M or N. M-ary equally likely data symbols are transmitted at a rate of one every T seconds. The signal transmitted by the kth user to send the μth symbol during the interval $[0, T)$ is

$$S(V_\mu^{(k)}, t) = \operatorname{Re}\left\{\sqrt{2P_s}\sum_{n=0}^{N-1}[V_{\mu,n}^{(k)}]^*\Gamma(t-nT_c) \cdot \exp(j\omega_c t + \theta_k)\right\} \tag{2}$$

where P_s is the average signal power. The chip duration T_c is T/N, $\Gamma(t)$ is the chip waveform, θ_k the carrier phase, ω_c is the carrier frequency common to all users and $\omega_c T_c = 2\pi n$, n an integer. The chip waveform is defined for $0 \le t < T$, is zero outside the range, and is normalized so that the energy per chip is equal to T_c. Therefore, the energy per symbol is $E_s = P_s T$ and the energy per bit is $E_b = E_s/\log_2 M$ since M bits are transmitted by each symbol. In fading multipath indoor channels the channel impulse response for each user is given by [10]

$$h_k(t) = \sum_{l=1}^{L}\beta_{lk}\delta(t-\tau_{lk})e^{j\phi_{lk}} \tag{3}$$

where β_{lk}, τ_{lk}, and ϕ_{lk} are the path gain, delay, and phase, respectively. The path gain is unity for the nonfading channel and assumed to be an independent Rayleigh distributed random variable for the fading multipath channel. The overall path phase given by $(\omega_c\tau_{lk} + \phi_{lk} + \theta_k)$ is assumed to be an independent uniformly distributed random variable in the region $[0, 2\pi)$. The received signal at the receiver for the first user is

$$r(t) = \operatorname{Re}\left\{\sum_{l=1}^{L}\beta_{l1}S(V_\lambda^{(1)}, t-\tau_{l1})\exp(j\phi_{l1}) + \eta(t)\right\}, \quad t \in [0, T) \tag{4}$$

when the message sent by the first user is λ. The additive noise term is

$$\eta(t) = \eta_I(t) + \sum_{k=2}^{K}\sum_{l=1}^{L}\beta_{lk}S(b^{(k)}, t-\tau_{lk})\exp(j\phi_{lk})$$

where $\eta_I(t)$ is the AWGN with power spectral density of height $N_o/2$, and the second term is the interference from other users with $S(b^{(k)}, t)$ representing the interfering signal from the kth user. The interference from other users can come from the preceding or the succeeding symbol in addition to the current symbol

$$S(b^{(k)}, t) = \operatorname{Re}\left\{\sqrt{2P_s}\sum_{n=0}^{2N-1}[b^{(k)}]^*\Gamma(t+T-nT_c) \cdot \exp(j\omega_c t + \theta_k)\right\} \quad t \in [\tau_{lk}-T, \tau_{lk}+T)$$

where the $2N$-tuple $b^{(k)}$ represents the concatenation of interfering sequences during the intervals $[\tau_{lk}-T, \tau_{lk})$ and $[\tau_{lk}, \tau_{lk}+T)$. A

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RAKE demodulator for square law combiner [11] is used as the receiver. The received signal is passed through a tapped delay line. The tapped signal is passed through a bank of matched filters, matched to the transmitted symbols. The sampled output of the identical matched filters from different taps are squared and added. The decision is made on the largest output of the adders. A square law combiner can be implemented without any information about the channel characteristics and closed-form equations for prediction of its performance can be derived.

III. Performance Analysis

Similar to [9], [12], it can be shown that from (3) and (4) the average SNR for each path is (see also [3], [5]):

$$\gamma = \left[\left(\frac{N_0}{E_s} + \frac{2M_\Gamma (K-1)L}{NT_c^3} \right)^{-1} \right]$$

where M_Γ is a constant dependent on the chip waveform. In fading channels γ is the average SNR; is nonfading channels γ is the SNR and $L = 1$. If the chip waveform is a sine pulse, then [9]:

$$M_\Gamma = T_c^3 \frac{(15 + 2\pi^2)}{12\pi^2} \approx 0.293 T_c^3,$$

thus:

$$\gamma = \left[\left(\frac{N_0}{E_s} + 0.586 \frac{(K-1)L}{N} \right)^{-1} \right]. \quad (5)$$

The codes used by each user are members of an orthogonal set, (see (1)), [9]. Therefore, equations derived for the M-ary signaling can be used for performance evaluations. The probability of error for M-ary orthogonal signaling in nonfading channels is given by [7], [11]

$$\Pr(\epsilon) \approx (M-1) Q(\sqrt{\gamma}) \quad (6)$$

where Q is the complementary cumulative Gaussian distribution function. For signals transmitted over a fading channel, the probability of error is a function of average signal-to-noise ratio, the number of diversified received signals, and the method used for the diversity combining.

In the flat (frequency-nonselective) fading, the only source of diversity is the explicit or external diversity D. In frequency selective fading channels, multipath arrival provides another source of diversity which is referred to as the implicit or internal diversity L. Equations derived for flat fading can be used for fading multipath channels with the diversity of LD [3], [4], [11]. The number of paths L used for implicit diversity is found by

$$L = \left\lfloor \frac{T_m}{T_c} \right\rfloor + 1$$

where T_m is the maximum delay spread and $\lfloor \cdot \rfloor$ is the function that returns the largest integer less than or equal to its argument. In a typical indoor radio channel, utilizing the FCC allocated 25 MHz bandwidth ($T_c = 40$ ns) [8], the number of paths for different multipath delay spreads are

T_m (ns)	25	50	100	150	200	250
L (paths)	1	2	3	4	6	7

In a frequency selective fading multipath channel with LD order of diversity, the average probability of error for the RAKE demodulator

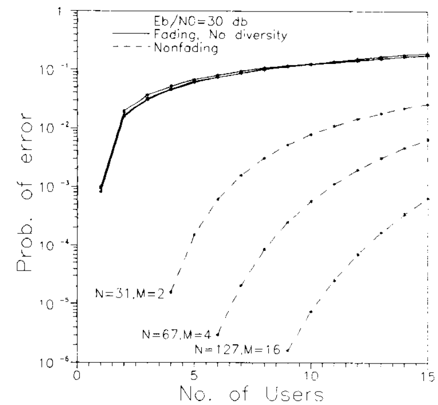

Fig. 1. Probability of error versus number of users over flat fading and nonfading channels with $\log_2 M/N = 0.032$, M is the number of codes and N is the length of the code.

with square law combiner is given by [11]

$$\Pr(\epsilon) = 1 - \int_0^\infty \left[\frac{u^{LD-1} \cdot e^{\frac{-u}{1+\gamma}}}{(1+\gamma)^{LD}(LD-1)!} \cdot \left(1 - e^{-u} \sum_{j=0}^{LD-1} \frac{u^j}{j!} \right)^{M-1} \right] du. \quad (7)$$

Given a Pr (ϵ) as an acceptable error rate, an important performance criteria is the bandwidth efficiency of the coding technique. Bandwidth efficiency η can be defined as [2]

$$\eta = \frac{KR_b}{W} = \frac{K \log_2 M}{N} \quad (8)$$

where R_b is the bit rate, W the bandwidth, and K the number of users.

IV. Results and Discussions

Equations (6) and (7) are used for calculation of the probability of error over nonfading and fading multipath channels with the SNR given by (5). Fig. 1 presents the performance for codes with $(\log_2 M)/N \approx 0.032$ bits/chip in fading and nonfading channels. In nonfading channels performance improves as the length of the code increases. The performance in fading channels is almost identical for different code lengths. The Pr (ϵ) is not better than approximately 10^{-3} for two or more users. Incorporating the implicit diversity provided by the resolved multipaths in the indoor environment, some improvement is observed. Fig. 2 shows the performance for a code of $N = 127$, $M = 16$, and the number of paths $L = 1$, 2, 4, and 6. With six paths, five users can be accommodated with a Pr (ϵ) $\leq 10^{-3}$. The effect of increasing code length N while maintaining the same number of codes M is shown in Fig. 3. At Pr (ϵ) of 10^{-4}, the number of users accommodated goes from two with $N = 127$ to about seven with $N = 509$. Therefore, an increasing number of users can be accommodated at a cost of lower data rate per user.

The effect of explicit diversity with one received path (flat fading) is shown in Fig. 4. The performance increase is at the expense of higher system complexity and cost. At increasing orders of diversity the performance can surpass that found in nonfading channels. An increase in the order of implicit diversity increases the interference noise caused by other users [see (5)] as well as the diversity of the received signal. The explicit diversity increases the diversity of the received signal without contributing to the interference noise. The contrast between the effectiveness of explicit and implicit diversities is observed by comparing figure (2) with figure (4). Fig. 5 shows the performance with different orders of implicit diversity and two

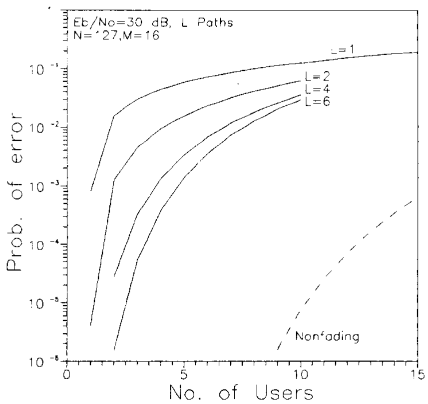

Fig. 2. Probability of error versus number of users over frequency selective fading multipath and nonfading channels. The solid lines represent the performance for different orders of implicit diversity L. The dashed line provides the performance in nonfading channels. $M = 16$ orthogonal codes with length $N = 127$ are used.

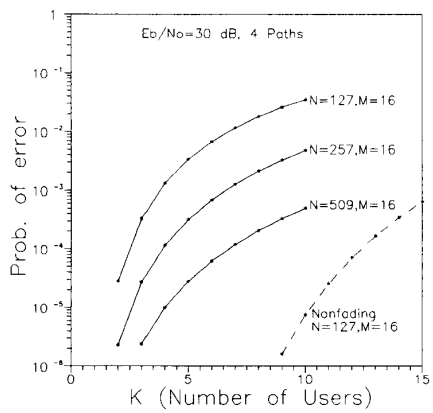

Fig. 3. Probability of error versus number of users over frequency selective fading multipath and nonfading channels. The number of paths are $L = 4$ and each terminal uses $M = 16$ orthogonal codes. The solid lines represent the performance for different code lengths. The dashed line provides the performance in nonfading channels.

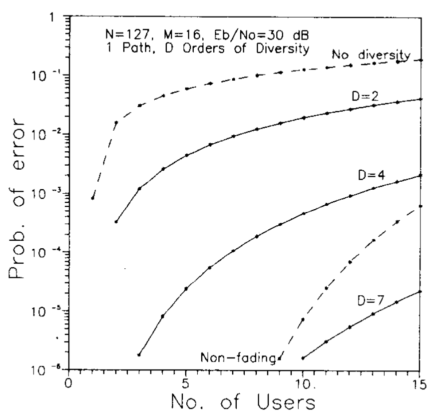

Fig. 4. Probability of error versus number of users over nonfading and flat fading channels utilizing explicit diversity; $M = 16$ codes with length $N = 127$ are used. The solid lines represent the performance for different orders of explicit diversity. The performance over fading channels with no diversity and nonfading channels are shown by the dashed lines.

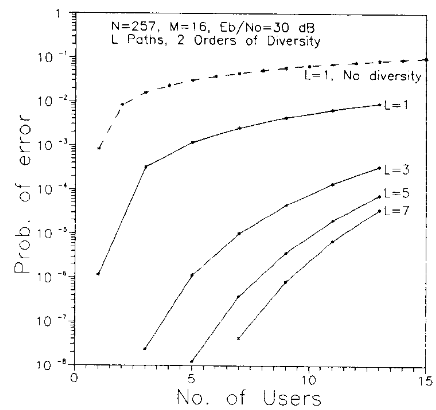

Fig. 5. Probability of error versus number of users, over nonfading and frequency selective fading channels utilizing two orders of explicit diversity; $M = 16$ codes with length $N = 256$ are used. The solid lines represent the performance for different number of paths. The performance over flat fading channels is shown by the dashed line.

TABLE I
BANDWIDTH EFFICIENCY OVER FADING MULTIPATH CHANNELS WITH $N = 256$, TWO ORDERS OF EXPLICIT DIVERSITY, DIFFERENT NUMBER OF SYMBOLS AND DIFFERENT ORDERS OF IMPLICIT DIVERSITY

Bandwidth Efficiency for N=256, E_b/N_0=30dB			
M	**2-Paths**	**4-Paths**	**7-Paths**
2	.0429	.0664	.0742
4	.0702	.1171	.1327
8	.0937	.1524	.1868
16	.1094	.1875	.2343
32	.1171	.2148	.2734
64	.1409	.2577	.3047

orders of explicit diversity for a code of $N = 257$ and $M = 16$. More than ten users can be accommodated with a Pr $(\epsilon) \leq 10^{-4}$ and three or more paths.

The above results can be used to determine the bandwidth efficiency of the system, defined in (8). The number of users K, was determined by taking the Pr (ϵ) of 10^{-4} and finding the nearest integer K. Table I presents the bandwidth efficiency for different number of codes per user M, the code length of 257 chips, and two orders of explicit diversity. The maximum bandwidth efficiency of 0.3035 is observed for maximum number of codes per user and maximum multipath spread. This efficiency would increase if the order of explicit diversity is increased or the constraint on the probability of error is reduced from 10^{-4}. For two paths the bandwidth efficiency increases approximately 3 times as the number of codes per user increases from 2 to 64; for 4-paths and 7-paths this increase is approximately 4 times. Table II shows the effect of increasing code length for $M = 16$ and two orders of explicit diversity. For a fixed bandwidth, as the code length increases, the data rate and consequently the bandwidth efficiency decreases. On the other hand, an increase in the code length reduces the interference noise from other users which improves the bandwidth efficiency. Considering both effects, Table II shows that for any number of paths, the bandwidth efficiency decreases slightly as the code length is increased.

V. CONCLUSIONS

Performance of the M-ary signaling system degrades considerably over the fading multipath channels as compared to the nonfading channel. In order to achieve acceptable levels of performance, a combination of implicit diversity (multipaths) and explicit (antenna) diversity is needed. To achieve higher data rates under the constraint

TABLE II
BANDWIDTH EFFICIENCY OVER FADING MULTIPATH CHANNELS WITH $M = 16$, TWO ORDERS OF EXPLICIT DIVERSITY, DIFFERENT LENGTHS OF SPREAD SPECTRUM CODE AND DIFFERENT ORDERS OF IMPLICIT DIVERSITY

Bandwidth Efficiency for M=16, E_b/N_0=30dB			
N	L=2	L=4	L=7
32	.125	.25	.25
64	.125	.25	.25
128	.125	.2188	.25
256	.1094	.1875	.2343
512	.1016	.1875	.2188
1024	.0977	.1797	.2148
2048	.0938	.1777	.2129

of the fixed bandwidth of the indoor radio channel, the CDMA coding scheme discussed can achieve acceptable levels of performance with the techniques described above. The bandwidth efficiency goes from 7% with two symbols to over 30% with 64 symbols using a combination of implicit and explicit diversity. This compares favorably to other multiple-access techniques.

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