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Error Rate Analysis of Coherent and Differential Multiphase Parallel Combinatorial Spread Spectrum Systems

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SUMMARY This paper investigates the error rate performance of parallel combinatorial spread spectrum (PC/SS) communication systems that use coherent and differential multiphase modulation: *multiphase parallel combinatorial spread spectrum* (MPC/SS) communication systems. The PC/SS systems are multicode SS systems based on orthogonal pseudo-noise (PN) sequences. Data is transmitted by delivering a combination of multiple PN sequences among a set of pre-assigned PN sequences. In the MPC/SS systems, every PN sequence on transmission is modulated by q-ary coherent or differential phase shift keying (PSK). Symbol error rate (SER) and average bit error rate (BER) in coherent and differential MPC/SS systems are investigated. The BER comparison between the MPC/SS systems and simple multicode SS systems with q-ary coherent and differential PSK is also presented. Numerical results show that the MPC/SS systems are superior to the conventional q-ary PSK systems, if they have equal spectral efficiency.

key words: *spread spectrum, multicode systems, multiphase modulation, symbol error rate, bit error rate*

1. Introduction

Code-division multiple access (CDMA) systems based on spread spectrum (SS) technology have been investigated in many recent studies to explore their use in various kinds of wireless communication systems [1]–[4]. The future mobile data communication systems and wireless LANs will need high-speed data transmission capability for advanced multimedia applications. Direct sequence spread spectrum (DS/SS) systems using orthogonal codes [5], such as M-ary/SS systems, and simple multicode DS/SS systems [6] have been studied, and the latter is attractive from the point of view on high-speed data transmission. Unfortunately, simple multicode SS systems cannot improve error rate performance over conventional DS/SS systems. An alternative SS method has to be developed.

In this paper, we propose one of multicode DS/SS systems: *multiphase parallel combinatorial spread spectrum* (MPC/SS) communication systems. PN sequences for simultaneous parallel transmission are selected by the R-out-of-M combination among a set of pre-assigned PN sequences, where R and M are the number of PN sequences to be transmitted and the number of pre-assigned PN sequences, respectively. In the proposed system, PN sequences to be transmitted are modulated by q-ary coherent or differential PSK in order to speed data transmission. If coherent PSK is applied, the proposed system is referred to as the coherent MPC/SS system. If differential PSK is applied, it is referred to as the differential MPC/SS system. Particularly the advantage of a differential MPC/SS system over a coherent MPC/SS system is that the former does not require the estimation of carrier phase, which is difficult in mobile communication environment. To clarify the fundamental properties, we focus our discussion on the analysis of the symbol error rate (SER) and average bit error rate (BER) analysis on additive white Gaussian noise (AWGN) channels.

In the next section, transmitter and receiver model of the MPC/SS systems is described. Symbol error rate and bit error rate analysis are presented in Sects. 3 and 4. Numerical results are presented and discussed in Sect. 5, and Sect. 6 is a concluding section.

2. System Model

The PC/SS system is one of the multicode DS/SS systems. In a PC/SS system, a different kind of M orthogonal PN sequences is in advance assigned to every user. R active PN sequences to be transmitted to a specific user are specified among the pre-assigned PN sequences. Every active PN sequence is modulated by q-ary PSK, and R modulated signals travels in parallel to a receiver. This parallelism is the major key to high-speed transmission. At a receiver, the received signal is demodulated by estimating the combination of active PN sequences and by detecting the phase of every active PN sequence, because the data consists of the R-out-of-M combination of modulated PN sequences. Information bit rate per PN sequence period is expressed by

$$m = R\left\lfloor \log_2 q \right\rfloor + \left\lfloor \log_2 \binom{M}{R} \right\rfloor \quad \text{(bits/baud)}, \quad (1)$$

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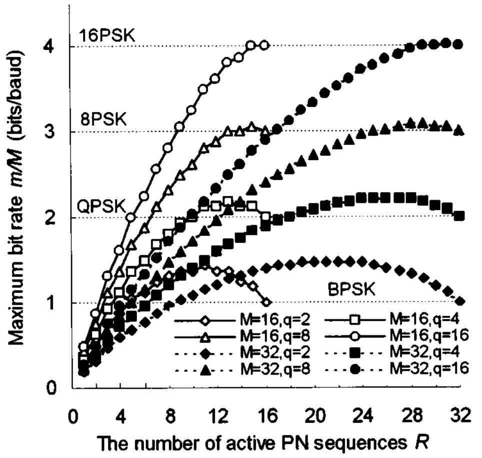

Fig. 1 Information bit rate of multiphase parallel combinatorial spread spectrum (MPC/SS) systems.

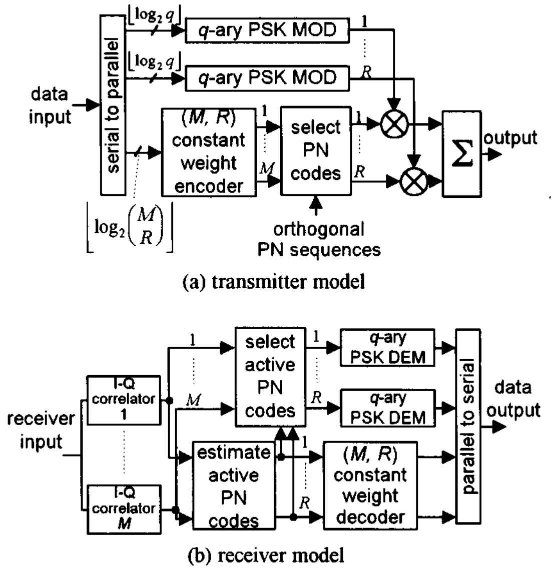

Fig. 2 Multiphase parallel combinatorial spread spectrum (MPC/SS) system model.

where $\lfloor x \rfloor$ stands for the largest integer smaller than or equal to x, and q is the number of possible phases. The first term depends on the phase of active PN sequences, and the second term depends on the combination of active PN sequences. The information bit rate per PN period is shown in Fig. 1, where maximum bit rates in conventional PSK counterparts are also drawn in dotted lines. The maximum bit rate increases in according with the increase in the multiplicity in modulation phase. The number of pre-assigned PN sequences controls the possible parallelism, and mainly contributes to the user capacity. Hence the MPC/SS systems are capable of making the data rate higher than that of DS/SS systems with PSK modulation.

2.1 Transmitter Model

Figure 2 (a) shows the transmitter model of the MPC/SS systems. To simplify the description, we show its baseband model. An assigned set of M orthogonal PN sequences having length N and chip duration T_c is expressed by an M-component vector.

$$\boldsymbol{a}(t) = \{a_1(t), a_2(t), a_3(t), \ldots, a_M(t)\} \tag{2}$$

$$a_i(t) = \sum_{j=0}^{N-1} a_{i,j} P_{Tc}(t - jT_c), \tag{3}$$

$$a_{i,j} \in \{+1, -1\}$$

where $a_{i,j}$ is the jth element of ith PN sequence, and $P_{Tc}(t)$ represents the chip waveform. Assigned PN sequences are mutually orthogonal. That is,

$$\int_0^T a_{i1}(t) a_{i2}(t) dt = \begin{cases} T & i1 = i2 \\ 0 & i1 \neq i2 \end{cases} \tag{4}$$

At the transmitter, an input data stream of bit duration T_d is converted to m parallel streams of bit duration T, where by definition $T = mT_d = NT_c$. To specify the R active PN sequences, $v_i(t)$, among the assigned set of M orthogonal PN sequences, (M, R)-CWC, constant weight codes with length M and weight R [9], are used in this system. The set of R active PN sequences is written by

$$\boldsymbol{v}(t) = \{v_1(t), v_2(t), v_3(t), \ldots, v_R(t)\} \tag{5}$$

Since an active PN sequence is modulated by q-ary PSK, phase signals of active PN sequences are expressed by

$$\boldsymbol{b} = \{b_1, b_2, b_3, \ldots, b_R\} \tag{6}$$

$$b_i = \exp\left(j\frac{2n}{q}\pi\right), \quad n = 0, 1, 2, \ldots, q-1 \tag{7}$$

All active PN sequences are assumed to have the same signal power P. The phase of active PN sequences and the active codes themselves are multiplied to form a transmission signal

$$s(t) = \sum_{i=1}^{R} \sqrt{P} b_i v_i(t) \tag{8}$$

and this travels to a receiver.

2.2 Receiver Model

Figure 2 (b) shows the receiver model. Since the channel is assumed to be an AWGN channel, the receiver input signal consists of the transmission signal and AWGN. The receiver input is expressed by

$$r(t) = s(t) + \nu(t), \tag{9}$$

where $\nu(t)$ is the AWGN component with the power spectral density of $N_0/2$.

The receiver input passes through M I-Q correlators, and they try to detect one of M assigned PN sequences. Of course, among those M outputs just R outputs are significant. The jth correlator output is described as

$$Z_j = \int_0^T r(t)a_j(t)dt = \sqrt{P}\sum_{i=1}^{R}\int_0^T b_i v_i(t)a_j(t)dt + \int_0^T \nu(t)a_j(t)dt \quad (10)$$

According to the descending order of the magnitude of Z_j, dominant R elements are decoded to '1,' and the others are decoded to '0.' This procedure forms an (M, R) CWC that gives an estimate of R active PN sequences.

From the correlator outputs and the estimated (M, R) CWC, signaling phase is reproduced by q-ary PSK demodulators. Finally, the receiver output with bit duration T_d is obtained through parallel-to-serial conversion.

If coherent detection is employed, the proposed system is referred to as a coherent MPC/SS system. If a differential encoder is equipped for PSK modulation and differential detection is used for PSK demodulation, the proposed system is referred to as a differential MPC/SS system.

3. Symbol Error Rate Analysis

3.1 Coherent MPC/SS Systems

To derive symbol error rate, we should investigate the correct decision probability for the combination of active PN sequences. Since active PN sequences are R different kinds of PN sequences among M kinds of PN sequences, correct detection is expected to come from taking R highest correlations among M correlator outputs and neglecting the other $M-R$ smallest correlations. The probability such that an active PN sequence is correctly detected has been derived from the correct decision probability of M-ary orthogonal signaling with noncoherent detection [11]. It is expressed by

$$P_{c1} = \sum_{n=1}^{R}(-1)^n \binom{M-R}{n}\frac{1}{n+1}e^{-\frac{n}{n+1}\frac{E_0}{N_0}}, \quad (11)$$

where E_0/N_0 stands for the signal-to-noise ratio (SNR) per active PN sequence. Since m bits are transmitted by using R PN sequences in a symbol duration, E_0/N_0 is related to the SNR per information bit E_b/N_0 as follows:

$$\frac{E_0}{N_0} = \frac{m}{R}\frac{E_b}{N_0} \quad (12)$$

Since all correlator outputs are mutually independent, the probability of the correct estimation of all active PN sequences is computed by simply taking the Rth power of Eq. (11).

The other information that we need to know is the conditional probability of detecting the phase of active PN sequences. It is obtained by the correct decision probability of a q-ary PSK system and its expression is of the form [11],

$$P_{s1} \approx \mathrm{erf}\left(\sqrt{\frac{E_0}{N_0}}\sin\frac{\pi}{q}\right) \quad (E_0/N_0 \gg 1) \quad (13)$$

When all active PN sequences are estimated correctly, the conditional probability of the correct detection of their phase is again computed by taking Rth power of Eq. (13). SER is thus expressed by

$$P_M = 1 - P_{c1}^R \cdot P_{s1}^R \quad (14)$$

3.2 Differential MPC/SS Systems

On differential MPC/SS systems, the probability of detecting the combination of active PN sequences correctly is derived in the same way as for the coherent MPC/SS systems. However, it is necessary to compute the influence of the previous symbol occurrence. Let all active PN sequences be correctly estimated after x faults in detecting R active PN sequences have happened at the previous symbol. The probability of such a case is expressed by $\binom{R}{x}P_{c1}^{2R-x}(1-P_{c1})^x$.

The conditional probability of the phase detection such that the previous combination detection has been false is equal to $(1/q)$. In contrast, the conditional probability of the phase detection such that the previous and present combinations have been successfully detected is expressed by [12]

$$P_s = \frac{\sin(\pi/q)}{2\pi}\int_{-\pi/2}^{\pi/2}\frac{e^{-\frac{E_0}{N_0}(1-\cos(\pi/q)\cos t)}}{1-\cos(\pi/q)\cos t}dt. \quad (15)$$

SER is thus calculated by

$$P_M = 1 - \sum_{x=0}^{R}\binom{R}{x}\left(\frac{1-P_{c1}}{q}\right)^x(1-P_s)^{R-x} \cdot P_{c1}^{2R-x}. \quad (16)$$

4. Bit Error Rate Analysis

4.1 Coherent MPC/SS Systems

In the PC/SS system, BER depends on the combination and phase of active PN sequences. At first, we are going to consider the BER controlled by the combination of PN sequences. Since m bits are transmitted for every symbol, the combination of R active PN sequences conveys the information of $m - R\lfloor\log_2 q\rfloor$ bits (see Eq. (1)). We assume that, when the combination estimation is false, all but except the single true bit pattern that is possible in $m - R\lfloor\log_2 q\rfloor$ bit sequence are randomly decoded. BER in detecting the PN sequence combination is thus obtained [11] as

$$P_{bc} = \frac{2^{m-R\lfloor\log_2 q\rfloor-1}}{2^{m-R\lfloor\log_2 q\rfloor}-1}(1-P_{c1}^R). \quad (17)$$

Next, suppose that x sequences among R active PN sequences were incorrectly estimated. There are $\binom{R}{x}$ cases on this type of faults, and there are hence $\binom{R-1}{x-1}$ cases such that a particular PN sequence be falsely estimated. Thus the error probability in estimating a specified active PN sequence is expressed by

$$P_n = \frac{\binom{R-1}{x-1}}{\binom{R}{x}} P_{c1}^{R-x}(1-P_{c1})^x = \frac{x}{R}P_{c1}^{R-x}(1-P_{c1})^x \quad (18)$$

The error probability in phase detection of an estimated PN sequence is expressed by $(q-1)/q$. Since there are $q/2-1$ cases such that correct decision takes place regarding a particular bit, the BER with respect to the false phase decoding is equal to one half.

BER in correct phase detection is given by [11]

$$P_{b0} = \begin{cases} \frac{1}{2}\mathrm{erfc}\left(\sqrt{\frac{E_0}{N_0}}\right) & q=2 \\ \frac{1}{\log_2 q}\mathrm{erfc}\left(\sqrt{\frac{E_0}{N_0}}\sin\frac{\pi}{q}\right) & q>2 \end{cases} \quad (19)$$

From (18) and (19), BER in false phase detection of x sequences among R active PN sequences is found to be

$$P_{bs0} = \left[\frac{x}{2R} + \frac{R-x}{R}P_{b0}\right]P_{c1}^{R-x}(1-P_{c1})^x. \quad (20)$$

The total BER in phase detection of R active PN sequences is obtained by averaging the above expression over x;

$$P_{bs} = \frac{1}{R}\sum_{x=0}^{R}\left[\frac{x}{2R} + \frac{R-x}{R}P_{b0}\right]P_{c1}^{R-x}(1-P_{c1})^x. \quad (21)$$

From (17) and (21), the comprehensive average BER is derived as follows.

$$P_{eb} = \frac{R\lfloor\log_2 q\rfloor}{m}P_{bs} + \frac{m-R\lfloor\log_2 q\rfloor}{m}P_{bc} \quad (22)$$

4.2 Differential MPC/SS Systems

In differential MPC/SS systems, P_{bc}, the BER with respect to the combination of active PN sequences is the same with that of coherent MPC/SS systems in Eq. (17).

For computing the BER in the phase detection of active PN sequences, we calculate the error probability in estimating an active PN sequence of present and previous symbols corresponding to a particular q-ary PSK demodulator. Calculation gives the following expression [10]

$$P_{ee}(u) = \sum_{v=0}^{u}\left\{\frac{v^2}{uR} + \frac{(u-v)^2}{u(R-v)}\left(1-\frac{v}{R}\right)\right\} \cdot \sum_{w=0}^{v}\{P_{c1}^{2R-u-w}(1-P_{c1})^{u+w}\} \quad (23)$$

Just as same as for coherent MPC/SS systems, BER with respect to false phase decoding is again one half. BER with respect to correct phase decoding about one active PN sequence is of the form [12]

$$P_b = \begin{cases} -2F\left(\frac{\pi}{2}\right) & q=2 \\ F\left(\frac{5\pi}{4}\right) - F\left(\frac{\pi}{4}\right) & q=4 \\ \frac{2}{3}\left[F\left(\frac{13\pi}{8}\right) - F\left(\frac{\pi}{8}\right)\right] & q=8, \end{cases} \quad (24)$$

where

$$F(\psi) = -\frac{\sin\psi}{4\pi}\int_{-\pi/2}^{\pi/2}\frac{e^{-\frac{E_0}{N_0}(1-\cos\psi\cos t)}}{1-\cos\psi\cos t}dt. \quad (25)$$

Thus, the BER with respect to phase decoding of R active PN sequences is given by

$$P_{bs} = \frac{1}{R}\sum_{i=1}^{R}\left[\frac{1}{2}P_{ee}(i) + P_b\{1-P_{ee}(i)\}\right]. \quad (26)$$

The overall average BER is of the same form to Eq. (22), where P_{bs} be however substituted by Eq. (26).

5. Numerical Results

5.1 SER Performance

Suppose a particular situation in which the number of

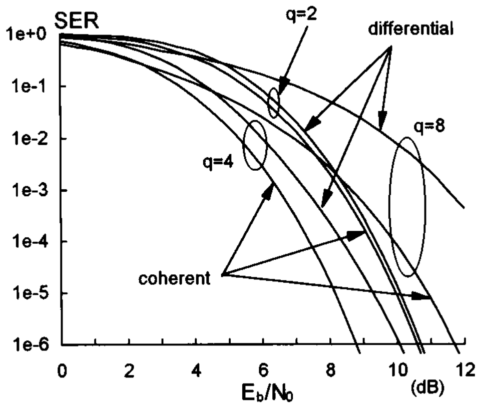

Fig. 3 SER of coherent and differential MPC/SS systems. $M = 16, m = 18$.

Table 1 BER comparison in coherent MPC/SS systems ($M=16, m=18, E_b/N_0=7.0$ dB).

number of phases q	number of active PN sequences R	information bit rate per PN sequence m/R	average BER P_{eb}	BER in combination estimation P_{bc}	BER in phase estimation P_{bs}
2	6	3	4.54E-03	6.80E-03	3.14E-05
4	4	4.5	8.01E-05	1.42E-04	2.48E-06
8	3	6	1.68E-04	2.81E-06	3.33E-04

assigned PN sequences, M, and the information bit rate per PN period, m, are constant. SER against E_b/N_0 is displayed in Fig. 3, where $M = 16$ and $m = 18$. SNR per bit that guarantees the 10^{-3} SER when $q = 4$ is lower by 2 dB than it is when $q = 2$.

In this case, E_0/N_0, SNR per active PN sequence, increases as q, because the number of active PN sequences decreases.

In both cases of $q = 2$ and $q = 4$, E_0/N_0 is as large as 3 and 4.5 times of E_b/N_0, respectively. The error probability in phase detection for each active PN sequences is much less than that in estimating the combination of PN sequences [13]. Thus SER characteristics of 2-phase and 4-phase MPC/SS systems strongly depend on the error probability in PN sequence combination estimation, and the SER can decrease by improving the estimation of PN sequence combination.

When $q = 8$, however, E_b/N_0 required to maintain the 10^{-3} SER is higher by 2.7 dB than that in the biphase system. In this case, E_0/N_0 is as large as 6 times of E_b/N_0. However, the error probability in estimating the phase of an active PN sequence is much greater than that in estimating the combination. Especially this observation is more likely to be found in differential MPC/SS systems. This is because the q-ary PSK has an extremely large SNR penalty as q exceeds four [11], [12], where large SER degradation is observed.

5.2 BER Performance

We are going to compare the coherent MPC/SS systems at first and then their differential counter systems both with conventional PSK systems. Figure 4 illustrates the BER performance of coherent MPC/SS systems which have different phases. The pre-assigned set comprises 16 PN sequences and the information bit rate is fixed at 18 bits/baud.

The performance of a conventional BPSK system is also drawn in a dashed line in the same figure. One can see that E_b/N_0 to maintain 10^{-6} BER in the 2-phase MPC/SS systems is lower by 0.3 dB than that in the BPSK system. In 4-phase MPC/SS systems, the gain in E_b/N_0 over the BPSK system amounts to 2.3 dB. For developing a discussion, additional comparison is listed in Table 1, where several parameters including average BER, BER in combination estimation, and BER in phase estimation are summarized in the order of phases. In the 2-phase and 4-phase systems, P_{bc} is dominant on overall BER, because it is much larger than P_{bs}. In addition, the 4-phase system has smaller P_{bc} and P_{bs} than the 2-phase system. As a consequence, large BER reduction is observed in the 4-phase system. Since m/R increases according to Eq. (1) and Eq. (12), P_{bc} decreases by increasing the number of phases.

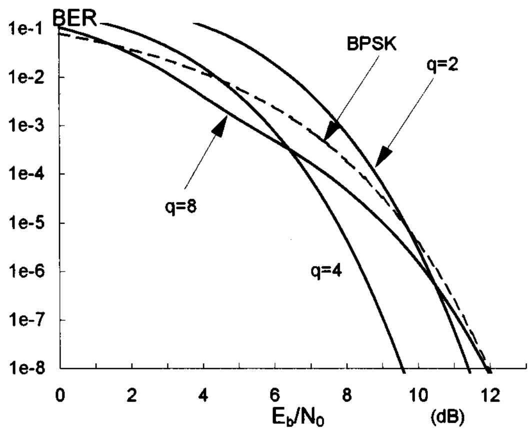

Fig. 4 BER of coherent MPC/SS systems versus E_b/N_0. $M = 16$ and $m = 18$.

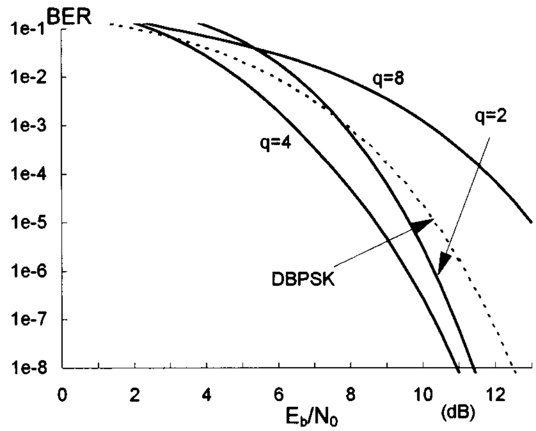

Fig. 5 BER of differential MPC/SS systems versus E_b/N_0. $M = 16$ and $m = 18$.

In contrast, an octal phase system has larger P_{bs} than a bi-phase system. This is because the penalty in SNR due to PSK modulation exceeds the SNR gain provided by increasing m/R. Therefore P_{bs} is dominant on overall BER if SNR becomes larger.

Figure 5 illustrates the BER performance of differential MPC/SS systems where again $M = 16$ and $m = 18$. Also, Table 2 lists the comparison in P_{eb}, P_{bc},

Table 2 BER comparison in differential MPC/SS systems ($M=16$, $m=18$, $E_b/N_0=7.0$ dB).

number of phases q	number of active PN sequences R	information bit rate per PN sequence m/R	average BER P_{eb}	BER in combination estimation P_{bc}	BER in phase estimation P_{bs}
2	6	3	4.66E-03	6.80E-03	3.75E-04
4	4	4.5	3.61E-04	1.42E-04	6.34E-04
8	3	6	1.66E-02	2.81E-06	3.32E-02

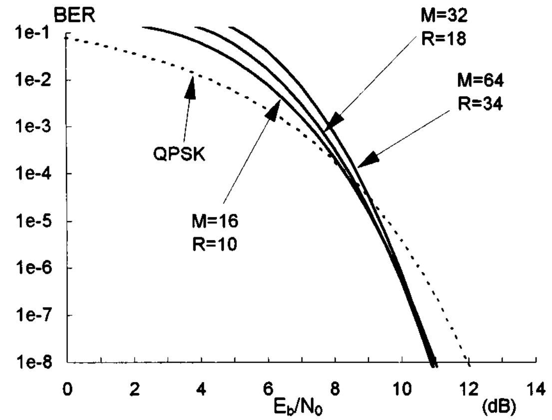

Fig. 6 BER comparison between coherent MPC/SS systems and the QPSK system. $q=4$ and $m=2M$.

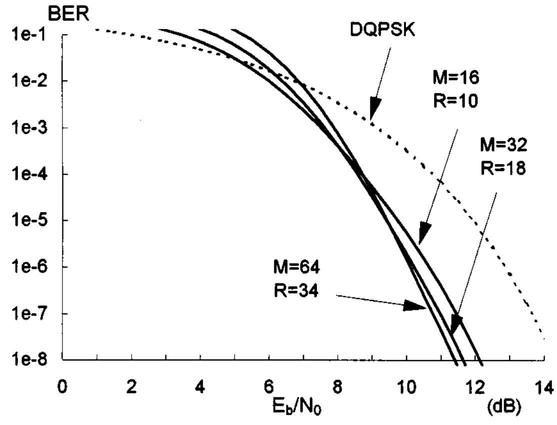

Fig. 7 BER comparison between differential MPC/SS systems and the DQPSK system. $q=4$ and $m=2M$.

and P_{bs}. E_b/N_0 required to achieve 10^{-6} BER in the 2-phase and 4-phase differential MPC/SS systems are lower by 0.6 dB and 1.6 dB than those in the differential BPSK system, respectively. The 4-phase PC/SS system has very smaller P_{bc} and slightly larger P_{bs} than the 2-phase system, leading to the improvement in P_{eb}. Since P_{bc} goes to a very large value in the 8-phase differential system, a discouraging drop is found in the overall BER.

The next topic to be discussed is the BER performance with respect to the number of PN sequences and the combination of active PN sequences. Under the same information bit rate of $m=2M$, BER performances are shown in Figs. 6 and 7 for 4-phase coherent and differential MPC/SS systems, respectively. If the number of PN sequences is equal to the length of the PN sequence, both MPC/SS systems and conventional QPSK systems will have the same spectral efficiency. MPC/SS systems are capable of guaranteeing a quite lower level of BER at lower E_b/N_0. The reduction in E_b/N_0 required to maintain the 10^{-6} BER amounts to almost 1 dB in the coherent systems and is 2-3 dB in the differential systems. For example, if the orthogonal PN sequence set comprises 16 PN sequences, the E_0/N_0 is equal to $3.2E_b/N_0$, while E_0/N_0 of the conventional QPSK is $2E_b/N_0$ [11]. E_0/N_0 in such an MPC/SS system is as high as 1.6 times to that in QPSK. Since BER in combination detection is dominant over P_{eb}, BER goes down at higher E_b/N_0 region as M increases. This behavior is just like as that in the M-ary orthogonal signaling [11].

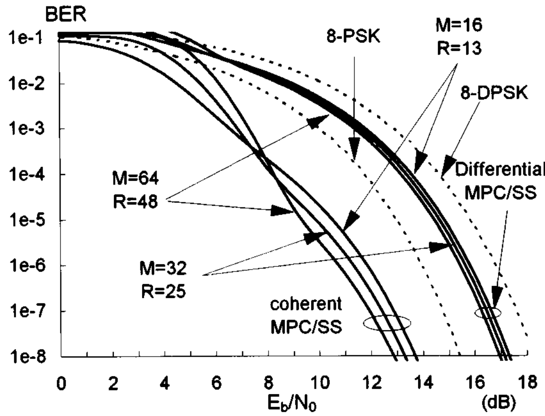

Fig. 8 BER comparison between MPC/SS systems and the 8-PSK system. $q=8$ and $m=3M$.

If many more phases are involved with these two types of MPC/SS systems, they show some different characteristics in their BER performance. BER performance of 8-phase coherent and differential MPC/SS systems is displayed in Fig. 8. One will observe slight dipping variations in the BER curves around E_b/N_0 of 6–8 dB. The major reason for these BER dips is that BER at higher E_b/N_0 regions is controlled by the error in phase detection, and that the phase detection becomes too difficult beyond some limit in E_b/N_0.

P_{bc} is dominant on P_{eb} if E_b/N_0 is low, but if E_b/N_0 grows larger, P_{bs} dominates over the total BER because of the excessively large penalty in SNR by 8PSK. Thus the dipping in the BER curve seems to be

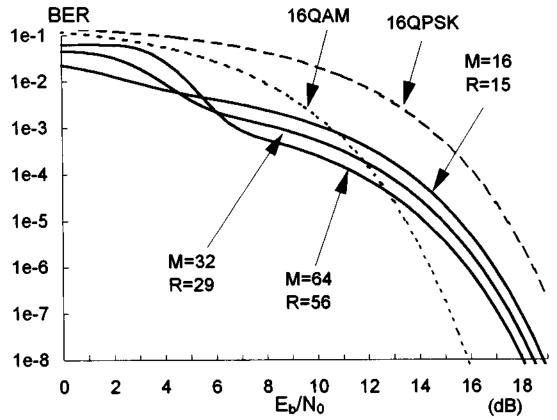

Fig. 9 BER performance of coherent MPC/SS systems and the 16-PSK and 16-QAM systems. $q = 16$ and $m = 4M$.

caused by the transitional behavior between two dominant modes.

BER performances of 16-phase MPC/SS systems, 16PSK systems, and 16QAM systems are compared in Fig. 9. The information bit rate of the MPC/SS systems is the same as that of 16QPSK and 16QAM systems. BER dipping appears where E_b/N_0 is around 6 dB. The reason is quite the same for the 8-phase systems.

The reduction in E_b/N_0 required to keep the 10^{-6} BER is 1.5 to 2.5 dB against the 16PSK systems. This advantage comes from the increase in E_0/N_0 with increasing m/R. However, comparing those many-phase MPC/SS systems to the 16QAM systems, no BER improvement is observed because of the excessively large SNR penalty by 16PSK.

6. Conclusions

The investigation of the symbol and average bit error rates of PC/SS systems using q-ary coherent and differential PSK modulation shows that the q-ary PSK modulation scheme is useful to increase the information bit rate per PN period. In coherent MPC/SS systems, both SER and BER performances are improved by the 4-ary PSK (QPSK) scheme. If one compares 'differential' and 'coherent' systems presented in this paper, differential MPC/SS systems, at least particularly those being 4-phase, give a greater BER improvement than that gained in coherent MPC/SS systems.

Error rate performance analysis in fading channels and multiple access performance evaluation are open problems to be addressed.

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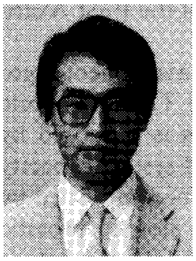

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