MULTIPLE-ACCESS INTERFERENCE OF GOLD CODES IN A DS-CDMA SYSTEM

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Abstract: Properties of spreading codes constitute a limiting factor on the performance of DS-CDMA systems. In this paper, we investigate the performance of certain sets of Gold codes in a multi-user DS-CDMA system, from a few users to full system load. Simulation results show that as the system load increases, BER graphs of all the codes maintain their steep high-SNR slopes, with no emergence of error floor or significant system saturation. The results indicate that certain sets of Gold codes have good cross-correlation properties that make them resistant to multiple-access interference, making them more suitable for multiple-access applications.

Keywords: Direct-sequence code division multiple access (DS-CDMA), multiple-access interference (MAI), Gold codes, pseudo-noise encoding, bit-error-rate (BER), error floor.

1. INTRODUCTION

Code Division Multiple Access (CDMA) is a multiple-access technique that relies on coding to achieve its multiple-access property. The performance of a Direct-Sequence (DS) CDMA system depends greatly on the properties of the code sequences used for the system. The type and properties of the codes set bounds on the capability of the system. Imperfect properties of codes are known to be a cause of multiple-access interference (MAI), which happens to be an important factor limiting the capacity of DS-CDMA systems. The significance of spreading codes is applicable not only to the basic DS-CDMA system, but also other emerging modern technologies like the wideband-CDMA (WCDMA) system, the multicarrier CDMA system and its space-time-coded counterparts [1-3].

The significance of spreading codes has made the search for better spreading codes an important research subject. For example in [4-9], Hsiao-Hwa et al. proposed the design of complementary codes for CDMA systems, and later proposed an interference-cancellation method for the same [10]. Another example is in [11], where Pal and Chattopadhyay proposed an algorithm for generating orthogonal minimum cross-correlation spreading codes.

Although there exists a vast amount of published work on spread spectrum systems, as well as works relating to the design, properties, performance and generation of spreading codes [1, 8, 11-27], we are yet to see any paper that examines multiple-access performance of Gold codes as a class. We seek to fill this gap. In this paper, we investigate the performance of a set of Gold codes in a DS-CDMA system. Effects of the codes' MAI on the system bit-error-rate (BER) in a multi-user environment, ranging from a few users to tens of users, are considered. The outcome of the work gives new insight on multiple-access performance of Gold codes.

Any particular code is normally expected to have a maximum number of users that would be tolerated, a number that is believed to be well below full load. In contrast, simulation results to be presented in this paper show that with good choice of codes, the number of available codes can go up to full-load. This is an important contribution of this paper. The outcome indicates the need for careful choice of spreading codes when designing a CDMA system.

In the rest of this paper, fundamental theory is contained in Section 2, followed by research methodology in Section 3, simulation results in Section 4, discussion in Section 5, suggested future work in Section 6, and lastly, conclusion in Section 7.

2. SYSTEM MODEL

In digital DS-CDMA, the message signal is multiplied directly by the code signal and the resulting signal modulates a carrier for transmission through a communication channel. At the other end, the receiver correlates the received signal with the code of the user. Correlating the received signal with the code for a certain user de-spreads (decodes) the signal for the user.

For a DS-CDMA system, the spread spectrum signal transmitted by a user k can be expressed as

$$s_k(t) = Ac_k(t)b_k(t)\cos(\omega_c t + \theta_k), \tag{1}$$

where $b_k(t)$ is the user binary data, $c_k(t)$ is spreading code and ω_c is carrier frequency. The spreading code $c_k(t)$ for the user can be denoted as

$$c_k(t) = \sum_{i=1}^{N} c_k^i P_c(t - iT_c), \qquad c_k^i \in \{-1,1\}, \tag{2}$$

where N is length of the code, and P_c is a rectangular pulse having a duration T_c. Let the wireless communication channel be represented by multiple paths having a real positive gain β_l, propagation delay τ_l and phase shift γ_l, where *l* is path index. The channel impulse response $h_k(t)$ for *L* independent paths can be modelled as

$$h_k(t) = \sum_{l=1}^{L} \beta_{kl} e^{j\gamma_{kl}} \delta(t - \tau_{kl}) \quad . \qquad (3)$$

At the receiving end, the received signal $r_k(t)$ for the user is obtained by convolving $s_k(t)$ with $h_k(t)$ and adding noise so that

$$r_k(t) = \int_{-\infty}^{\infty} s_k(\tau) h_k(t-\tau) d\tau \ + \ n(t), \qquad (4)$$

where $n(t)$ represents the channel noise. Substituting the expressions for $s_k(t)$ and $h_k(t)$ into this integral, and using relevant properties of the Dirac delta function $\delta(t)$ gives

$$r_k(t) = \sum_{l=1}^{L} \begin{matrix} A\beta_{kl} e^{j\gamma_{kl}} c_k(t-\tau_{kl}) b_k(t-\tau_{kl}). \\ cos(\omega_c t - \theta_{kl}) + \ n(t) \end{matrix} \qquad (5)$$

For a multi-user system comprising *K* users, the received signal $r(t)$ is a linear superposition of the signals for the users, and is given by

$$r(t) = \sum_{k=1}^{K} \sum_{l=1}^{L} \begin{matrix} A\beta_{kl} e^{j\gamma_{kl}} c_k(t-\tau_{kl}) b_k(t-\tau_{kl}). \\ cos(\omega_c t - \theta_{kl}) + \ n(t) \end{matrix} \qquad (6)$$

Let user-1 be the reference user. Assuming coherent demodulation, the receiver output $z(m)$ for m^{th} bit during the bit duration T_b of the user is given by

$$z_1(m) = \int_{mT_b}^{(m+1)T_b} r(t) c_1(\mathrm{t}) \cos \omega_c t \, dt$$

$$= \int_{mT_b}^{(m+1)T_b} \left\{ \sum_{k=1}^{K} \sum_{l=1}^{L} \begin{matrix} A\beta_{kl} e^{j\gamma_{kl}} c_k(t-\tau_{kl}) b_k(t-\tau_{kl}). \\ cos(\omega_c t - \theta_{kl}) + \ n(t) \end{matrix} \right\} c_1(\mathrm{t}) \cos\omega_c t \, dt$$

$$= \int_{mT_b}^{(m+1)T_b} \left\{ \sum_{l=1}^{L} \begin{matrix} A\beta_{1l} e^{j\gamma_{1l}} c_1(t-\tau_{1l}) b_1(t-\tau_{1l}) \\ cos(\omega_c t - \theta_{1l}) \end{matrix} \right\} c_1(\mathrm{t}) \cos \omega_c t \, dt$$

$$+ \int_{mT_b}^{(m+1)T_b} \left\{ \sum_{k=2}^{K} \sum_{l=1}^{L} \begin{matrix} A\beta_{kl} e^{j\gamma_{kl}} c_k(t-\tau_{kl}) b_k(t-\tau_{kl}). \\ cos(\omega_c t - \theta_{kl}) \end{matrix} \right\} c_1(\mathrm{t}) \cos \omega_c t \, dt$$

$$+ \int_{mT_b}^{(m+1)T_b} n(t) c_1(\mathrm{t}) \cos \omega_c t \, dt$$

$$= \ z_{11} \ + \ z_{12} \ + \ z_{13} \qquad (7)$$

where

$$z_{11} = \int_{mT_b}^{(m+1)T_b} \left\{ \sum_{l=1}^{L} \begin{matrix} A\beta_{1l} e^{j\gamma_{1l}} c_1(t-\tau_{1l}). \\ b_1(t-\tau_{1l}) cos(\omega_c t - \theta_{1l}) \end{matrix} \right\} c_1(\mathrm{t}) \cos \omega_c t \, dt$$

$$z_{12} = \int_{mT_b}^{(m+1)T_b} \left\{ \sum_{k=2}^{K} \sum_{l=1}^{L} \begin{matrix} A\beta_{kl} e^{j\gamma_{kl}} c_k(t-\tau_{kl}). \\ b_k(t-\tau_{kl}) \ cos(\omega_c t - \theta_{kl}) \end{matrix} \right\} c_1(\mathrm{t}) \cos \omega_c t \, dt$$

and

$$z_{13} = \int_{mT_b}^{(m+1)T_b} n(t) c_1(\mathrm{t}) \cos \omega_c t \, dt, \qquad (8)$$

where z_{11} represents the desired signal for the reference user, z_{12} is interference term, and z_{13} is noise term.

Gold codes are a type of pseudo-noise (PN) sequences derived from combination of certain pairs of *m*-sequences called *preferred sequences*, implemented using Linear Feedback Shift Registers (LFSR). A Gold code has a period $N = 2^n - 1$, where *n* is the length of the shift register. Gold codes exhibit three-valued cross-correlation function [28-30] with values {-1, -*t*(n), *t*(n)-2}, where

$$t(n) = \begin{cases} 2^{(n+1)/2} + 1, & n \text{ odd} \\ 2^{(n+2)/2} + 1, & n \text{ even.} \end{cases} \qquad (9)$$

At zero shift, the autocorrelation function of the codes has the value *N,* where $N = 2^n - 1$*;* at all other phase lags, the autocorrelation takes on one of the values predicted by its cross-correlation function.

3. METHODOLOGY

Software simulations were carried out for the transmission of 64,000 random quadrature phase shift keying QPSK symbols in an additive white Gaussian noise (AWGN) channel having a zero-mean and unit variance, using Gold code-encoding for code length *N* = 31, 127, 511 and 2047 chips. The Gold codes were generated from appropriate combinations of preferred pairs of *m*-sequences (Table 1), obtained from software implementation of LFSRs. The LFSRs were pre-filled with ones. The codes used were selected in the order of generation. For example, for a simulation involving five users, the first five codes of the set concerned were used as spreading sequences for the users, with the first member of the set being for the reference user.

Table 1. Generator polynomials for the Gold codes

n	$P_i^n(x)$	*Generator polynomial	*N*
5	$P_1^5(x)$	$x^5 + x^2 + 1$	31
	$P_2^5(x)$	$x^5 + x^4 + x^3 + x^2 + 1$	
6	$P_1^6(x)$	$x^6 + x^5 + 1$	63
	$P_2^6(x)$	$x^6 + x^5 + x^4 + x + 1$	
7	$P_1^7(x)$	$x^7 + x^6 + 1$	127
	$P_2^7(x)$	$x^7 + x^4 + 1$	
8	$P_1^8(x)$	$x^8 + x^7 + x^6 + x + 1$	255
	$P_2^8(x)$	$x^8 + x^7 + x^5 + x^3 + 1$	
9	$P_1^9(x)$	$x^9 + x^5 + 1$	511
	$P_2^9(x)$	$x^9 + x^8 + x^7 + x^2 + 1$	
10	$P_1^{10}(x)$	$x^{10} + x^7 + 1$	1023
	$P_2^{10}(x)$	$x^{10} + x^9 + x^8 + x^5 + 1$	
11	$P_1^{11}(x)$	$x^{11} + x^9 + 1$	2047
	$P_2^{11}(x)$	$x^{11} + x^{10} + x^9 + x^7 + 1$	
12	$P_1^{12}(x)$	$x^{12} + x^{11} + x^{10} + x^4 + 1$	4095
	$P_2^{12}(x)$	$x^{12} + x^{11} + x^{10} + x^2 + 1$	

*$P_1^n(x)$ and $P_2^n(x)$ are the generator polynomials of the preferred pair used for obtaining corresponding set of Gold codes of degree *n*.

At the receiving end, recovered data were compared to the original transmitted data for the determination of BER. Parametric BER graphs were generated for the various code lengths. For the simulations, perfect synchronization and perfect power control were assumed. We do realise that factors such as Doppler effects do affect system performance, but in a fading channel. This study only relates to an AWGNchannel, in which such factors do not apply.

4. RESULTS

This section presents results of simulations that we carried out, starting with the performance for a single user.

4.1 Performance for a single user

We shall start by considering simulation results for a single user, Fig. 1. The right-most curve on this figure is that of uncoded data transmission for a single user. The figure shows the close agreement between analytic and simulation results for the uncoded data transmission. [1]For reference purposes, this curve will be retained on all results to be presented in this paper. The rest of the curves on Fig. 1 show the performance for coded data transmission for different code lengths.

Clearly, Fig. 1 shows that longer Gold codes give better error-rate performance. The figure also shows that the use of Gold codes brings about some coding gain. With reference to uncoded data transmission, at a BER of 10^{-4}, the Gold codes provide coding gain of about 15.6, 21.7, 27.8 and 33.9 dB when N = 31, 127, 511 and 2048 respectively. From this we see that there is a constant 6.1-dB-step in coding gain between adjacent code lengths, which can be explained in terms of the ratio of the process gain of the codes.

It should be noted that the penalty for the coding gain obtained from the use of Gold codes is increase in bandwidth requirements. Each 6 dB improvement in coding gain corresponds to quadrupling of the bandwidth.

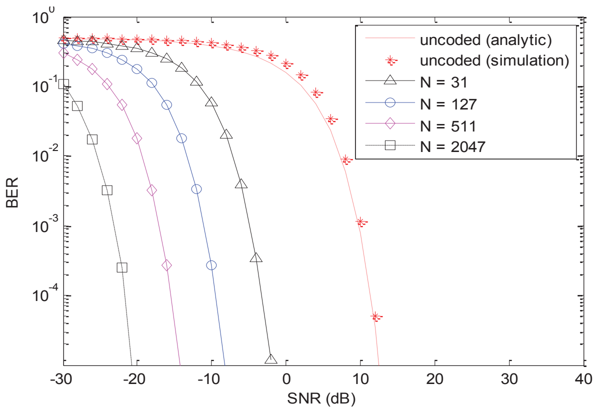
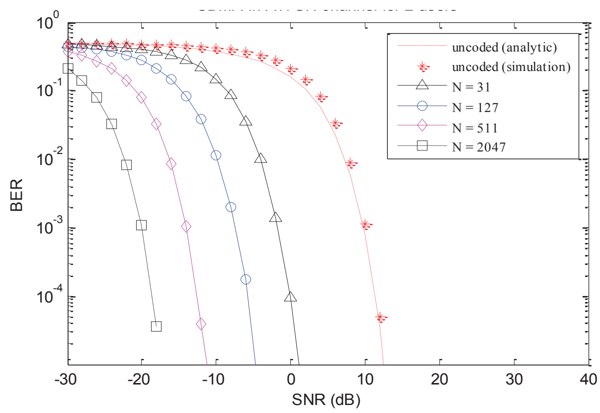


Fig. 1. Bit-error-rate for a single user

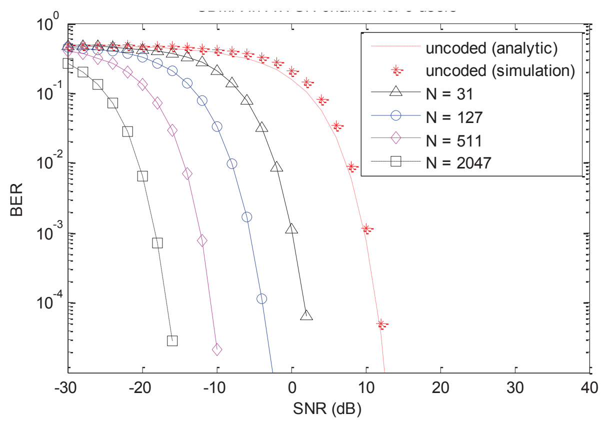
[1] An analytic result is obtained by direct implementation of an analytic expression; simulation result is obtained by sending random data through the channel, and then counting the number of bits in error at the receiving end. For the uncoded data transmission, the analytic equation for the BER is: $BER = Q\left(\sqrt{2\left(\frac{E_b}{N_0}\right)}\right)$, where Q is q-function, and E_b/N_0 is bit-energy-per-noise ratio.

4.2 Performance for two to five users

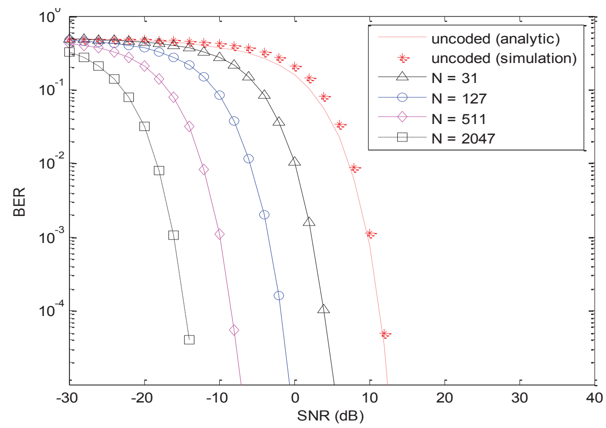
Next, we shall consider the results for a few multiple users. Figs. 2(a) to 2(c) show the BER for two, three and five users respectively. A look at these figures shows that an increase in the number of interferers worsens the system BER. That is, MAI worsens with increasing system load. The results show, for example, that for the code length N = 31 chips, at an SNR of -5 dB, BER is 1.1 x 10^{-3} for a single user, 2.1 x 10^{-2} for two users, 4.9 x 10^{-2} for three users and 1.1 x 10^{-1} for five users. The BERs for the other code lengths (N = 127, 511 and 2047) show a similar trend.



(a)



(b)



(c)

Fig. 2. Bit-error-rate for (a) two users, (b) three users, and (c) five users.

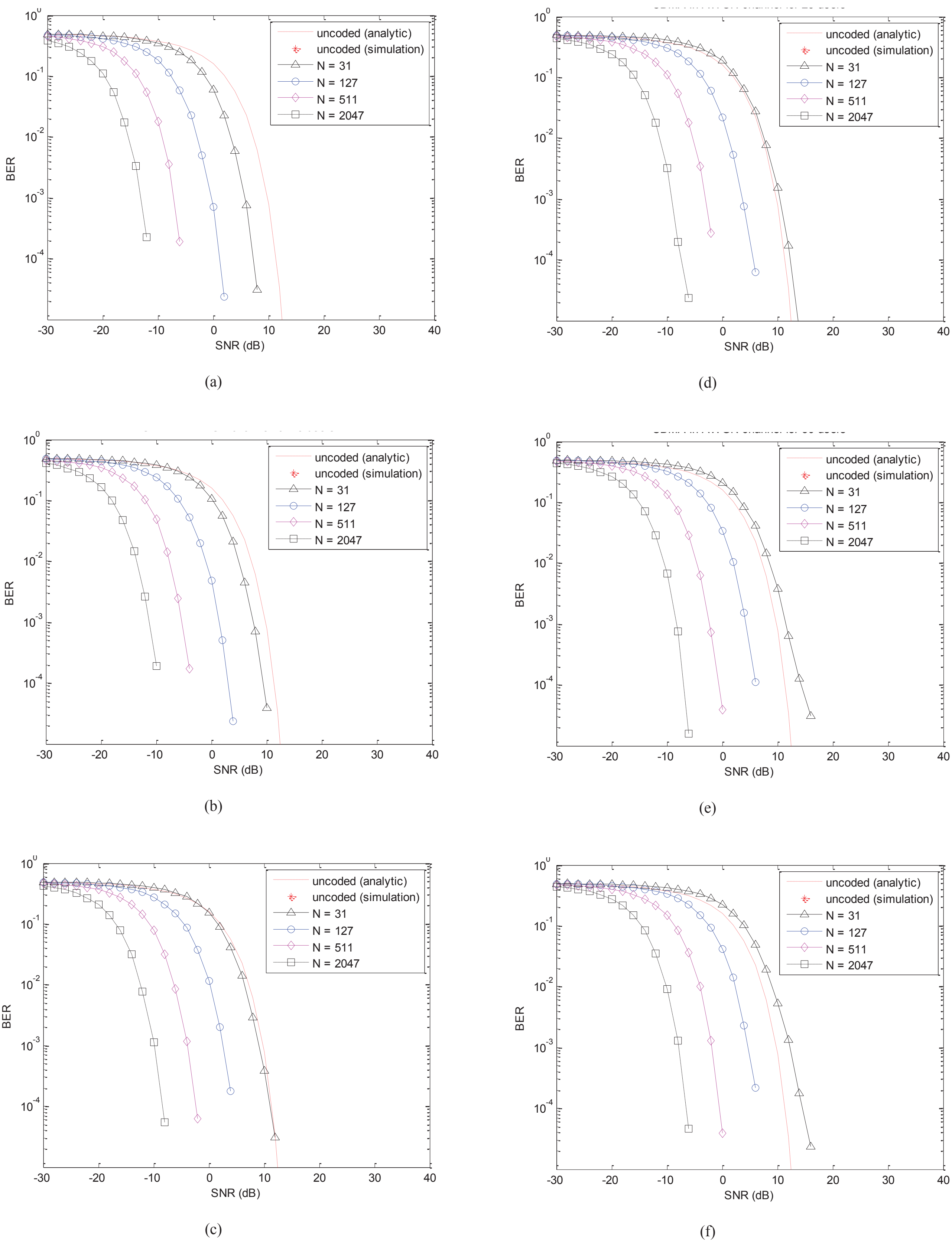


Fig. 3. Bit-error rate for (a) 10 users, (b) 15 users, (c) 20 users, (d) 25 users, (e) 30 users and (f) 31 users.

4.3 Performance for ten or more users

We shall now consider simulation results for higher numbers of users. Figs. 3(a) to 3(f) show the BER for 10, 15, 20, 25, 30 and 31 users respectively. As with the previous results, these figures show that as the number of users increase, the system BER worsens, resulting from increasing MAI.

For the code length N = 31 chips, for example, the results show that at an SNR of 8 dB, BER is 3.13 x 10^{-4} for ten users, 6.98 x 10^{-4} for 15 users, 2.94 x 10^{-3} for 20 users, 7.71 x 10^{-3} for 25 users, and 1.45 x 10^{-2} for 30 users. Because of the MAI, obtaining the same BER for a system involving a higher number of simultaneous users requires higher SNR. For example, for the 31-chip code, obtaining a BER of 10^{-4} requires an SNR of about -3.27 dB for a single user (Fig. 1), 4.01 dB for five users (Fig. 2c), 7.28 dB for 10 users, 11.07 dB for 20 users and 14.32 dB for 30 users (Figs 3a, c & e).

5. DISCUSSION

The simulation results that have just been presented confirm that as the number of users increases, the system BER worsens. This is consistent with expectation because increasing the number of simultaneous users implies higher MAI. However, a closer look at the results reveals that the simulation results have some surprises, explained as follows.

The simulation results show that as the number of users increase, the system BER degrades at similar rates for all the different code lengths: in general, BER curves for all the code lengths shift together, with all possessing similar slopes at high SNRs (Figs. 2 and 3). In contrast to this, as the number of users increase, system BER is expected to degrade faster for shorter Gold codes. A reason for this is that shorter codes have higher peak cross-correlation coefficients (Table 2). Also, by virtue of their length, shorter codes approach full-load condition earlier than longer codes.

Table 2. Peak cross-correlation of Gold codes*

n	N	t(n)	t(n)/φ(0)
3	7	5	0.7143
4	15	9	0.6000
5	31	9	0.2903
6	63	17	0.2698
7	127	17	0.1339
8	255	33	0.1294
9	511	33	0.0646
10	1023	65	0.0635
11	2047	65	0.0318
12	4095	129	0.0315

*In the last column, peak cross-correlation function, *t(n)*, for Gold code sequence is normalised by peak autocorrelation function *φ(0)*.

Apart from this, for a given code length, BER is expected to increase rapidly as full-load is approached. For example, the BER for a 31-chip Gold code is expected to increase rapidly, to flatten out horizontally, and to exhibit error floor as the number of users approaches 31. In connection with this, the slopes of the BER curves for different code lengths are expected to become increasingly different when the number of users increases. In contrast, the simulation results give no indication of this: even under full load, the 31-chip Gold code does not show any error floor or system saturation.

As a consequence of the difference in rate of degradation of BER with increasing number users, coding gains between BER curves of adjacent code lengths are expected to become increasingly unequal, as opposed to a single-user case, where the coding gain is constant. In contrast to this, the simulation results show no significant difference in coding gain between BERs of adjacent code lengths. The set of curves appears to maintain similar slopes at high SNR, with no visible difference in their coding gain.

The following are explanations for these surprising results:

1. **Selected reference user.** Any set of Gold codes comprises N+2 members. Two of these represent the preferred pair of *m*-sequences from which the remaining members are derived. In every instance of the current investigation, one of the preferred pairs was used for the encoding (and the decoding) of the data stream of the reference user. Hence, the outcome of the simulation indicates that the preferred pair has low cross-correlation with the rest of the code set.
2. **Peak correlation coefficient.** Peak correlation coefficient (Table 1) only gives the peak value that the correlation function (Equation 9) of a Gold code could have, but not the frequency of occurrence or the distribution of the peaks. If the peak value happens to be few and sparsely distributed for a particular code set, its degrading effect on MAI may not be very significant.
3. **Bipolarity of Gold codes.** Gold codes are bipolar codes, being +1 at one instant, and -1 at another. The same fact applies to the cross-correlation coefficients of the codes. As a result, there is the possibility of interference from one user cancelling out that of another. If a code set happens to be well-behaved, the mutual cancelling of the inteference from offending users might turn out to enhance the system BER performance.
4. **Synchronisation.** For the work reported in this paper, perfect synchronisation was assumed, and this might be a factor.

At first sight, the absence of error floor, even when the system was heavily loaded, raises a question on the validity of the simulation results. Regarding this, further investigation reveals that the outstanding performance is peculiar to the sets of Gold codes that have just been considered in this paper. Additional simulation results show that some other sets of Gold codes lack such excellent performance. Fig. 4 shows examples of these. Looking at this figure, it is clear that the BER performance of this category of codes has error floor when the system is significantly loaded. Results show that this inferior behaviour is peculiar to even-degree codes. These results indicate the need for careful choice of spreading codes when designing a CDMA system.

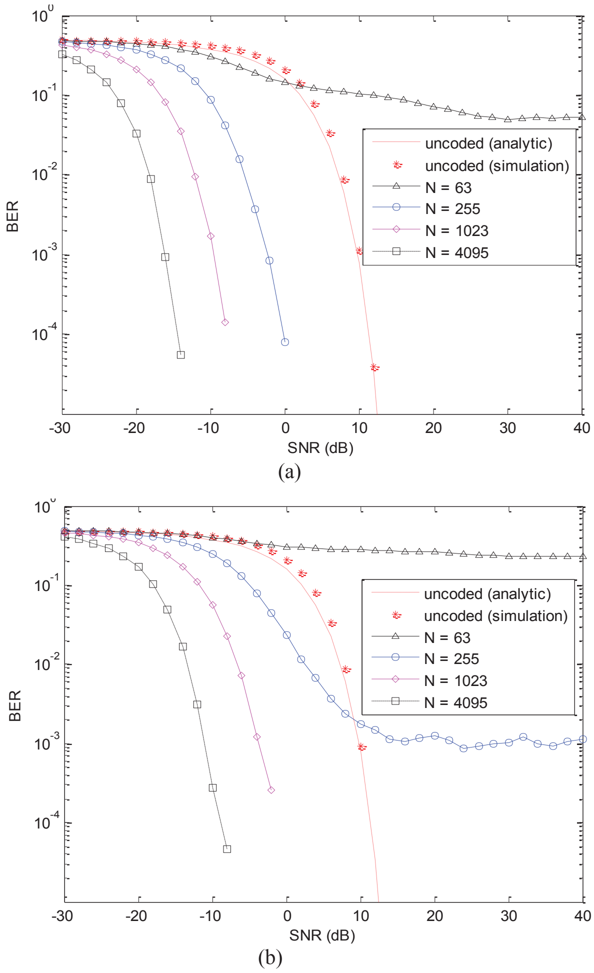


Fig. 4. Samples of results showing inferior performance of some other sets of Gold codes for (a) 10 users and (b) 30 users. These codes exhibited error floor and system saturation when the system was significantly loaded.

6. FUTURE WORK

The work reported in this paper involved the use of odd-degree Gold codes. As an extension of this, an effort is being made to investigate the system performance for even-degree Gold codes.

Apart from this, this paper considered the system performance in an AWGN channel. In the future, the system performance in a frequency-selective channel shall be investigated. This would entail the modelling of the performance of a multi-user, multi-carrier CDMA system in a frequency-selective channel.

This paper also assumed perfect synchronisation, which is only possible in the downlink. The system performance in an asynchronous environment might be considered in the future.

7. CONCLUSION

In this paper, we studied the performance of certain sets of Gold codes in a multi-user DS-CDMA system. Using simulation results, we examined the system BER performance under increasing system load for different code lengths. The sets of Gold codes performed significantly better than expected, with no indication of error floor or system saturation even when the system was heavily loaded. The outcome of this work indicates that the sets of Gold codes have better cross-correlation properties that make them more suitable for use in multi-user CDMA systems. The results also suggest that certain important properties of Gold codes are yet to be discovered.

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