Ternary Zero Correlation Zone Sequences for Multiple Code UWB

Di Wu, Predrag Spasojević and Ivan Seskar
WINLAB, Rutgers University
73 Brett Road, Piscataway, NJ 08854
{diwu,spasojev,seskar}@winlab.rutgers.edu

***Abstract*— We construct a ternary zero correlation zone (ZCZ) sequence set with both periodic and aperiodic ZCZ based on mutually orthogonal complementary sets. A multicode UWB system based on ternary ZCZ sequence sets can adapt its data rate by changing the size of the code set to satisfy different data rate requirements without compromising its BER performance. Multicode systems based on constructed ZCZ sequences can have a notably improved performance over a single code system employing m-sequences and over multicode systems based on comparable binary and ternary ZCZ sequences. We argue that the improvement over comparable binary and ternary ZCZ sequences is due to the unique periodic and aperiodic ZCZ property of the proposed sequence sets.**

***Index Terms*— Ternary sequence, zero correlation zone (ZCZ), ultra-wideband (UWB) , complementary sets**

I. Introduction

In this paper, we focus on signal designs based on ternary direct sequence UWB (TS-UWB) which includes epochs of zero signal amplitude as a natural extension of binary antipodal signaling [1, 2]. Ternary signaling is suitable for impulse based systems and, as further demonstrated here, enables significant improvement in the signal correlation properties.

A zero correlation zone (ZCZ) sequence set has the periodic and/or aperiodic correlation values equal to zero for a contiguous set of delays starting with a single delay. Thus, it can significantly alleviate the multipath interference and multiple access interference. Recently, there has been a considerable interest in applying the ZCZ sequences in the quasi-synchronous CDMA type systems.

ZCZ sequence set design was first studied by Suehiro in [3]. Fan *et al.* proposed binary, quadriphase and polyphase sequence sets derived from complementary sets [4–6], Torii and Nakamura proposed ZCZ set construction based on perfect sequences and unitary matrices [7]. Cha *et al.* proposed a ternary ZCZ sequence set constructed by cyclically shifting preferred ternary pairs [8].

Here, we propose ternary ZCZ sequence set construction based on mutually orthogonal (MO) complementary sets [9]. Compared with earlier work on ZCZ sets, constructed sets have both periodic and aperiodic zero correlation zone. For example, a binary periodic ZCZ sequence set with $(N, M, L_{zcz}) = (32, 4, 4)$ can be generated by Fan's method [6], where N is the length of the sequence, M is the family size (namely, the number of sequences in the set) and L_{zcz} is the length of the periodic ZCZ. Corresponding constructed sequences allow for an improved system performance relative to Fan's sets due to the fact that the ZCZ is both in the periodic and aperiodic sense.

Multicode approach [10] suggests splitting high data rate streams into several low rate data substreams. Each data substream is spread by a sequence and all the substreams are transmitted in parallel using synchronous multicode channels. Since a higher data rate is achieved by increasing the number of parallel code channels, the processing gain can be kept sufficiently large to alleviate the ISI for any particular sequence. Different data rates can be supported by changing the size of the sequence set assigned to a user. Instead of being limited by single sequence ISI, the data rate is limited by the sequence set correlation properties.

We study the BER performance of a multicode TS-UWB system employing the proposed ternary ZCZ set and experiencing a dense multipath [11]. A comparison is given with the performance of a single spreading sequence (with a reduced processing gain per sequence), and with comparable examples employing Fan's [6] and Cha's [8] ZCZ sets.

The paper is organized as follows. In Section II, we describe the recursive approach to construction of ternary ZCZ sequence sets with periodic and aperiodic ZCZ. In Section III, the single user multicode UWB system and the UWB channel models are introduced. Simulation results are presented in Section IV. In Section V, we draw the concluding remarks.

II. Ternary ZCZ Sequence Set Design

A. Basic Concepts and Notations

Before describing the ternary ZCZ set construction, we briefly describe a few basic concepts and notations.

Let $\theta_{\mathbf{a}_i,\mathbf{a}_i}$ denote the aperiodic autocorrelation function of the sequence $\mathbf{a}_i$ with length N. A set of M sequences $\{\mathbf{a}_i\}_{i=1}^{M}$ is said to be a complementary set, if the sum of their aperiodic autocorrelation functions vanishes, i.e.,

$$\sum_{i=1}^{M}\theta_{\mathbf{a}_i,\mathbf{a}_i}(l) = \sum_{i=1}^{M}\sum_{n=0}^{N-1-l} a_{i,n}a_{i,n+l} = 0, \forall l \neq 0.$$

where $a_{i,n}$ denotes the nth element in the sequence $\mathbf{a}_i$.

A set of complementary sequences $\{\mathbf{b}_i\}_{i=1}^M$ is a mate of the set $\{\mathbf{a}_i\}_{i=1}^M$ if their sequence length is equal, and $\sum_{i=1}^M \theta_{\mathbf{a}_i,\mathbf{b}_i}(l) = 0$ for any l. Complementary sets of sequences are mutually orthogonal if all pairs are mates.

We denote the ternary ZCZ sequence set as $T_{zcz}(N, M, L_{zcz})$, where N is the sequence length and M is the family size and L_{zcz} is the minimum auto and cross zero correlation zone over the set T_{zcz} in both periodic and aperiodic sense. The new ternary ZCZ sequences sets are constructed based on either binary or ternary MO complementary sequence sets.

B. Ternary ZCZ Set Construction Algorithm

Step 1: Construct the seed matrix $\Delta^{(0)}$.

Starting with either a binary or ternary complementary pair (TCP) $\{\mathbf{c}_1, \mathbf{c}_2\}$ [12], the seed matrix $\Delta^{(0)}$ is constructed as follows,

$$\Delta^{(0)} = \begin{bmatrix} \mathbf{c}_1 & \overleftarrow{\mathbf{c}_2} \\ \mathbf{c}_2 & -\overleftarrow{\mathbf{c}_1} \end{bmatrix} \tag{1}$$

where $\overleftarrow{\mathbf{c}_2}$ denotes the reverse of the sequence $\mathbf{c}_2$ and $-\overleftarrow{\mathbf{c}_1}$ denotes the sequence whose ith element is the negation of ith element in sequence $\overleftarrow{\mathbf{c}_1}$. Note that $\Delta^{(0)}$ can be partitioned into two MO complementary sets $\{\mathbf{c}_1, \mathbf{c}_2\}$ and $\{\overleftarrow{\mathbf{c}_2}, -\overleftarrow{\mathbf{c}_1}\}$.

Example 1: Let $\{\mathbf{c}_1, \mathbf{c}_2\} = \{++, +-\}$. Based on (1), the seed matrix is given by

$$\triangle^{(0)} = \begin{bmatrix} ++ & -+ \\ +- & -- \end{bmatrix}$$

where $'+'$ denotes 1 and $'-'$ denotes -1.

Note that $\triangle^{(0)}$ is comprised of two mutually orthogonal complementary sequence sets ($\begin{matrix} ++ \\ +- \end{matrix}$) and ($\begin{matrix} -+ \\ -- \end{matrix}$).

Step 2: Recursively construct larger MO complementary sets based on the seed matrix $\Delta^{(0)}$ [9].

Let $\triangle^{(p)}$ be a matrix of sequences with $M^{(p)}$ rows, each row contains $M^{(p)}$ sequences with equal length $N^{(p)}$. The recursive procedure constructs a larger matrix of sequences $\triangle^{(p+1)}$ with $2M^{(p)}$ rows, each row containing $2M^{(p)}$ sequences with length $2N^{(p)}$. That is,

$$\triangle^{(p+1)} = \begin{bmatrix} \triangle^{(p)} \otimes \triangle^{(p)} & -\triangle^{(p)} \otimes \triangle^{(p)} \\ -\triangle^{(p)} \otimes \triangle^{(p)} & \triangle^{(p)} \otimes \triangle^{(p)} \end{bmatrix} \tag{2}$$

where $-\triangle^{(p)}$ denotes the matrix whose ijth entry is the negation of the ijth entry of $\triangle^{(p)}$ and $'\otimes'$ denotes interleaving. Two sequences $\mathbf{a} = \{a_1, a_2, a_3, ...\}$ and $\mathbf{b} = \{b_1, b_2, b_3, ...\}$ are interleaved as $\mathbf{a} \otimes \mathbf{b} = \{a_1, b_1, a_2, b_2, ...\}$. The two matrices of sequences are interleaved by interleaving their corresponding sequences as described in Example 2.

Example 2: Based on the seed matrix $\Delta^{(0)}$

$$\Delta^{(0)} = \begin{bmatrix} ++ & -+ \\ +- & -- \end{bmatrix}$$

we use the recursive procedure (2) to construct larger MO complementary set matrix $\Delta^{(1)}$.

$$\begin{aligned} \Delta^{(0)} \otimes \Delta^{(0)} &= \begin{bmatrix} ++\otimes++ & -+\otimes-+ \\ +-\otimes+- & --\otimes-- \end{bmatrix} \\ &= \begin{bmatrix} ++++ & --++ \\ ++-- & ---- \end{bmatrix} \end{aligned} \tag{3}$$

and

$$\begin{aligned} -\Delta^{(0)} \otimes \Delta^{(0)} &= \begin{bmatrix} --\otimes++ & +-\otimes-+ \\ -+\otimes+- & ++\otimes-- \end{bmatrix} \\ &= \begin{bmatrix} -+-+ & +--+ \\ -++- & +-+- \end{bmatrix} \end{aligned} \tag{4}$$

From (2), we obtain the mutually orthogonal complementary sets

$$\begin{aligned} \Delta^{(1)} &= \begin{bmatrix} ++++ & --++ & -+-+ & +--+ \\ ++-- & ---- & -++- & +-+- \\ -+-+ & +--+ & ++++ & --++ \\ -++- & +-+- & ++-- & ---- \end{bmatrix} \\ &= \begin{bmatrix} \Delta_{1,1}^{(1)} & \Delta_{1,2}^{(1)} & \Delta_{1,3}^{(1)} & \Delta_{1,4}^{(1)} \\ \Delta_{2,1}^{(1)} & \Delta_{2,2}^{(1)} & \Delta_{2,3}^{(1)} & \Delta_{2,4}^{(1)} \\ \Delta_{3,1}^{(1)} & \Delta_{3,2}^{(1)} & \Delta_{3,3}^{(1)} & \Delta_{3,4}^{(1)} \\ \Delta_{4,1}^{(1)} & \Delta_{4,2}^{(1)} & \Delta_{4,3}^{(1)} & \Delta_{4,4}^{(1)} \end{bmatrix} \end{aligned} \tag{5}$$

Therefore,

$$\sum_{i=1}^{4} \theta_{\Delta_{i,k}^{(1)},\Delta_{i,k}^{(1)}}(l) = 0 \ \ \forall l \neq 0, \ k = 1,2,3,4. \tag{6}$$

and

$$\sum_{i=1,k\neq j}^{4} \theta_{\Delta_{i,k}^{(1)},\Delta_{i,j}^{(1)}}(l) = 0 \ \ \forall l, \ k,j = 1,2,3,4. \tag{7}$$

Step 3: Construct a ternary ZCZ sequence set by reorganizing the MO complementary set matrix $\Delta^{(p)}$ as

$$\begin{aligned} \Delta^{(p)} &= \begin{bmatrix} \Delta^{(p-1)} \otimes \Delta^{(p-1)} & -\Delta^{(p-1)} \otimes \Delta^{(p-1)} \\ -\Delta^{(p-1)} \otimes \Delta^{(p-1)} & \Delta^{(p-1)} \otimes \Delta^{(p-1)} \end{bmatrix} \\ &= \begin{bmatrix} \Delta_{1,1}^{(p)} & \Delta_{1,2}^{(p)} & \cdots & \Delta_{1,M}^{(p)} \\ \Delta_{2,1}^{(p)} & \Delta_{2,2}^{(p)} & \cdots & \Delta_{2,M}^{(p)} \\ \vdots & \vdots & \ddots & \vdots \\ \Delta_{M,1}^{(p)} & \Delta_{M,2}^{(p)} & \cdots & \Delta_{M,M}^{(p)} \end{bmatrix} \end{aligned} \tag{8}$$

where $M = 2^{p+1}$ is the number of complementary sets in the MO complementary set matrix $\Delta^{(p)}$ and $\Delta^{(p)}_{i,j}$, $i = 1, 2, ...M$, $j = 1, 2, ...M$ are the complementary sequences with equal sequence length.

By reorganizing the MO complementary set matrix $\Delta^{(p)}$, we construct the ternary ZCZ sequence set $T^{(p)}_{zcz}$ containing $M = 2^{p+1}$ ternary ZCZ sequences and with the following matrix form:

$$T^{(p)}_{zcz} = \begin{bmatrix} \Delta^{(p)}_{1,1} \circ \mathbf{Z}_M \circ \Delta^{(p)}_{2,1} \circ \mathbf{Z}_M \cdots \circ \Delta^{(p)}_{M,1} \circ \mathbf{Z}_M \\ \Delta^{(p)}_{1,2} \circ \mathbf{Z}_M \circ \Delta^{(p)}_{2,2} \circ \mathbf{Z}_M \cdots \circ \Delta^{(p)}_{M,2} \circ \mathbf{Z}_M \\ \vdots \\ \Delta^{(p)}_{1,M} \circ \mathbf{Z}_M \circ \Delta^{(p)}_{2,M} \circ \mathbf{Z}_M \cdots \circ \Delta^{(p)}_{M,M} \circ \mathbf{Z}_M \end{bmatrix}$$

where $\mathbf{Z}_M$ denotes sequence with M zero elements, i.e. $\mathbf{Z}_M = (00 \cdots 0)$. The notation $\mathbf{a} \circ \mathbf{b}$ denotes the concatenation of two sequences **a** and **b**.

Thus, the jth row of the matrix $T^{(p)}_{zcz}$ is a ternary ZCZ sequence T_j, $j = 1, 2, ...M$, with sequence length

$$N^{(p)} = 4^{p+1} N^{(0)} \tag{9}$$

where $N^{(0)}$ is the sequence length of the seed complementary pair in Step 1. The resulting both periodic and aperiodic ZCZ length of sequence T_j is given by

$$L^{(p)}_{zcz} = 2^p N^{(0)} \tag{10}$$

Example 3: For $p = 1$, the ternary ZCZ set $T^{(1)}_{zcz} = (N, M, L_{zcz}) = (32, 4, 4)$ with 4 ternary ZCZ sequences (i.e. T_1, T_2, T_3, T_4) can be constructed by reorganizing (5),

$$\begin{aligned} T^{(1)}_{zcz} &= \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \end{bmatrix}_{4\times 32} \\ &= \begin{bmatrix} \Delta^{(2)}_{1,1} \circ \mathbf{Z}_4 \circ \Delta^{(2)}_{2,1} \circ \mathbf{Z}_4 \circ \Delta^{(2)}_{3,1} \circ \mathbf{Z}_4 \circ \Delta^{(2)}_{4,1} \circ \mathbf{Z}_4 \\ \Delta^{(2)}_{1,2} \circ \mathbf{Z}_4 \circ \Delta^{(2)}_{2,2} \circ \mathbf{Z}_4 \circ \Delta^{(2)}_{3,2} \circ \mathbf{Z}_4 \circ \Delta^{(2)}_{4,2} \circ \mathbf{Z}_4 \\ \Delta^{(2)}_{1,3} \circ \mathbf{Z}_4 \circ \Delta^{(2)}_{2,3} \circ \mathbf{Z}_4 \circ \Delta^{(2)}_{3,3} \circ \mathbf{Z}_4 \circ \Delta^{(2)}_{4,3} \circ \mathbf{Z}_4 \\ \Delta^{(2)}_{1,4} \circ \mathbf{Z}_4 \circ \Delta^{(2)}_{2,4} \circ \mathbf{Z}_4 \circ \Delta^{(2)}_{3,4} \circ \mathbf{Z}_4 \circ \Delta^{(2)}_{4,4} \circ \mathbf{Z}_4 \end{bmatrix} \end{aligned} \tag{11}$$

where, e.g., $T_1 = (+ + + + \ 0000 \ + + - - 0000 \ - + - + 0000 \ - + + - 0000)$ is of length $N^{(1)} = 4^{p+1} N^{(0)} = 4^2 \cdot 2 = 32$.

Figure 1 depicts ZCZ sequences T_1, T_3 in Example 3 and their periodic and aperiodic auto and cross correlation properties. From (6) and (7), we can derive L_{zcz}, the length of ZCZ in both periodic and aperiodic sense. For $T^{(1)}_{zcz}$ we have $L_{zcz} = 4$.

Table 1 lists the sequence lengths N and ZCZ lengths L_{zcz} for constructed ternary sequence sets with family sizes M=2,4, and 8. The sequence length of Cha's ternary ZCZ sequence is of the form 4×2^n, $n = 1, 2, 3...$ [8] which is a subset of lengths described by (9). Thus, proposed construction approach is more flexible in terms of spreading sequence length selection.

Two of the proposed sets will be employed for the design of the multicode UWB system described in the next section.

TABLE I

N AND L_{zcz} OF CONSTRUCTED TERNARY ZCZ SEQUENCE SETS WITH FAMILY SIZE M=2,4,8

$M = 2$

L_{zcz}	2	3	4	5	6	7	8	$\cdots$
N	8	12	16	20	24	28	32	$\cdots$

$M = 4$

L_{zcz}	4	6	8	10	12	14	16	$\cdots$
N	32	48	64	80	96	112	128	$\cdots$

$M = 8$

L_{zcz}	8	12	16	20	24	48	32	$\cdots$
N	128	192	256	320	384	448	512	$\cdots$

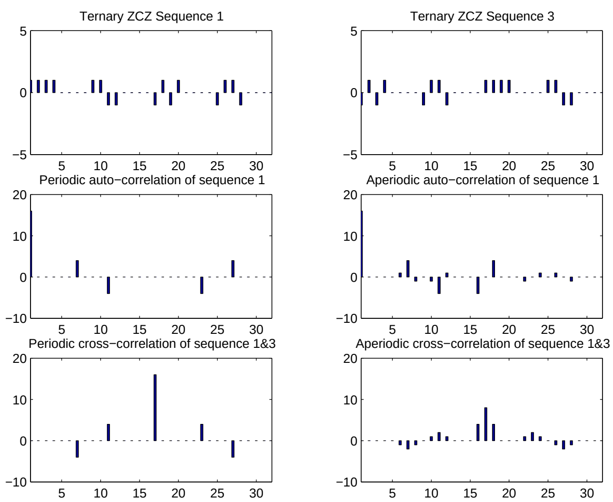

Fig. 1. ZCZ sequence T_1, T_3 and their correlation properties

III. MULTICODE UWB SIGNAL MODEL

A set of spreading sequences $C = \{\mathbf{c}_m\}_{m=1}^{M}$ of M sequences with length N is assigned to a single user. For simplicity we assume uncoded transmission. In this case, M consecutive information symbols $\{b_1, b_2, ...b_M\}$ are transmitted over M parallel code channels simultaneously. Thus, the symbol rate $R_s = M/T_s$, where T_s is the symbol period containing N chips of duration T_c. By increasing the number of code channels from 1 to M, we can adapt the system data rate from $1/T_s$ to M/T_s.

The transmitted baseband signal is given by

$$S(t) = \sum_r \sum_{m=1}^{M} b_{m,r} \sum_{n=0}^{N-1} c_{m,n}\psi(t - nT_c - rT_s) \qquad (12)$$

where $b_{m,r}$ is the r-th binary antipodal symbol transmitted using the m-th multicode sequence; $\psi(t)$ is the unit energy chip pulse with duration T_c and assumed known to the receiver. The spreading sequence set $\{\mathbf{c}_m\}_{m=1}^{M}$ is suggested to be the ternary ZCZ sequence set introduced in the preceding section.

The UWB channel with L resolvable paths is modeled as

$$h(t) = \sum_{l=0}^{L-1} \alpha_l \delta(t - \tau_l) \qquad (13)$$

where α_l and τ_l denote the channel gain and the propagation delay of the l-th path, respectively.

When sufficient multipath resolution is available, small changes in the propagation time only affect the path delay and path component distortion can be neglected. Under these assumptions, path coefficients α_l can be modelled as independent real valued random variables whose sign is a function of the material properties and, generally, depends on the wave polarization, angle of incidence, and the frequency of the propagating wave [13].

For simplicity, we quantize the multipath delay into bins, i.e. $\tau_l = lT_c$. In this case, for a single user multicode UWB system, the corresponding received signal model is:

$$r(t) = \sum_{l=0}^{L-1} \alpha_l S(t - lT_c) + n(t) \qquad (14)$$

where $n(t)$ is a white Gaussian noise process with power spectral density $N_0/2$.

IV. Numerical Results

We first compare the single user correlator receiver BER performance for multiple and single code systems employing a ternary ZCZ set and an m-sequence, respectively. Two data rates, i.e., Rate A and Rate B are assumed. For Rate A, $N = 16$ for single code scheme employing an m-sequence of length 15 padded with a zero and $N = 128$ for the multicode scheme with $M = 8$. For Rate B, $N = 8$ for a single code scheme employing an m-sequence of length 7 padded with one zero and $N = 32$ for the multicode scheme with $M = 4$.

The mean power of the multipath component is selected equal to the average value given in [14], which is based on the indoor line of sight (LOS) measurements performed in 23 homes. In [14], it is observed that the line of sight component and the first 10 multipath bins account for 33% and 75% of the total power, respectively. The sign of the reflected path coefficient is modeled as a uniformly distributed random variable [15]. The path power is quantized into 0.4 nanosecond bins corresponding to a chip duration T_c. We assume that each bin contains exactly one multipath component (emulating a dense multipath environment) and that the delay spread is restricted to be 4 nanoseconds. The effect of interchip interference has been assumed negligible.

In Figure 2, the average BER is plotted against the SNR per bit. For a multicode system, we employ the ternary ZCZ sequence set constructed in the Section II with parameter $(N, M, L_{zcz}) = (128, 8, 8)$ and $(N, M, L_{zcz}) = (32, 4, 4)$ for Rate A and B respectively. For single code scheme, we employ m-sequence with ending zero $\{---+--++-+-++++0\}$ and $\{+++-+--0\}$ for Rate A and Rate B respectively. BER performance improvement can be observed for both Rate A and Rate B. E.g., larger than $2dB$ and $1dB$ gain can be achieved by using ternary ZCZ set based multicode scheme over single code scheme when the target BER is 10^{-3}.

Figure 3 demonstrates that when employing ternary ZCZ set, the BER performance does not change when we the data rate is varied by increasing the number of code channels. The ternary ZCZ sequence set parameters are $(N, M, L_{zcz}) = (128, 8, 8)$, the number of code channels varies from 1 to 8. The three almost flat BER performance curves lie at $BER = 10^{-2}, 10^{-3}$ and 10^{-4} for $SNR = 8, 10$ and $12dB$ respectively.

In Figure 4, we compare the BER performance of the multicode UWB system employing Cha's ternary ZCZ set $(N, M, L_{zcz}) = (32, 4, 5)$ [8], Fan's binary ZCZ set $(N, M, L_{zcz}) = (32, 4, 4)$ [6] and the ternary ZCZ set with parameter $(N, M, L_{zcz}) = (32, 4, 4)$ constructed in this paper. At $BER = 10^{-4}$, the system employing constructed ternary ZCZ set can achieve $2dB$ and $4dB$ gains over the system using Fan's binary ZCZ set and Cha's ternary ZCZ set, respectively. This is due to the fact that the proposed ternary sets have a ZCZ in both periodic and aperiodic sense. Note that, the sequences from the constructed ternary set have the same peak to average power ratio (PAR) as that ones proposed by Cha.

V. Conclusion

Based on either binary or ternary mutually orthogonal complementary sets, the ternary ZCZ sequence set with both periodic and aperiodic zero correlation duration is constructed. Multicode systems employing the constructed ZCZ sequence set can have a notably improved performance over a single code system using m-sequences and over multicode systems based on comparable earlier binary and ternary periodic ZCZ sequences. We argue that the improvement over comparable binary and ternary ZCZ sequences is due to the unique periodic and aperiodic ZCZ property of the proposed sequence set.

REFERENCES

[1] D. Wu, P. Spasojević, and I. Seskar, "Multipath beamforming UWB signal design based on ternary sequences," *Proc. of 40th Allerton conference on Communication, Control, and Computing, Allerton, IL*, Oct. 2002.

[2] D. Wu, P. Spasojević, and I. Seskar, "Multipath beamforming for UWB: channel unknown at the receiver," *Conference Record of the Thirty-Sixth Asilomar Conference on Signals, Systems and Computers*, vol. 1, pp. 599 –603, Nov. 2002.

[3] N. Suehiro, "A signal design without co-channel interference for approximately synchronized CDMA systems," *IEEE J. Sel. Areas Commun.*, vol. 12, pp. 837 –841, June 1994.

[4] P. Fan, N. Suehiro, N. Kuroyanagi, and X. Deng, "Class of binary sequences with zero correlation zone," *Electronics Letters*, vol. 35, pp. 777–779, May 1999.

[5] X. Deng and P. Fan, "Spreading sequence sets with zero correlation zone," *Electronics Letters*, vol. 36, pp. 993–994, May 2000.

[6] P. Fan, "New direction in spreading sequence design and the related theoretical bounds," *IEEE 2002 International Conference on Communications, Circuits and Systems and West Sino Expositions*, vol. 1, pp. xliii–xlviii, 29 June-1 July 2002.

[7] H. Horii and M. Nakamura, "Extension of family size of ZCZ sequence sets derived from perfect sequences and unitray matrices," *IEEE Seventh International Symposium on Spread Spectrum Techniques and Applications*, vol. 1, pp. 170 –174, 2002.

[8] J. Cha, "Class of ternary spreading sequences with zero correlation duration," *Electronics Letters*, vol. 37, pp. 636 –637, May 2001.

[9] C. C. Tseng and C. Liu, "Complementary sets of sequences," *IEEE Transactions on Information Theory*, vol. 18, pp. 644 –652, Sep. 1972.

[10] Chih-Lin I and R. Gitlin, "Multi-code CDMA wireless personal communications networks," *IEEE International Conference on Communications*, vol. 2, pp. 1060 –1064, June 1995.

[11] M. Win and R. Scholtz, "On the energy capture of ultrawide bandwidth signals in dense multipath environments," *IEEE Communications Letters*, vol. 2, pp. 245–247, Sept. 1998.

[12] A. Gavish and A. Lempel, "On ternary complementary sequences," *IEEE Transactions on Information Theory*, vol. 40, pp. 522 –526, Mar. 1994.

[13] T. S. Rappaport, *Wireless Communications Principles and Practice*. Prentice Hall, 1997.

[14] S. Ghassemzadeh, R. Jana, V. Tarokh, C. Rice, and W. Turin, "A statistical path loss model for in-home UWB channels," *Ultra Wideband Systems and Technologies, 2002. Digest of Papers. 2002 IEEE Conference on*, pp. 59 –64, May 2002.

[15] G. Durisi and G. Romano, "Simulation analysis and performance evaluation of an UWB system in indoor multipath channel," *IEEE Conference on Ultra Wideband Systems and Technologies, 2002. Digest of Papers*, pp. 255–258, May 2002.

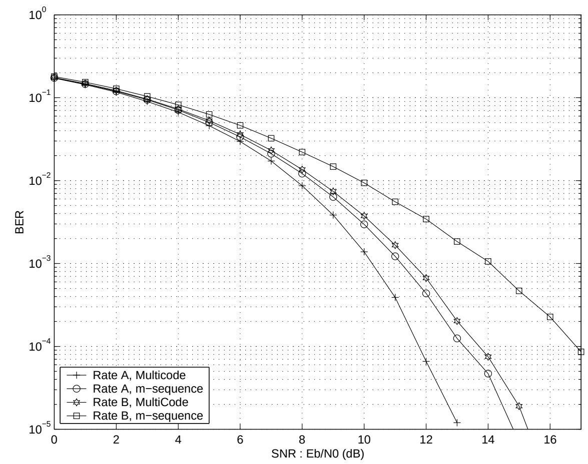

Fig. 2. BER performance for multicode system using ternary ZCZ sequences versus that of single code system using m-sequence

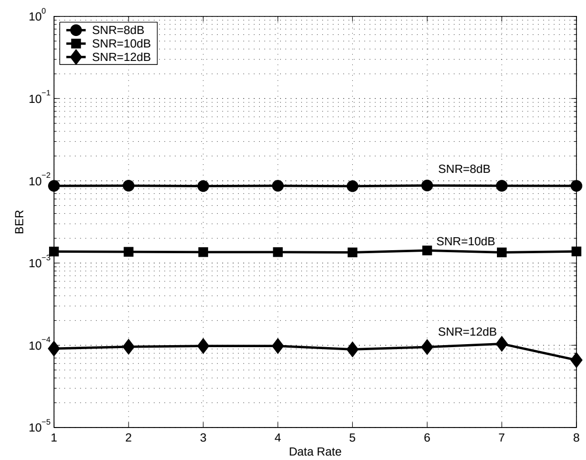

Fig. 3. BER performance for multicode system using ternary ZCZ sequences vs number of code sequences

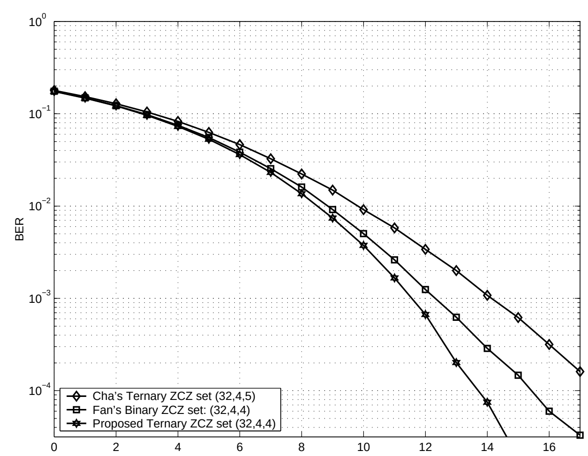

Fig. 4. BER performance comparison for multicode UWB system for different ZCZ sets