Walsh-Like Nonlinear Phase Orthogonal Codes for Direct Sequence CDMA Communications

Ali N. Akansu, *Senior Member, IEEE*, and Radha Poluri

***Abstract*—Walsh codes are perfectly orthogonal binary (antipodal) block codes that found their use in many popular applications over several decades including synchronous multiuser communications. It is well known in the literature that they perform poorly for the case of asynchronous multiuser communications. Therefore, the near-orthogonal and nonlinear phase Gold codes with better performance are the preferred user codes in asynchronous direct sequence code division multiple access (DS-CDMA) communications standards. In this paper, we relaxed linear phase requirements and new sets of Walsh-like nonlinear phase binary orthogonal user codes (transforms) are obtained for asynchronous and synchronous spread spectrum multiuser communications. It is shown that the proposed binary user code family outperforms the Walsh codes significantly and they match in performance with the popular, nearly orthogonal Gold codes closely for asynchronous multiuser communications in additive white Gaussian noise (AWGN) channels. It is also shown that all of the binary code families considered in this paper performed comparable for Rayleigh flat-fading channels. We present in this paper that there are a good number of such desirable code sets available in the binary sample space with different transform sizes. These new binary sets with good performance and flexible code lengths might help us to improve the spread spectrum multiplexing capabilities of future wireline and wireless CDMA communications systems.**

***Index Terms*—Additive white Gaussian noise (AWGN) channel, code division multiple access (CDMA), Gold sequences, orthogonal binary codes, Rayleigh flat-fading channel, Walsh sequences.**

I. Introduction

WALSH TRANSFORM (WT) has been widely used in many applications including direct sequence code division multiple access (DS-CDMA) communications. The orthogonality property and the ease of use due to its binary valued basis sequences make it attractive in implementations [1]–[3], [5], [8], [19]. On the other hand, it was shown that Walsh sequences (linear phase and orthogonal) are significantly inferior to the binary Gold codes (nonlinear phase and near-orthogonal) of similar length and their extensions for the case of asynchronous multicarrier communications [6], [7]. In contrast, Walsh sequences are superior to the near-orthogonal Gold family for synchronous communications due to their orthogonality feature. Orthogonal transmultiplexers provide a unified theoretical framework for multicarrier communications where the carrier sequences might pose different types of time-frequency properties [9]. Our main focus in this paper is on binary valued orthogonal carrier sequences that are simultaneously spread in the time and the frequency domains [9]–[11]. Therefore, they are called spread spectrum user codes in a DS-CDMA communications system or spread spectrum perfect reconstruction quadrature mirror filters (PR-QMF) in a critically sampled orthogonal filter bank configured in its multiplexer (synthesis/analysis filter bank) form with shortest possible filter sequences in time domain [10].

The Hadamard form of WT, the so-called Walsh–Hadamard transform (WHT), is defined with its built-in scalability as follows:

$$H_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \tag{1}$$

$$H_{2N} = \frac{1}{\sqrt{2}} \begin{pmatrix} H_N & H_N \\ H_N & -H_N \end{pmatrix} = H_N \otimes H_N \tag{2}$$

where the notation $\otimes$ indicates the matrix Kronecker product operator [1], [19]. These sequences are utilized in the current wireless communications standards such as IS-95, CDMA2000, WCDMA as binary user codes or multicarriers [20]. More specifically, WHT codes (row sequences of WT matrix) are employed for downlink (from cell tower to mobile handheld units) and Gold codes are used for uplink (from mobile handheld units to cell tower) communications as binary carriers or user signatures in some standards although they might coexist within the same channel.

Remark 1: As many other orthogonal transforms, WHT has a constant (DC) sequence in the function set. This feature is a requirement from any practical transform being employed in source coding applications where DC component of a signal is significant in many signal types.

Remark 2: Similar to all other popular orthogonal transforms, WHT basis functions are linear phase sequences.

Remark 3: Any binary sequence in an orthogonal Walsh set has a unique number of zero-crossings in the time domain. In a typical $N \times N$ size WHT matrix, row indices $(i = 0, 1, 2, \ldots, N-1)$ also indicate the numbers of zero crossings of the corresponding row sequences.

Remark 4: Except the DC sequence, the remaining sequences in a Walsh set have zero-mean values. In contrast, theoretically speaking, all sequences of the proposed Walsh-like nonlinear phase orthogonal transform (NPOT) sets and the Gold sets have nonzero-mean values.

Block transforms have been used for source coding applications where orthogonality, having a DC basis function, and

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The authors are with the Department of Electrical and Computer Engineering, New Jersey Institute of Technology, Newark, NJ 07102 USA (e-mail: akansu@njit.edu; rp74@njit.edu).

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linear phase features are important requirements for a good performance. As an example, discrete cosine transform (DCT) and discrete-time subband (wavelet) transforms employed in the international compression standards like JPEG and MPEG for image and video coding meet these requirements [11].

II. Walsh-Like NPOT

All binary sequences and transforms belong to the binary sample space. The basis generation kernels and built-in scalable nature of WT family make it easy to obtain them analytically [1], [2], [19]. On the other hand, the entire Walsh family is basically generated out of the unique 2×2 orthogonal matrix with linear phase row sequences through the matrix Kronecker product operator as shown in (2). Therefore, the Walsh sequences of any dimension have linear phase responses inherently.

Walsh family is a subset of available binary orthogonal spaces within the overall binary sample space. Although linear phase response is an inherent feature of orthogonal Walsh sequences, one of their most popular applications, namely, spread spectrum CDMA communications does not have such a requirement. In addition to the linear phase property, Walsh sets are also restricted not to include more than one sequence with the same number of time-domain zero crossings.

In this paper, we propose a new, Walsh-like binary orthogonal transform with nonlinear phase basis sequences. Relaxing linear phase property (even/odd symmetry in time sequences) allows us to enlarge the search region within the binary sample space that has orthogonal codes with better correlation properties than the Walsh family. We also relaxed the strict condition of having basis sequences with unique number of time-domain zero-crossings in the set. In addition, any of these new sets does not have to have DC basis sequence. Due to the availability of computational resources today, we performed brute force searches in the binary sample space in order to obtain some of these new orthogonal sets. The binary sample space for n-length orthogonal code sets generated through brute force search consists of $(2^n - 1)$ integer numbers. Code sets with n-basis functions are obtained by sequentially searching for orthogonal binary sequences in the sample space. The complexity of the sequential search algorithm employed in this paper is limited to the maximum of $(2^n - 1)^n$ iterations.

Table I displays the decimal values of binary basis sequences of the proposed Walsh-like transforms for the sizes of 8, 16, and 32 bits along with WTs where -1 value of binary sequence samples are replaced by 0 valued bits for this representation. The interested reader is referred to [12] for additional Walsh-like binary codes with various lengths.

Remark 5: Although the orthogonal WT of binary sequences is limited to power of two in its sizes, it is found that there are many other orthogonal and near-orthogonal transforms of various sizes in the binary sample space with nonlinear and linear phase basis sequences [12], [13]. Similarly, available code lengths are also very limited in the Gold family [14], [15]. The flexibility in sizes of available binary codes is a significant advantage in implementation of emerging spread spectrum multicarrier and multiuser radio applications like dense sensor networks with low-power and low-complexity constraints.

TABLE I

Decimal Values of Typical Nonlinear Phase Walsh-Like and Walsh Codes for 8, 16, 32 Bits (-1 Value of Binary Sequence Samples Is Replaced by 0 Valued Bits)

Index	*NLP Walsh-like(8bit)*	*Walsh (8bit)*	*NLP Walsh like(16bit)*	*Walsh (16bit)*	*NLP Walsh-like(32bit)*	*Walsh (32 bit)*
1	7	255	112	65535	61183585	4294967295
2	8	170	779	43690	150228466	2863311530
3	52	204	3223	52428	352724423	3435973836
4	59	153	4076	39321	509083300	2576980377
5	82	240	12428	61680	632502326	4042322160
6	93	165	13303	42405	786621269	2779096485
7	97	195	15467	50115	856722320	3284386755
8	110	150	16144	38550	943804419	2526451350
9			21797	65280	1155073796	4278255360
10			21978	43605	1334368679	2857740885
11			23102	52275	1383772514	3425946675
12			23233	39270	1496018737	2573637990
13			26182	61455	1657777299	4027576335
14			26297	42330	1771991744	2774181210
15			26973	49980	1953241845	3275539260
16			27042	38505	2134754390	2523502185
17					2249029968	4294901760
18					2371658291	2863289685
19					2427374086	3435934515
20					2617184661	2576967270
21					2686179319	4042264335
22					2873756772	2779077210
23					3065537697	3284352060
24					3186212802	2526439785
25					3245467845	4278190335
26					3391108758	2857719210
27					3620888147	3425907660
28					3699605744	2573624985
29					3882304418	4027518960
30					3963002113	2774162085
31					4056216884	3275504835
32					4204079975	2523490710

In Section III, we present performance of the proposed Walsh-like binary, nonlinear phase orthogonal codes. We compared their performance with the popular codes such as Gold and Walsh families. Our comparisons include their time-domain properties like auto- (intracode) and cross- (intercode) correlations, and bit error rate (BER) performances for the asynchronous multicarrier communications scenarios in additive white Gaussian noise (AWGN) and Rayleigh flat-fading channels. We also compared their BER performance as a function of the number of users in a multiuser communications system. It is shown that the proposed Walsh-like nonlinear phase binary orthogonal transform significantly outperforms Walsh codes, and provides a performance comparable to the Gold codes in AWGN channels for all performance metrics and communications scenarios considered in this paper. In contrast, it is also observed that all of the binary code families considered in this paper performed comparable for Rayleigh flat-fading channels. Moreover, it is shown that all of the code families

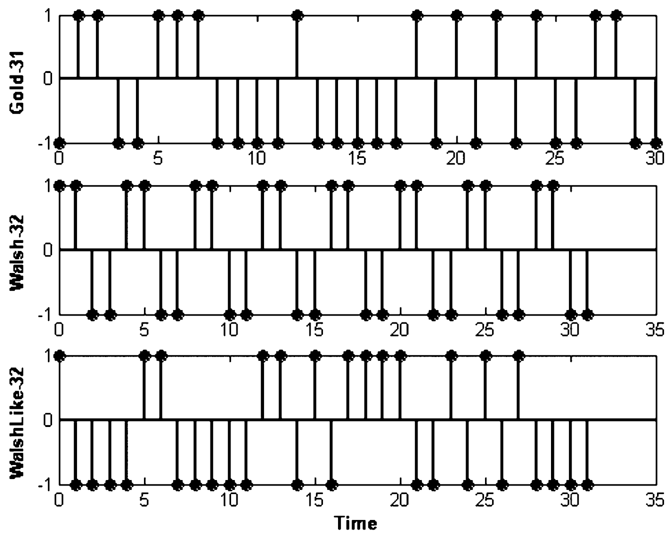


Fig. 1. Typical 32-length Walsh code, a typical 32-length proposed Walsh-like (NPOT) code along with a typical 31-length Gold code.

tested tend to perform comparable for all channel types when the number of users in the channel is increased.

III. Performance Comparisons

A. Time-Frequency and Correlation Properties

A typical 32-bit orthogonal Walsh code, a typical 32-length proposed Walsh-like code, and a 31-length Gold code are displayed in Fig. 1. Magnitude and phase functions of these codes are also shown in Fig. 2(a) and (b), respectively. Note that the sample sequence of the proposed orthogonal codes has more evenly spread frequency spectrum compared to the sample Walsh code of the same length. Additionally, proposed Walsh-like and Gold sequences have nonlinear phase functions while Walsh sequences are linear phase functions.

Autocorrelation sequences for typical codes of three families are displayed in Fig. 3(a). The cross-correlation sequences between an arbitrary pair of codes [for two-user case with codes $x_i(n)$ and $x_j(n)$ defined as $R_{xx}(m) = \Sigma_n x_i(n)x_j(n+m)$] are displayed in Fig. 3(b) for the three binary families under consideration. It is observed from the figure that the Gold and the proposed nonlinear phase Walsh-like orthogonal codes have similar autocorrelation (intracode correlation) and cross-correlation (intercode correlation) sequences while sample Walsh pair has worse correlation properties than the others.

For 32-bit codes, maximum, mean, deviation (variance/mean), square sum of correlation values of even, odd, aperiodic cross correlations between all the pairs of codes for Walsh, Gold, and the proposed codes (a typical one) are given in Table II [4]. It is observed from the table that the maximum cross-correlation value for Walsh is 32 whereas for Gold and for Walsh-like values, it is less than 32. Deviation value for proposed orthogonal codes is comparable to Gold codes. It is much higher for Walsh codes. Sums of square of correlation values are similar for different types of codes. Hence, as a metric, sum of square of correlations has no effect on the communications performance for the total family. These inter-

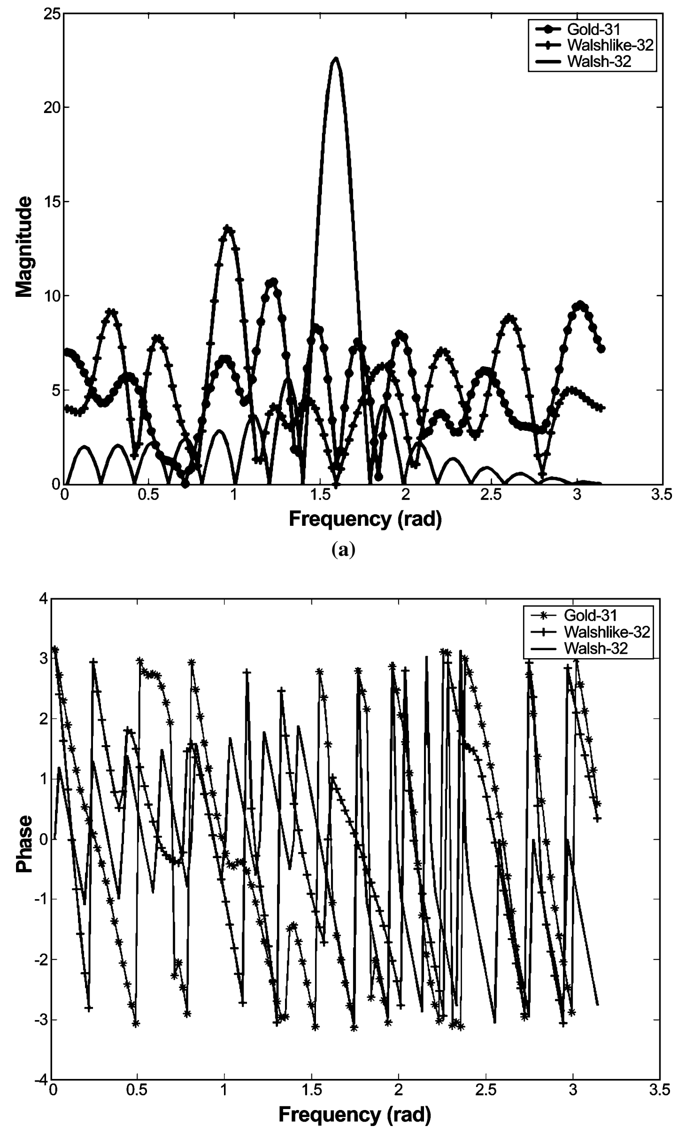
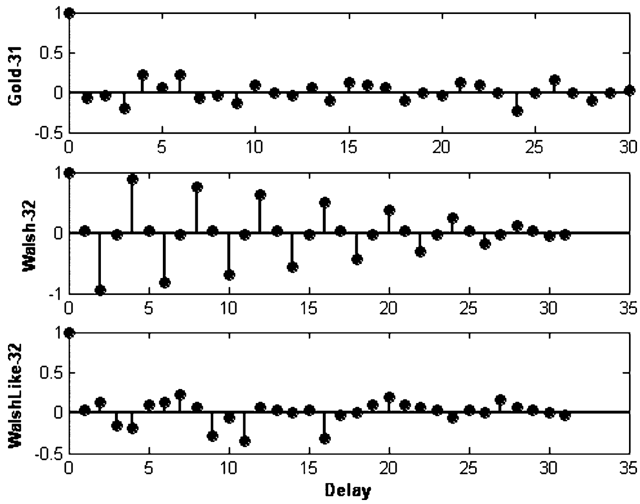


Fig. 2. (a) Magnitude functions and (b) phase functions of Walsh, Gold, and proposed Walsh-like binary codes plotted in Fig. 1.

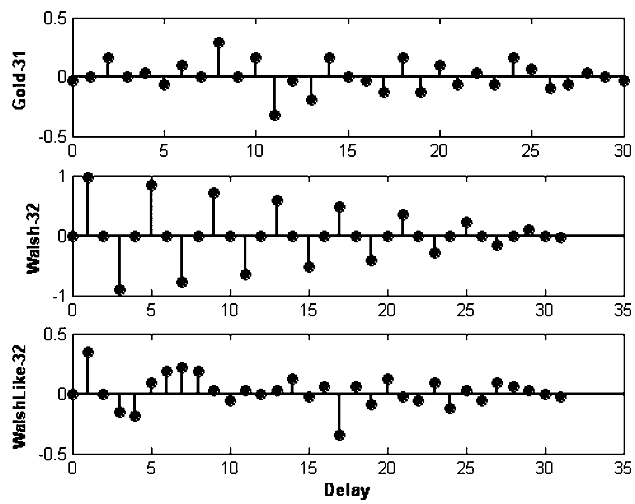
and intracode correlation properties (multiuser interference) along with the channel noise conditions imposed on them dictate the performance of a multiuser communications system at the receiver. Therefore, choosing the best possible user codes with minimum intra- and intercode correlation properties will significantly improve the performance of a DS-CDMA communications system, particularly for the cases with high signal-to-noise ratio (SNR) and low number of users.

B. AWGN Channel Performance

We first considered an asynchronous communications scenario with two users in the system. The goal here is to investigate the BER performance of the communications system with AWGN noise assumption for different user code families considered. This helps us to better understand the variations of the intra- and intercode correlations at the receiver whenever the channel noise is present since it dominates the performance



(a)



(b)

Fig. 3. (a) Autocorrelation (intracode correlation) and (b) cross-correlation (intercode correlation) sequences for typical Gold, Walsh, and Walsh-like codes.

TABLE II
CROSS-CORRELATION METRICS FOR 32- AND 31-LENGTH CODES

Parameter	***LP Walsh-32***	***NLP Gold -31***	***NLP WalshLike-32***
Maximum Even Correlation Def: Max($R_{xx}(m)+R_{xx}(m-N)$), $-(N-1)\leq m \leq (N-1)$, N is code length and $R_{xx}(m)=\Sigma_n x_i(n)x_j(n+m)$)	32	9	20
Maximum Odd Correlation Def :Max($R_{xx}(m)-R_{xx}(m-N)$)	32	17	24
Maximum Aperiodic Correlation Def :Max($R_{xx}(m)$)	31	12	19
Mean Even Correlation Def : Mean($R_{xx}(m)+R_{xx}(m-N)$)	1.82	4.25	4.21
Mean Odd Correlation Def: Mean($R_{xx}(m)-R_{xx}(m-N)$),	3.17	4.39	4.35
Mean Aperiodic Correlation Def : Mean($R_{xx}(m)$)	2.04	2.93	2.99
Deviation – Even Correlation Def: variance($R_{xx}(m)+R_{xx}(m-N)$)/Mean Even	11.4	2.77	3.15
Deviation – Odd Correlation Def: variance($R_{xx}(m)-R_{xx}(m-N)$)/Mean Odd	5.7	2.44	2.78
Deviation – Aperiodic Correlation Def: variance($R_{xx}(m)$)/Mean aperiodic	4.45	2.26	2.28
$\sum$ Even correlation^2	358400	432015	491072
$\sum$ odd correlation^2	419500	432383	492736
$\sum$ aperiodic correlation^2	388960	432199	491904

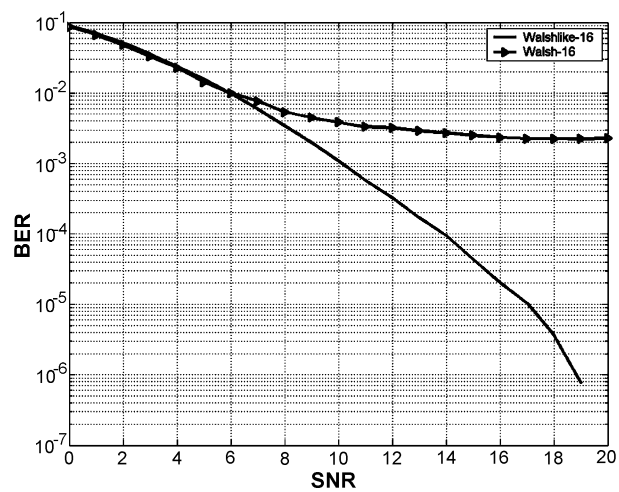


Fig. 4. BER performance of size 16 Walsh and proposed nonlinear phase Walsh-like orthogonal codes of size 16 for asynchronous communications channel and two-user scenario in AWGN.

of the binary detector especially for low SNR cases. The randomness of the channel noise will perturb the noise-free correlation properties of the user codes presented in Table II. The communications performance of a multiuser communications system is computed by taking the average of BER measurements over all possible pairs of codes and all possible delays for any given code family. Fig. 4 displays BER performances of 16-bit Walsh and proposed Walsh-like code families. It is clearly seen from this figure that the latter significantly outperforms the first one. Similarly, Fig. 5 displays the BER curves for 32-bit Walsh and Walsh-like and 31-bit Gold codes. It is observed from these curves that the proposed nonlinear phase Walsh-like orthogonal code family outperforms Walsh codes significantly, and its performance closely matches with the Gold codes. Fig. 6(a) and (b) shows the multiuser performance comparisons of proposed Walsh-like orthogonal codes along with the other two code families for SNR = 15 dB and SNR = 20 dB, respectively, as a function of number of users in the channel. As the number of simultaneous users in the communications system increases, multiple inter- (multiuser interference) and intracode correlations (self-induced multipath interference) dominate the BER performance. Therefore, BER performances of the three families considered in this paper merge together for higher number of simultaneous users in a multiuser communications system as seen in those curves. Note that this point is oversighted quite often and many of the comparative performance studies reported in the literature are mostly limited to only two-user and infinite-user scenarios. In a real-world system, there are a finite number of users, usually more than two. The authors are currently studying this problem from the multiuser interference modeling perspective.

Since the proposed nonlinear phase Walsh-like codes are orthogonal in their nature, theoretically speaking, they outperform the Gold codes for the synchronous communications chan-

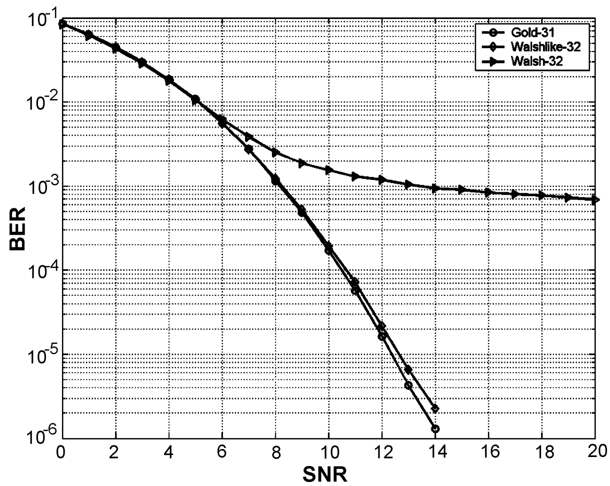


Fig. 5. BER performances of size 31 (near-orthogonal) Gold, size 32 Walsh, and 32 size nonlinear phase Walsh-like (orthogonal) codes for asynchronous communications channel and two-user scenario in AWGN.

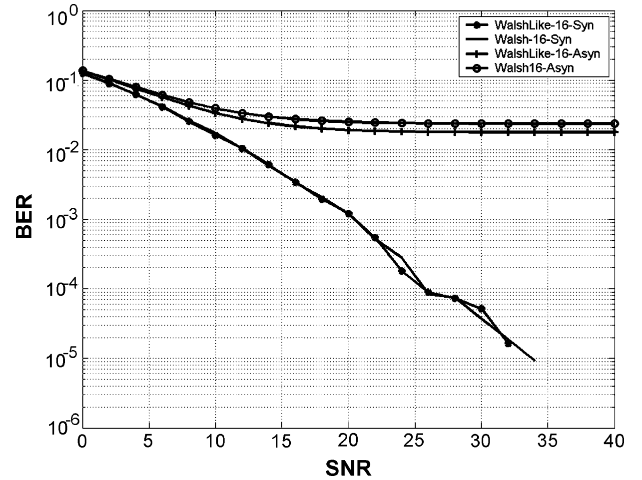


Fig. 7. BER performances of size 16 Walsh and size 16 nonlinear phase Walsh-like (orthogonal) codes for synchronous and asynchronous communications in Rayleigh flat-fading channels with two-user scenario.

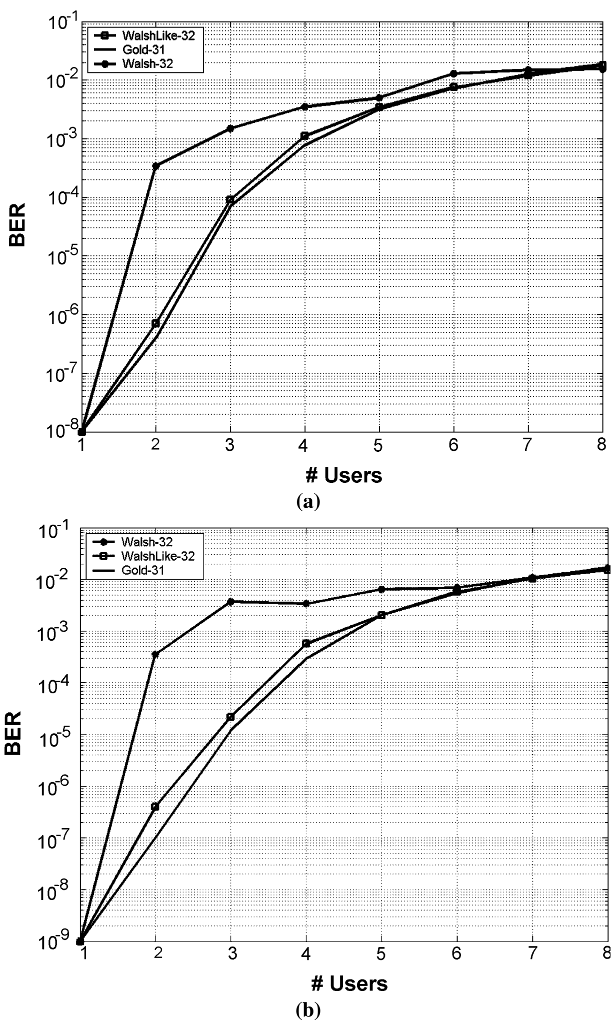


Fig. 6. (a) Multiuser performances of size 31 (near-orthogonal) Gold, size 32 Walsh, and size 32 nonlinear phase Walsh-like (orthogonal) codes in AWGN channel for (a) SNR = 15 dB and (b) SNR = 20 dB as a function of number of users in the system.

nels (as Walsh sequences) while performing comparable with them for the asynchronous AWGN case. Moreover, they provide much wider selection of orthogonal and near-orthogonal binary codes with respect to their lengths, and with good BER performances.

C. Rayleigh Flat-Fading Channel Performance

Under Rayleigh flat fading, channel has a constant gain and linear phase over a bandwidth which is greater than the transmitted signal bandwidth [16], [18]. Here, the channel conditions are assumed to remain the same during a symbol interval. Spectral characteristics of the transmitted signal are preserved at the receiver whereas the amplitude of the received signal changes with time. Fading channel for each user is modeled independently of the other users in the uplink scenario. Rayleigh fading is a multiplicative distortion and modeled as $y(t) = h(t)*s(t)+n(t)$, where $h(t)$ is the channel waveform, $s(t)$ is the transmitted signal, $n(t)$ is the AWGN, and the notation $(*)$ is the multiplication [17]. For flat-fading channel, $h(t)$ consists of a single tap with zero delay. $h(t)$ is a wide-sense stationary (WSS) complex Gaussian process, with zero-mean and unit variance, whose amplitude varies as a Rayleigh probability density function (pdf). Clark's model is used to define the spectral characteristics of the channel that are controlled by the Doppler frequency of the mobile [16]. Smith's simulation model is employed for generating the fading model [16]. Complex Gaussian samples generated for $h(t)$ are masked with a filter whose power spectral density (PSD) function is given by

$$\mathrm{S}_{hh}(f) = 1.5/\pi f_d \sqrt{1-(f/f_d)}^2 \quad |f| < f_d$$

where f_d is the Doppler frequency. Inverse fast Fourier transform (FFT) followed with square-root operation is applied on the resulting samples to generate Rayleigh distributed amplitude pdf.

Fig. 7 displays the BER performances of the proposed Walsh-like code family of size 16, and Walsh codes of size 16 in synchronous and asynchronous Rayleigh flat-fading channel conditions for a two-user case. Performance of the proposed code is similar to that of Walsh with length 16 in both cases. Similarly, Fig. 8 shows the BER performances of the Walsh-like codes of size 32, Gold codes of size 31, and Walsh codes of size

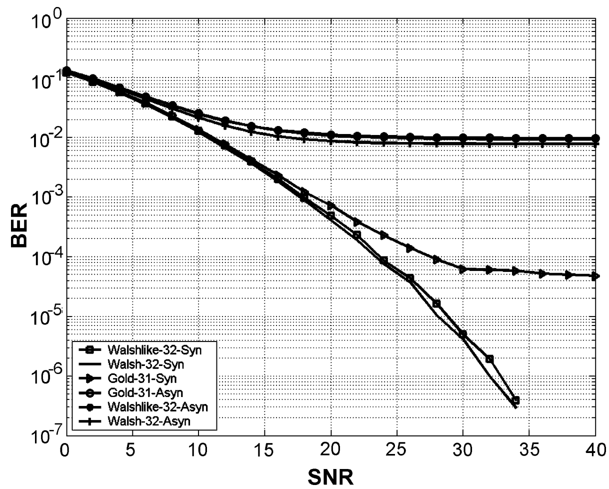
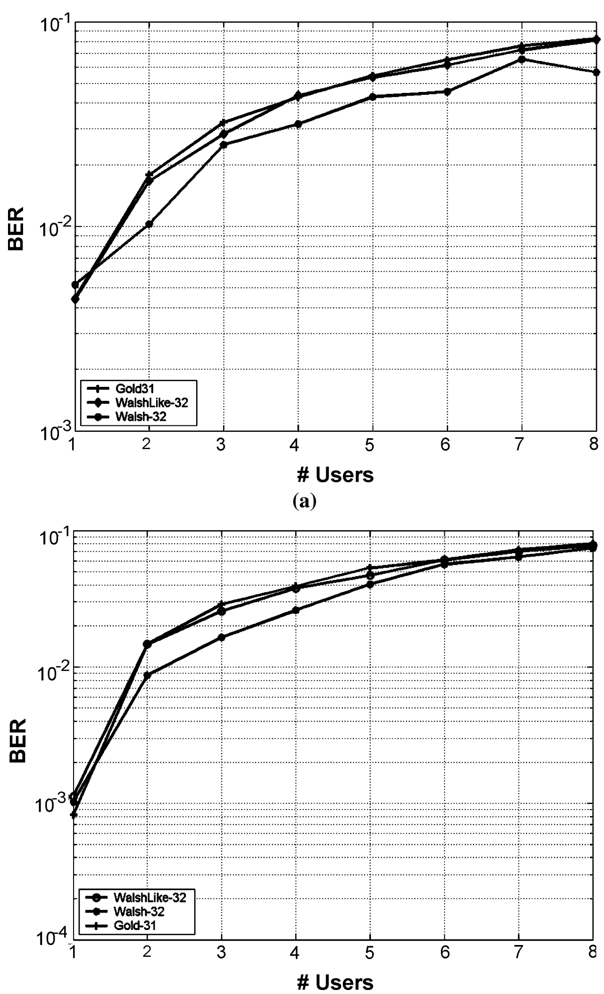


Fig. 8. BER performances of size 31 (near-orthogonal) Gold, size 32 Walsh, and nonlinear phase Walsh-like (orthogonal) codes for the two-user, synchronous and asynchronous Rayleigh flat-fading channel scenarios.



(b)

Fig. 9. Multiuser BER performances of size 31 (near-orthogonal) Gold, size 32 Walsh, and size 32 nonlinear phase Walsh-like (orthogonal) codes for Rayleigh flat-fading channel with (a) SNR = 15 dB (asynchronous case) and (b) SNR = 20 dB as a function of number of users in the system.

32 for both synchronous and asynchronous Rayleigh flat-fading channel conditions for the two-user case. It is observed from this figure that the performance of proposed codes closely matches with the other codes. It is also observed that orthogonal codes perform better than near-orthogonal Gold codes under Rayleigh flat-fading channel conditions for synchronous case. This figure also shows that all of the codes tested perform poorly for asynchronous scenario. Fig. 9(a) and (b) shows the multiuser BER performance of the proposed Walsh-like orthogonal, Gold, and Walsh codes as a function of the number of users in the channel at SNR = 15 dB and SNR = 20 dB, respectively, for Rayleigh flat-fading channels. It is seen from these BER curves that all codes perform comparable in Rayleigh flat-fading channels.

IV. Conclusion

The growing demand for orthogonal, fixed power (binary/antipodal) user codes challenges us to design additional orthogonal codes to be employed in the emerging and future applications of multicarrier spread spectrum communications with flexible code sizes and power requirements than the ones used in the current wireless technologies. We made an attempt to address that need in this paper. We show that the Walsh codes utilize only a small subset of the orthogonal binary sample space due to their intrinsic restrictions that are not necessarily important for spread spectrum CDMA communications. We proposed a design methodology, and searched and obtained a number of nonlinear phase Walsh-like orthogonal code sets that outperform Walsh codes, and closely match with or outperform the Gold codes for asynchronous and synchronous multicarrier CDMA applications under a variety of channel assumptions. The communications capabilities of the existing spread spectrum systems using Walsh and Gold codes might be improved in their next generations by employing these new code sets and others. Additionally, having a rich library of binary code sets, with flexible lengths and good performance, will offer further efficiencies and additional information about security options in the user code level for the wireless communications and sensor networks applications in the future.

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Ali N. Akansu (SM'95) received the B.S. degree from the Technical University of Istanbul, Istanbul, Turkey, in 1980 and the M.S. and Ph.D. degrees from the Polytechnic University, Brooklyn, NY, in 1983 and 1987, respectively, all in electrical engineering.

Since 1987, he has been with the New Jersey Institute of Technology (NJIT), Newark, where currently, he is a Professor of Electrical and Computer Engineering. He was a Founding Director of the New Jersey Center for Multimedia Research (NJCMR) between 1996–2000, and the national Science Foundation (NSF) Industry-University Cooperative Research Center (IUCRC) for Digital Video between 1998–2000. He spearheaded the National Security Agency (NSA) Center of Academic Excellence in Information Assurance Education at NJIT in 2003 and led it until October 2005. He was the Vice President for Research and Development of IDT Corporation [NYSE: IDT] between June 2000 and September 2001. He was the founding President and CEO of PixWave, Inc. (an IDT subsidiary). He was an academic visitor at IBM T.J. Watson Research Center and at GEC-Marconi Electronic Systems Corp. during the summers of 1989 and 1996 and 1992, respectively. He has published about 200 refereed conference papers, journal articles, and books on block, subband and wavelet transforms and their applications in image/video coding, digital communications, Internet multimedia, and information security. He is the coauthor (with R.A. Haddad) of the book *Multiresolution Signal Decomposition: Transforms, Subbands and Wavelets* (New York: Academic Press, 1992 and 2000), and a coeditor (with M.J.T. Smith) of a book entitled *Subband and Wavelet Transforms: Design and Applications* (Norwell, MA: Kluwer, 1996). He is the coeditor of the book (with M.J. Medley) *Wavelet, Subband and Block Transforms in Communications and Multimedia* (Norwell, MA: Kluwer, 1999). He is also the coauthor of a research monograph (with H.T. Sencar and M. RamKumar) *Data Hiding Fundamentals and Applications: Content Security in Digital Multimedia* (New York: Elsevier-Academic Press, 2004). He regularly consults to the industry and legal sector. Currently, he sits on the boards of directors of a few companies and a private equity fund in the field of CleanTech and Green Development. His research and entrepreneurial interests include signal theory, linear transforms and algorithms, next generation Internet including security aspects, signal processing for radio communications and RF engineering, signal processing for financial engineering, renewable energy, and clean technologies.

Dr. Akansu has served as an Associate Editor of IEEE TRANSACTIONS ON SIGNAL PROCESSING. He has served as a member of the Signal Processing Theory and Methods, and Multimedia Signal Processing technical committees of the IEEE Signal Processing Society. He organized the first Wavelets Conference in the United States in April 1990. He was the technical program chairman of IEEE Digital Signal Processing Workshop 1996, Loen, Norway. He served as a member of the Steering Committee and the Publications Chair of IEEE ICASSP 2000, Istanbul, Turkey. He was the Lead Guest Editor of two special issues on theory and application of IEEE TRANSACTIONS ON SIGNAL PROCESSING on filter banks and wavelet transforms (April 1998), and on signal processing for data hiding in digital media and secure content delivery (June 2003).

Radha Poluri received the B.S. degree in electronics and communication engineering from Regional Engineering College, Warangal, India, in 1983 and the M.S. degree in computer science from Osmania University, Hyderabad, India, in 1995. Currently, She is working towards the Ph.D. degree in electrical engineering at the New Jersey Institute of Technology, Newark.

She was formerly with DRDO, India, where she worked on different airborne signal processing systems. Her current research interests include the theory and design of orthogonal transforms and multiplexers, multiuser interference analysis and multiuser detection techniques in OFDM and CDMA technologies, and secure sensor communications.