Scale Time Offset Robust Modulation (STORM) in a Code Division Multiaccess Environment

David M. Jenkins Jr.

Abstract—Scale Time Offset Robust Modulation (STORM) [1]–[3] is a high bandwidth waveform design that adds time-scale to embedded reference modulations using only time-delay [4]. In an environment where each user has a specific delay and scale, identification of the user with the highest signal power and that user's phase is facilitated by the STORM processor. Both of these parameters are required in an efficient multiuser detection algorithm. In this paper, the STORM modulation approach is evaluated with a direct sequence spread quadrature phase shift keying (DS-QPSK) system. A misconception of the STORM time scale modulation is that a fine temporal resolution is required at the receiver. STORM will be applied to a QPSK code division multiaccess (CDMA) system by modifying the spreading codes. Specifically, the in-phase code will use a typical spreading code, and the quadrature code will use a time-delayed and time-scaled version of the in-phase code. Subsequently, the same temporal resolution in the receiver is required before and after the application of STORM. In this paper, the bit error performance of STORM in a synchronous CDMA system is evaluated and compared to theory, and the bit error performance of STORM incorporated in a single user WCDMA downlink is presented to demonstrate the applicability of STORM in a modern communication system.

Keywords—Pseudonoise coded communication, Cyclic codes, Code division multiaccess

I. INTRODUCTION

TRANSMITTED-REFERENCE (TR) communication systems using time delay decode the information bits by an autocorrelation process. When the received signal contains an excessive amount of noise, the correlation of that signal is noisy. Under the same noise conditions, the SNR of a transmitted reference system is 3dB lower than a coherent communication system [5]. This decrease in SNR is due to splitting the transmit power between the base and reference waveforms under the same noise conditions. If the environment and SNR requirements permit the use of a TR system, the advantages of a TR system include, for example, the absence of a coherent carrier and stored symbols [6]. In this paper, a base signal and reference signal will be modulated using spread quadrature phase shift keying.

Scale Time Offset Robust Modulation (STORM) [2] has been proposed to supplement the area of TR signaling by adding additional information or time scale to the reference signal. The STORM detector is an autoambiguity function which can be viewed as an cross-correlation between two signals with one signal being a time-scaled and time-delayed replica of the second signal. This correlation yeilds deterministically time varying peak that changes with offset from

synchronization. A time varying peak allows rapid synchronization using a low rate processor. In addition, STORM offers robustness in a dispersive environment. In a dispersive environment, the received signal is time scaled to some degree irrespective of modulation type. Using the STORM detector, the information is decoded using a approach that relies on the relative time-scale correlation of the received waveforms. In this paper, the transmitted reference is imposed by modifying the pseudorandom binary sequence (PRBS) spreading codes, and it will be shown in Section III-C that this modification of the PRBS increases the maximum cross-correlation properties of the code set but minimal impact on the subsequence properties. The impact of this increase is evaluated in a general CDMA and a specific WCDMA system in Section V.

A general spread quadrature phase shift keying system is shown in Figure 1. In this figure, the in-phase and quadrature information bits b_i and b_q are spread by in-phase and quadrature spreading codes c_i and c_q, respectively. In general, the in-phase or quadrature spreading codes can be the same or different codes from the same code family. In this paper, the quadrature code is obtained by mapping the in-phase code through an algorithm that imposes a time-scale correlation in the received signal that allows a STORM detector to be effective, and the focus of this paper is to determine the impact of the spreading code modification on the standard performance metrics of CDMA systems. In a DS-QPSK system, the best STORM performance is achieved if $b_i = b_q$ which halves the data rate. This is a common approach to increase the signal-to-noise ratio [7].
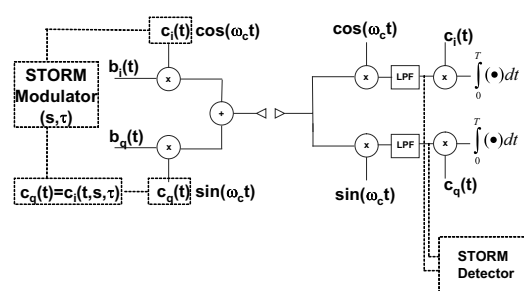

Fig. 1. A general spread quadrature phase shift keyed system with the addition of a STORM detector (in dashed lines).

A waveform design incorporating STORM is proposed in Section II, and this waveform is based on Kasami and Gold codes. Reasons for selecting these codes and a procedure for generating a STORM code from the initial code sequence is discussed in Section III. A general multiuser code division

D. Jenkins is with the Applied Research Laboratory, The Pennsylvania State University P.O. Box 30 State College, PA 16804 Email: dmj114@psu.edu. This paper is an enhancement of the work presented in [1].

World Academy of Science, Engineering and Technology
International Journal of Electronics and Communication Engineering
Vol:5, No:8, 2011

multiacces environment will be presented in Section IV along with a discussion of a general Code Division Multiaccess (CDMA) system and a modern Wideband Code Division Multiaccess (WCDMA). CDMA and WCDMA simulation results will be presented in Section V. Finally, results will be summarized in Section VI.

II. WAVEFORM DESIGN

The STORM waveform design is proposed to be incorporated into modern CDMA systems. Generally, the scale time offset robust modulation (STORM) [2], [3] is a transmitted reference scheme given by

$$x(t) = b_s(t) + \frac{a_m}{s_m} b_s \{s_m(t - \tau_m)\}, \qquad (1)$$

where $x(t)$ is the temporal waveform for one symbol, $b_s(t)$ is the base signal, s_m is the scale introduced at the modulator, a_m is the amplitude imparted at the modulator, and τ_m is the time-delay introduced at the modulator. In order to normalize the energy for both the base and offset signal, the amplitude of the offset signal is also amplified by the time-scale factor s_m. The base signal is given by

$$b_s(t) = \sum_{n=0}^{L-1} c[n] \text{rect}\left(\frac{t - nt_c}{2t_c}\right) \cos(2\pi f_c t), \qquad (2)$$

where $c[n]$ are samples of a binary phase shifted spreading sequence of length L, f_c is the carrier frequency, and the rectangle function that creates each chip is defined by

$$\text{rect}(t) = \begin{cases} 1, & |t| < \frac{1}{2}, \\ \frac{1}{2}, & |t| = \frac{1}{2}, \\ 0, & |t| > \frac{1}{2}. \end{cases} \qquad (3)$$

In order to circumvent a precise timimg requirement, the STORM approach will operate on the spreading codes. For this paper, the STORM modulation is given by

$$x(t) = b_i(t) (b_s(t) + j o_s(t)), \qquad (4)$$

where b_i is ± 1 the binary information bit, j is the $\sqrt{-1}$, and the offset sequence is defined as

$$o_s(t) = \sum_{n=0}^{L-1} \hat{c}[n] \text{rect}\left(\frac{t - nt_c}{2t_c}\right) \cos(2\pi f_c t). \qquad (5)$$

In the offset sequence, $\hat{c}[n]$ is a spreading code that is a scaled and delayed version of the base sequence code $c[n]$. A procedure for obtaining $\hat{c}[n]$ from $c[n]$ is discussed in Section III-C.

The complex wideband autoambiguity function is used to decode the modulated amplitude, scale, and time-delay is given by [8] as

$$\hat{\phi}_{xx}(t_o, s_i, \tau_i) = \frac{1}{T} \int_{t_o}^{t_o+T} x(t) x^* \{s_i(t - \tau_i)\} dt, \quad (6)$$

where $*$ denotes complex conjugate, s_i is the demodulator scale, τ_i is the demodulator time-delay, t_o is the start of the

measurement window, and T is the duration of the processor and is matched to the transmitted signal length. The autoambiguity function is a correlation surface with time-scale and time-delay as independent variables. A slice of this surface at a time-scale $s_i = 1$ is the partial period autocorrelation function.

III. SPREADING CODE SELECTION AND GENERATION

Since properly decoding the transmitted reference modulator scale and delay can be viewed as an autocorrelation process, the autocorrelation properties of the spreading sequence govern the accuracy in selecting the peak location and peak amplitude. These quantities are important because peak location is the modulated delay τ_m and the peak value is the modulated amplitude a_m. If there is one user, a maximal length binary sequence has autocorrelation properties that most nearly approximate white noise using a deterministic sequence [9]. In the case of a small number of users, the small set of Kasami codes [10] are a spectrum spreading codes that have desireable properties. The autocorrelation of a Kasami sequence approximates an impulse and there is minimal cross-correlation between codes. The minimal cross-correlation between codes is necessary to reduce multiaccess interference (MAI) in CDMA. In the case of a large number of users, Gold codes [11] have suitable autocorrelation and cross-correlation properties. While they are orthogonal and ideal for multiuser systems, Walsh-Hadamard sequences are less desirable for STORM because of their autocorrelation properties. An examples of a Walsh-Hadamard code is an alternating sequence of ones and zeros, and this sequences has a nonunique autocorrelation peak.

Key features of the Kasmi Code are presented in Section III-A. Similarly, features of the Gold code are discussed in Section III-B. Algorithms necessary to construct the STORM code are presented in Section III-C.

A. Kasami Code Generation

Features of the small set of Kasami codes will be presented in this section. These sequences are generated by starting with a length $2^N - 1$ maximal length sequence $b[n]$ where N is constrained to be an even integer. Decimate this sequence by $a[n] = b[qn]$ where $q = 2^{N/2} + 1$. The result $a[n]$ is another maximal length sequence of length $N/2$. The sequence $b[n]$ and the modulo-two addition of $b[n] + a[n + \Delta]$ where Δ is a time shift yields the small set of Kasami codes. In total, there are $2^{N/2}$ codes because the $a[n]$ sequence is repeating. Kasami code have a maximum circular cross-correlation between codes of $2^{\frac{N}{2}} - 1$. A circular cross-correlation is defined by [12] as

$$R_{ab}[n] = IDFT \{DFT(a[n])^* DFT(b[n])\}, \qquad (7)$$

where the DFT is the discrete Fourier transform, $IDFT$ is the inverse discrete Fourier transform, and $*$ denotes complex conjugate.

World Academy of Science, Engineering and Technology
International Journal of Electronics and Communication Engineering
Vol:5, No:8, 2011

B. Gold Code Generation

Gold codes [11] are a set of codes whose number, 2^N, is greater for a given shift register length than the $2^{N/2}$ set of Kasami codes. However, the cross-correlation properties are not good as the Kasami codes. In order to generate the Gold codes, start with two length $2^N - 1$ maximal length sequences $a[n]$ and $b[n]$ where N is an integer. A required property of $a[n]$ and $b[n]$ is they have a three valued circular cross-correlation. A three valued cross-correlation is not shared by all maximal length sequences. The modulo-two addition of the two maximal length sequences with all phase offsets and the original sequences comprise 2^N Gold codes. Compared to the Kasami codes, the Gold codes have higher cross-correlation values for the same length sequence. For a Gold code with an even number of shift registers, the maximum correlation between codes is $2^{\frac{N+2}{2}} - 1$.

C. STORM Code Modification

A STORM spreading sequence is generated by operating on an initial set of codes. Time advance or delay is obtained by cirular shifts of the original code sequence, c, given by

$$g[n] = c[(n + d) \bmod L], \qquad (8)$$

where the g is the time-delayed code sequence, d is the delay, L is the sequence length, and mod is the modulus or the remainder of $\frac{n+d}{L}$. In order to time-scale, the STORM modification repeats or drops samples as governed by the time scale parameter. If the scale $s_i = 0.999$, one sample in a thousand is dropped, and if the scale $s_i = 1.001$, one sample in a thousand is repeated. In the case of time-scales $s_i < 1$, the final STORM modified code sequence is given by the algorithm:

```
1:  n = 0
2:  m = 0
3:  while  n < L  do
4:     if  (n mod (1000s_i)) > 0 then
5:        c[n] = g[m]
6:        m = m + 1
7:        n = n + 1
8:     else if  (n mod (1000s_i)) = 0 then
9:        m = m + 1
10:    end if
11: end while
```

The constant 1000 is used to convert the time scale to sample assuming that scale factors are in the range of $0.991 \leq s_i \leq 0.999$. In the case of time scales $s_i \geq 1.001$, the final STORM modified code sequence is given by the algorithm:

```
1:  n = 0
2:  m = 0
3:  while n < L do
4:     if  (n mod (1000s_i)) > 0 then
5:        c[n] = g[m]
6:        m = m + 1
7:        n = n + 1
8:     else if  (n mod (1000s_i)) = 0  then
9:        c[n] = g[m]
```

Sequence	Number of Chips	Maximum Cross-correlation
Gold	262143	1023
STORM $s_i = 0.999$	262143	2987
STORM $s_i = 1.001$	262143	2937
Gold	38400	1088
STORM $s_i = 0.999$	38400	1086
STORM $s_i = 1.001$	38400	1094

Sequence	Number of Chips	Maximum Cross-correlation
Kasami	262143	511
STORM $s_i = 0.999$	262143	2759
STORM $s_i = 1.001$	262143	2847
Kasami	38400	1100
STORM $s_i = 0.999$	38400	1200
STORM $s_i = 1.001$	38400	1056

```
10:       n = n + 1
11:       c[n] = g[m]
12:       n = n + 1
13:       m = m + 1
14:    end if
15: end while
```

The maximum value of the circular cross-correlation is used as a measure for suitability of multiple sequences to be used in CDMA. For this reason, eighty Gold codes were generated using the maximal length shift register sequences specified by the primitive polynomials $1 + z^{-7} + z^{-18}$ and $1 + z^{-5} + z^{-7} + z^{-10} + z^{-18}$ defined in the WCDMA specification [?] where z^{-1} is a delay operator. Two sets of STORM codes were generated from the initial set of codes with a delay parameter of 30 chips and scale factors of 0.999 and 1.001.

The circular cross-correlation was calculated between all combinations of sequences taken pairwise, and the maximum values are listed in Table I. In this table, the maximum cross-correlation values using the STORM sequences are almost three times higher than the original Gold sequence cross-correlation value. The elevated STORM cross-correlation value is approximately 1% of the complete sequence autocorrelation value of 262143. The complete code is not always used in practice. For example, the WCDMA downlink scrambling code is based on a subsequence of a longer code. For this reason, the maximum cross-correlation between the first 38400 chips of the Gold and STORM codes are shown in Table I. In this case, the subsequence correlation comparing the Gold and STORM sequences are comparable.

The primative polynomial $1 + z^{-7} + z^{-18}$ was also used to generate a Kasami sequence, and maximum cross-correlation values between 80 codes taken pairwise are shown in Table II. Optimality of the Kasami sequence cross-correlation is observed in the first row of the table, and the maximum correlation for the STORM sequences for the complete sequence are comparable to the Gold code results. In Table II, the subsequence results for the Kasami and STORM codes are consistent with the Gold subsequence results.

World Academy of Science, Engineering and Technology
International Journal of Electronics and Communication Engineering
Vol:5, No:8, 2011

IV. STORM IN MULTIUSER ENVIRONMENTS

Ultimately, STORM is to be incorporated into a DS-QPSK environment. In [13], synchronized QPSK can be considered as two independent spread DS-CDMA systems. In asynchronous CDMA, the in-phase and quadrature codes can interact to increase the multiaccess interference (MAI). A basic CDMA system will be presented in Section IV-A. This will study the case of the STORM codes interacting and causing MAI on a synchronized quadrature channel.

A. CDMA

A baseband multiuser received signal is given by

$$r(t) = A_1 b_1(t) c_1(t) + \sum_{k=2}^{K} A_k b_k(t-\tau_k) c_k(t-\tau_k) cos(\phi_k) + n(t), \quad (9)$$

where A_i is the amplitude of the ith user, b_i is the transmitted bit, c_i is the ith code sequence, ϕ_i is the phase offset for the ith user relative to the first user, K is the number of users, and $n(t)$ is additive white Gaussian noise process. In order to decode the modulated information, the received waveform is cross-correlated with the code sequence of each user given by

$$Z = \int_0^T r(t) c_1(t) dt. \quad (10)$$

A decision on the value of the bit is made by the sign of Z. The mean and variance of Z is calculated to determine an analytically based probability of error. In Z, random variables are the transmitted bits, each user's phase, each user's delay, and noise term. When calculating the mean, the noise term and other users bit values have zero mean, time delay is uniformly distributed over a chip duration, and phase is uniformly distributed over $[0, 2\pi]$. Under the assumption of orthogonal codes in white noise, a lower bound for the probability of error is given by [14] as

$$P_e = \frac{1}{2} \text{ erfc } \left\{ \left(\frac{K-1}{3L} + \frac{N_o}{2E_b} \right)^{-\frac{1}{2}} \right\}, \quad (11)$$

where $erfc$ is the complimentary error function, E_b is the bit energy, and N_o is the noise spectral density. Considering nonorthogonal codes, there would be additional terms containing the cross-correlation between codes.

B. WCDMA

WCDMA is discussed in [7], [15] as well as the Third Generation Partnership Project Technical Standards. In Wideband Code Division Multiaccess (WCDMA), the frame rate is 10 ms with fifteen slots per frame and 38400 chips per frame. WCDMA uses Walsh-Hadamard codes as the spreading codes and Gold codes as scrambling codes in the downlink. In WCDMA, the scrambling code chip rate is the same as the spreading code chip rate and helps insure complete bandwidth utilization. In the downlink, the scrambling code is 38400 chips long and there is one scrambling code per base station. For the uplink, the scrambling code can be a short Kasami

code or long Gold code. Each user is assigned a unique code by the controller and assigned a second code to communicate to a second base station for soft handover [15].

WCDMA employs power control to adjust the power output from multiple users in order to prevent a single user from dominating the channel. If the channel dynamics are changing at the same rate as power control, the algorithm could be expected to have difficulties. In WCDMA, the maximum power control update rate is 1500 Hz. As discussed in [7], power control does not work well when the velocity of the mobile unit is appoximately 100 km/h. A key component of the power control problem is the synchronization of the base station to the multiple users. STORM could be viewed as a facilitator for WCDMA power control because the addition of time scale makes STORM a time varying modulation and subsequently permits rapid synchronization.

In WCDMA, one downlink slot is comprised of control information in a Dedicated Physical Control Channel (DPCCH), and data in a Dedicated Physical Data Channel (DPDCH) using time division multiplexing. The spreading factor of the DPDCH ranges from 4 to 512 and governs the number of bits-per-slot. It is important to note that the DPCCH is spread by the Walsh-Hadamard code zero (a sequence of ones) and is scrambled by the Gold sequence. For this reason, the DPCCH pilot is a deterministic sequence with a portion common to the in-phase and quadrature channel, and it is this portion of the signal that has a time scale correlation after the scrambling operation and facilitates the application of STORM.

For the DPCCH, there are transmitter power control (TPC) bits, transport format combination indicator (TFCI) bits to identify simultaneous services, and pilot bits for synchronization. The number of control bits vary for a given WCDMA service, however, there are a maximum of 64 control bits available separated between the three control functions. The largest number of control bits are generally available to the pilot. A slot consists of 2560 chips with at most 64 chips having time scale correlation which corresponds to 2.5% of the signal. It is also permitted in the standard [?], to vary the transmitter power between the DPCCH and DPDCH. This could compensate for the decreased signal available for STORM provided that a total power constraint and spectrum emmissions are maintained within acceptable bounds.

The addition of a transmitted reference modulation would be difficult for an existing spread spectrum system but WCDMA uses QPSK. This paper applies STORM to WCDMA through the quadrature scrambling code. The modified scrambling code will be changed to a time delayed and time scaled version of the in-phase scrambling code. With this modification, WCDMA can operate within its design space and permit the rapid synchronization features of STORM.

V. RESULTS

Monte Carlo simulations [16], [17] will be performed with standard sequences and STORM modified sequences in order to evaluate the performance of the modified code in ideal DS-CDMA communication system and a modern WCDMA system. The simulation of a synchronous DS-CDMA system

World Academy of Science, Engineering and Technology
International Journal of Electronics and Communication Engineering
Vol:5, No:8, 2011

is presented in Section V-A. A physical layer WCDMA simulation is presented in Section V-B.

A. CDMA Simulation

Using the primative polynomial $1 + z^{-1} + z^{-4} + z^{-6} + z^{-12}$, Kasami codes of length $L = 4095$ were generated along with STORM modified codes of the same length. One to ten users were simulated in AWGN environment of varying levels. One million information bits were tested to determine bit error performance. The STORM code was generated using a delay of 20 chips and scale of 0.99.

The results using the Kasami sequence are shown in Figure 2, and results using the STORM modified Kasami sequence are shown in Figure 3. Up to 10 users, the impact of increased correlation between codes is not significant comparing the lower bound error probability to the simulation results. These results are consistent with the original Kasami sequence. Considering equation (11), if the sequence length L is much greater than the number of users, the impact of multiaccess interference goes to zero.
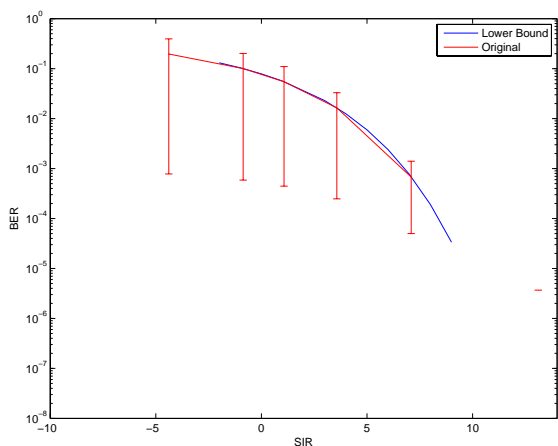

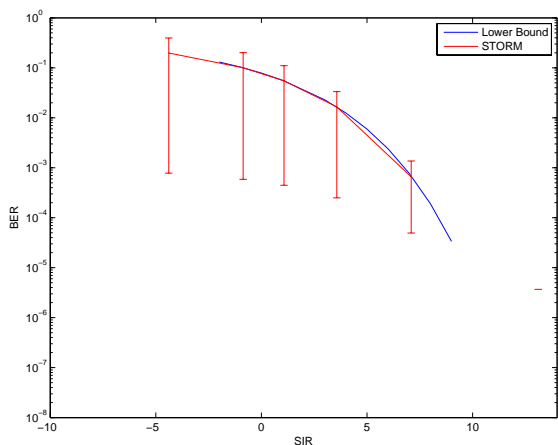
Fig. 2.   Multiple user CDMA bit error performance.

Fig. 3.   STORM modified CDMA multiple user bit error performance.

B. WCDMA Simulation

MATLAB® contains a WCDMA physical layer downlink simulator in the Simulink Communications Toolbox. This code was operated in its original state and a modified state that allowed the STORM scrambling code to be transmitted on the quadrature channel. Bit error rates were calculated for WCDMA operating at 384,000 bits-per-second in additive white Gaussian noise (AWGN) and in a multipath AWGN environment. The multipath case had two signal paths temporally separated by 3.7 chips, and the signal power of the second path was 10 dB less that the direct path. The simulation time span was five seconds for a total of 1.92 million information bits.

The unpreturbed WCDMA physical layer simulator bit error results are shown in Figure 4. In this figure, the effect of coding gain [15] in the AWGN and multipath environment is observed. Bit error performance for the STORM modified sequence is shown in Figure 5. The original and STORM modified results are consistent within the confidence interval of the simulation. These results were expected from the consistency of the maximum subsequence correlation for the original and STORM modified sequences in Table I.

Initially, the power on the control channel is 6.5 Decibels (dB) less than the data channel. AWGN results after changing the power on the control channel to be 3 dB higher than the data channel are shown in Figure 6. There is a degradation in BER performance because less of the signal power is assigned to carry the information bits, but as shown in Figure 7 the STORM detector signal-to-noise ratio improves. Figure 7 shows the normalized imaginary part of the autoambiguity estimate of the transmitted signal using rate 1/3 coding. A STORM detector signal to noise ratio is defined as the peak autoambiguity level divided by two times the root-mean-square (rms) value outside the peak location. Using this definition, the STORM detector SNR improves by 5.5 dB to 13 dB by increasing the control power. For reference, the original scrambling code "noise free" STORM detector SNR is 17 dB. The signal value is approximately $10 \log(38400)$ since the autoambiguity peak is in units of power, and the noise term is the residual correlation at various time-delays that is dominated by correlation of 999 chip subsequences or $10 \log(999)$.

VI. SUMMARY

The STORM modified spreading codes circular cross-correlation properties are greater than the original spreading code, however, the difference is within the same order of magnitude. For the sequences evaluated, the subsequence correlations are similar for Gold, Kasami, and STORM. The comparison to the Gold subsequence is extremely relevant since it is presently used in WCDMA downlink.

The ideal synchronized CDMA properties are consistent between a Kasami code of length 4095 and STORM code of the same length. More work should be done to determine the extent that these results apply to a greater number of users.

A method for modifying WCDMA is presented that modifies the quadrature scrambling code by adding a time scale

World Academy of Science, Engineering and Technology
International Journal of Electronics and Communication Engineering
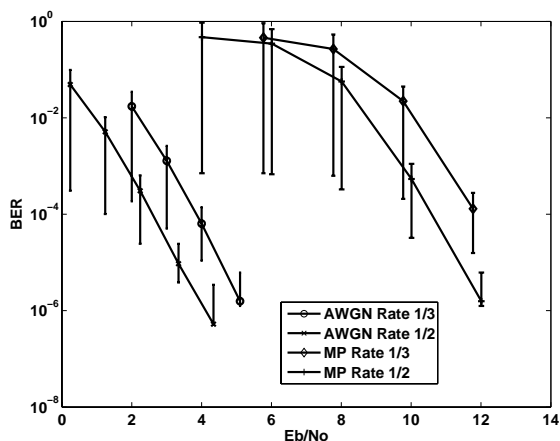Vol:5, No:8, 2011

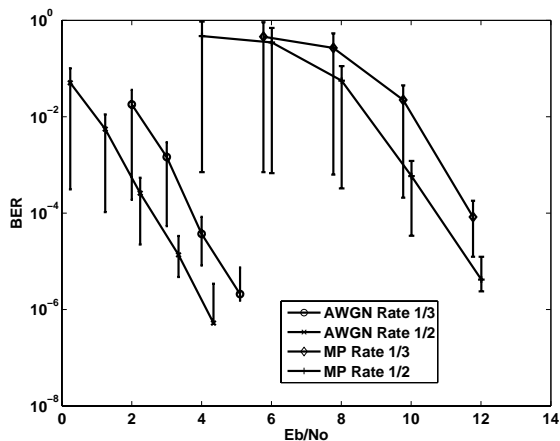Fig. 4.   Single user WCDMA bit error performance.

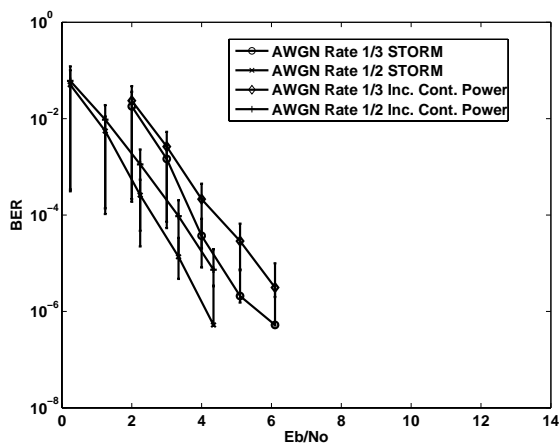Fig. 5.   STORM modified WCDMA single user bit error performance.

Fig. 6.   WCDMA single user bit error performance in AWGN with and without increased power on the control channel.
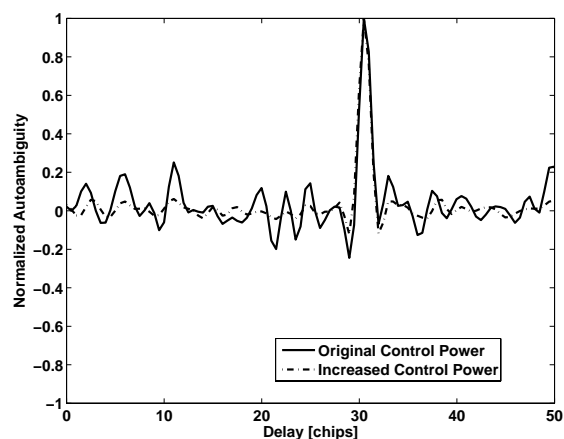

Fig. 7.   Comparison of the noise free STORM detector performance with and without increased control power.

and delay to the in-phase code. The subsequence correlation properties of the original and modified code are consistent, and for this reason, there should be a minimal BER penalty to incorporate STORM into this communication design. This result is supported by a MATLAB$^{\circledR}$ physical layer WCDMA simulation with and without STORM scrambling codes. However, the STORM detector performance suffers without customizing the WCDMA parameters. A STORM detector performance increase is observed by increasing the power available to control relative to the power available to the information bits, but a BER increase also results from this modification.

REFERENCES

[1] D. M. Jenkins, "Scale Time Offset Robust Modulation for code division multiaccess," in *IEEE Military Communications Conference*, pp. 1–4, October 2009.
[2] P. S. Wyckoff, R. K. Young, and D. McGregor, "Scale Time Offset Robust Modulation," in *IEEE Military Communications Conference*, pp. 330–335, October 2003.
[3] P. S. Wyckoff and R. K. Young, "Comparing STORM and matched filtering for Part 15 indoor multi-path communication channels," in *IEEE Consumer Communications and Networking Conference*, pp. 347–351, January 2004.
[4] Y. Chao and R. A. Scholtz, "Optimal and suboptimal receivers for ultra-wideband transmitted reference systems," in *IEEE Global Telecommunications Conference*, vol. 2, pp. 759–763, December 2003.
[5] R. M. Gagliardi, "A geometrical study of transmitted reference communication systems," *IEEE Transactions on Communication Technology*, vol. 12, pp. 118–123, December 1964.
[6] M.-H. Chung and R. A. Scholtz, "Comparison of transmitted- and stored-reference systems for ultra-wideband communications," in *2004 IEEE Military Communications Conference*, vol. 1, pp. 521–527, October 2004.
[7] M. R. Karim and M. Sarraf, *W-CDMA and CDMA2000 for 3G Mobile Networks*. McGraw-Hill, 2002.
[8] R. K. Young, *Wavelet Theory and Applications*. Kluwer Academic Publishers, 1993.
[9] W. D. T. Davies, *System Identification for Self-Adaptive Control*. Wiley-Interscience, 1970.
[10] T. Kasami, "Weight distribution formula for some class of cyclic codes." University of Illinois, April 1966. Coordinated Science Laboratory Report R-285.
[11] R. Gold, "Maximal recursive sequences with 3-valued recursive cross-correlation functions," *IEEE Transactions on Information Theory*, vol. IT-14, pp. 154 – 156, 1968.
[12] N. K. Bose, *Digital Filters; Theory and Applications*. Krieger, 1993.

[13] S. S. Argawal and D. W. Matolak, "Quadrature phase shift keying direct sequence-spread spectrum code division multiple access with disparate quadrature chip and data rates," in *Proceedings of the 38th Southeastern Symposium on System Theory*, pp. 118–122, March 2006.

[14] M. B. Pursley, "Performance evaluation of phase coded spread spectrum communication - part I system analysis.," *IEEE Transactions on Communications*, vol. 25, no. 8, pp. 795–799, 1977.

[15] A. Richardson, *WCDMA Design Handbook*. Cambridge University Press, 2005.

[16] M. C. Jeruchim, P. Balaban, and K. S. Shanmugan, *Simulation of Communication Systems Modeling, Methodology and Techniques*. Kluwer Academic Publishers, 2000. Second Edition.

[17] J. G. Proakis, M. Salehi, and G. Bauch, *Contemporary Communications Systems Using Matlab and Simulink*. Thomson Brooks Cole, 2004. Second Edition.