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Analysis of Outage Probability for MC-CDMA Systems Using Different Spread Codes

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Abstract **- Modern communication systems demand proper utilisation of bandwidth, high throughput, integration of services and flexibility. To meet these requirements, spread spectrum code-division multiple access (CDMA) techniques have been proposed for various wireless communication systems. Here the individual user is assigned a unique binary code called spreading code used to increase capacity and provide higher robustness to interference. This paper investigates outage probability performance of MIMO multicarrier spread spectrum code-division multiple access (CDMA) with different robust spreading codes namely Walsh-Hadamard (WH), Gold and Kasami codes. Outage probability Poutage is significant performance measure to evaluate the effect of co-channel interference. System's performance is initially evaluated in terms of outage probability by varying spreading factor (code length L) L= 4, 16, 64,256 for the number of subcarriers (N_C) N_C =4. In the second case spread factor SF is kept constant at L=64 and Poutage is analysed for varying number of subcarriers N_C = 4, 16, 64. Outage probability analysis for system shows that under similar load conditions Kasami spread sequences outperforms Gold codes and WH codes in terms of outage probability for different spreading factor (SF) of codes and for varying number of subcarriers. This is because of its improved peak isolation and low cross-correlation than other.**

Keywords: **Multi-Carrier (MC) Systems, Code Division Multiple Access (CDMA), Outage Probability, Spreading Codes, Wireless Communication**

I. INTRODUCTION

Today wireless networks require higher data rate, widespread services, capacity improvement and higher spectral efficiency. Development of next-generation wireless networks greatly depends on the proper selection of suitable wireless access schemes. The main requirements of next-generation wireless communication are high throughput, integration of existing technologies on a common platform and flexibility [1]. Spread spectrum code-division multiple access (CDMA) system has been proposed to meet the above requirements of next-generation systems. Spread spectrum uses signals having transmission bandwidth much higher than the information rate R in bits/s. The considerable redundancy in spread spectrum is used to overcome the interference that is faced during the transmission [2]. These systems provide significant benefits such as anti-jamming, reduction of interference, low probability of intercept, high resolution ranging, and selective addressing capability [2]. In this type of system, narrow band information sequence is made wide band like random noise with Pseudo-randomness to make it challenging to demodulate by receivers other than the desired one. The waveform is pseudorandom as it nearly satisfies statistical requirements of a truly random sequence as generated by mathematically precise rules. The bandwidth expansion factor of the spread spectrum signal is much higher than unity. The system spectral efficiency is good as several users share the same bandwidth but distinct code or sequence assignment to each transmitter. Since most cellular systems today employ code-based spreading for ensuring high security and scalability, it is crucial to examine how outage probability and outage capacity is affected by the spreading sequences used by cellular systems.

A lot of research is dedicated to the development of robust and highly scalable spreading sequences. This technique uses binary sequences with desired correlation properties as codes to spread data signals and to assign to individual users. The selection of spreading codes is essential as these spreading sequences have been used in multiple-access applications for their effective safeguard against unauthorised access due to their noise resistance characteristics. The transmitted signal is spread and at the receiver, it is correlated with its identifier sequence. Ramjee Prasad and Shinsuke Hara [5] analysed BER performance of new multiple access schemes based on a combination of code division and multicarrier in frequency selective channel. Olanrewaju B. Wojuola *et al.* [6] investigated the performance of a space-time coded CDMA system in a fading channel. Authors in [7] compare single and multicarrier spread spectrum systems. Andrea Conti in [11] proposed a novel multi-carrier CDMA system using equal gain combining (EGC), maximal ratio combining (MRC) and orthogonal restoring combining (ORC) and evaluated outage condition in the downlink case. Vojcic *et al.* [12] derived bounds for outage conditions for a DS-CDMA based satellite system channels primarily with Rayleigh fading. Outage probability approximation for Hoyt and Rice fading models are calculated by an infinite series method in [13]. Authors in [14] presented a Mathematical analysis of outage probability. Luciano Tombain [15] presented the evaluation of outage probability in Code Division Multiple

Access (CDMA) cellular systems. Authors in [16] investigated outage performance for next-generation scenarios like co-operative receivers and device-to-device (D2D) communication. A lot of research is going on to study spreading sequences influence on outage performance. This paper analyses the applicability of different spreading sequences to MC-CDMA systems and on outage probability performance. This paper is organised in six sections Section 2 explains the details of the system model. Section 3 explains various spreading codes used for multicarrier CDMA systems. Section 4 explains the concept of outage probability for MC-CDMA system. Section 5 discusses simulation results and conclusion is reported in Section 6.

II. SYSTEM MODEL

Multicarrier techniques have been proposed for wireless communication system since they make maximum use of frequency diversity. The orthogonality is a powerful property that could cancel interference signals significantly in spread spectrum systems. So a promising combination of Orthogonal Frequency Division Multiplexing (OFDM) and CDMA is popular and efficiently used in 4G standards [3]. Unlike conventional OFDM system information sequence is spread over several subcarriers using spreading codes and despread at receiver to improve diversity gain in frequency-selective channels. OFDM combined with antenna arrays at the transmitter and receiver (MIMO) called as the MIMO-OFDM system improves diversity gain, system capacity on time-variant and frequency-selective channels.

A. Transmitter

In the proposed system initially, a data of binary information sequence is generated by a random sequence generator. The data bits are then mapped to data symbols by using each block of $k = \log_2(M)$ bits. The corresponding complex-valued data symbol from $m = 2^k$ constellation symbols are available for transmission over the channel. We used Gray mapping scheme where neighbouring points in the constellation differ by one single bit only.

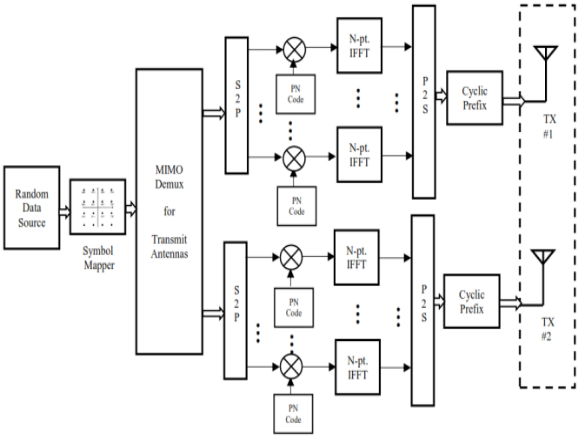

Fig. 1 MIMO Multi-Carrier Spread Spectrum system transmitter

Data symbols are then transferred to two MC spread spectrum system branches since we use a 2 Tx- 2 Rx MIMO system. Data symbols $d^{(k)}$ are further multiplied with a user-specific spreading code

$$c^{(k)} = \left(c_0^{(k)}, c_1^{(k)}, \ldots., c_{L-1}^{(k)}\right)^T \quad (1)$$

Where one complex-valued data symbol $d^{(k)}$ is assigned to user k. The sequence obtained after spreading is given by

$$S^{(k)} = d^{(k)} c^{(k)} = \left(s_0^{(k)}, s_1^{(k)}, \ldots., s_{L-1}^{(k)}\right)^T \quad (2)$$

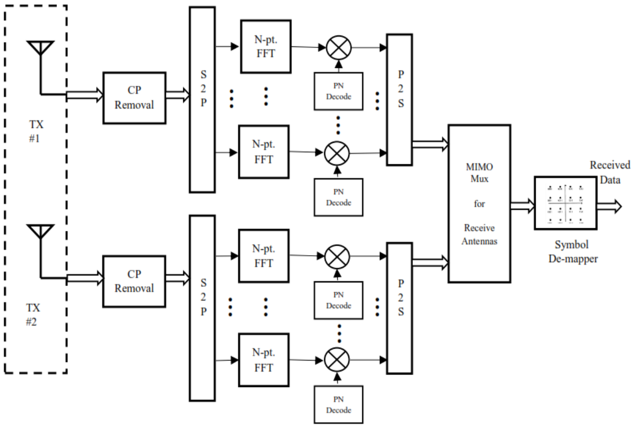

Fig. 2 MIMO Multi-Carrier Spread Spectrum system receiver

Walsh-Hadamard, Gold and Kasami codes have been used as spreading codes in the proposed system.

Further OFDM operation is performed in a discrete time domain by using IFFT blocks. The data sub-streams are converted from frequency to time domain as,

$$x(n) = \sum_{k=0}^{N_C-1} s_k e^{j2\pi \frac{k}{N_C}} \quad (3)$$

Each IDFT sub-stream is combined to form output from each antenna. A cyclic prefix of 25%, denoted by $N_g = 0.25N_c$ is inserted on every stream as a guard interval.

At the transmitter, resultant baseband signal is

$$s(t) = \sum_{i=-\infty}^{\infty} \sum_{k=0}^{N_c+N_g-1} s(iT_s + kT_d)\mathrm{rect}(t - iT_s - kT_d) \quad (4)$$

The resultant baseband signal is further upconverted to RF signal which can be expressed as

$$S_{RF}(t) = Re\{s(t)e^{j2\pi f_c t}\} \quad (5)$$

where f_c is the carrier frequency.

B. Receiver

The MIMO multicarrier carrier spread spectrum system receiver model is given in the Figure 2.

At the receiver, signal is initially downconverted from RF signal to baseband signal. Baseband signal with noise and channel fading is sampled at $\frac{1}{T_d}$bit rate.
The resulting signal is denoted as shown in eq (6)

$$r(iT'_s + kT_d) = \int_0^{\tau_{max}} s(iT_s + kT_d - \tau)h(iT_s + kT_d\tau)\,d\tau + n(iT'_s + kT_d\tau) \qquad (6)$$

The cyclic prefix removal block removes N_g guard samples as they contain ISI. The time domain signal is converted to frequency domain N_c point FFT operation over ISI free samples.

$$Y_k = \frac{1}{\sqrt{T_s}} \sum_{k=0}^{N_c-1} r(iT_s + kT_d)e^{j2\pi\frac{k}{N_C}} \qquad (7)$$

$$Y_k = H_k S_k + N_k \qquad (8)$$

Where N_k denotes the noise matrix.
Signals coming from different sub-carriers are weighted by suitable combining coefficients Gm (m being the sub-carrier index). This is essential because a different fading level causes the loss of orthogonality between the sequences of different users. This loss causes an increase of multiuser interference.

M-subcarriers after demodulated by Fast Fourier Transform (FFT) (OFDM demodulation) is multiplied by gain $q_m$to combine received signal energy scattered in the frequency domain. The decision variable is given by [5].

$$D^{j'} = \sum_{m=1}^{L} q_m^{j'} j_m \qquad (9)$$

$$y_m = \sum_{j=1}^{j} z_m^j a^j {c_m}^j + n_m \qquad (10)$$

Where y_m and n_m are complex baseband component of the received signal and complex Gaussian noise at m^{th} subcarrier respectively. z_m^j and a^j are the complex envelope of m^{th} subcarrier and transmitted symbol of a j-th user, respectively. j is the number of active users.

The frequency domain samples are then decoded using user codes allotted during transmission.
The low-rate sub-streams are then combined and up-sampled to retain the original bit rate. The symbol de-mapper converts complex-valued data to digital data based on the maximum-likelihood detection.

C. Equal Gain Combining (EGC) and Maximum Ratio Combining (MRC)

Receiver structure of the proposed system uses Maximum Ratio Combining (MRC) to achieve spatial diversity. Consider simple two receive antenna system. Let h_1, h_2 denote fading coefficient between transmit antenna and receive antenna $R_1\ and\ R_2$; then multiple antenna system models can be vectored as

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} h_1 \\ h_2 \end{bmatrix} X + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix} \qquad (11)$$

Consider two received symbols $y_1,\ y_2$. If they are combined to produce

$$\tilde{y} = w_1 y_1 + w_2 y_2 \quad = [w_1 \quad w_2]\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} \qquad (12)$$

where w is received beamformer.
For SNR to be maximum and $w\ and\ h$ has to be aligned i,e $w \propto h$, one possible choice is

$$w = \frac{h}{\|h\|} \qquad (13)$$

This choice of receive beamformer $w = \frac{h}{\|h\|}$ is termed as Maximum Ratio Combiner (MRC).

III. SPREADING CODES

Interference management, multiple accesses and the capacity increment is essential to increase user density in next-generation wireless systems. To achieve this, spreading sequences with correlation properties has been used [3]. CDMA systems are prone to interference as the number of users increases interference increases. So the most crucial challenge in such a system is to mitigate the effect of interference [8]. Here we consider primarily traditional sequences such as Pseudo-Noise (PN), m-sequences Kasami and Gold. Secondly, Hadamard Sequences having orthogonal matrices. [10].

A. Gold Codes

Gold Codes are sequences derived from the result of the modulo-2 addition of two different m-sequences of length $N = 2^m - 1$ generated by two distinct polynomials with registers of the same length and m positive integer not multiple of 4 [3].

The correct selection of such pair of sequences can exhibit three-valued correlation functions.

$$\left\{ {}^{-1}\!/_{N}, {}^{t(m)}\!/_{N}, \left(t(m) - {}^{2}\!/_{N} \right) \right\} \qquad (14)$$

Where t(m) are known as preferred pairs which are defined as

$$t(m) = \begin{Bmatrix} 2^{(m+1)/2} + 1, for\ odd\ m \\ 2^{(m+1)/2} + 1, for\ even\ m \end{Bmatrix}$$

The set of codes that form the Gold codes with the desired correlation function is large, and this makes Gold codes attractive for wireless communication systems. The problem is that one code needs two m-sequences to generate one Gold code, which cuts in half the available number of possible simultaneous users. [3].

B. Kasami Codes

Kasami codes one of the essential binary systems constructed for all even degrees of m-sequences with length $N = 2^m - 1$.They have very low cross-correlation and good auto-correlation [1].

Kasami sequences are classified as small sets and large sets. Gold sequences will generate the small set of Kasami sequences with$M = 2^{m/2}$ .They have three values of Cross-correlation function$\left(-1, -\left(2^{n/2}+1\right), 2^{n/2}-1\right)$. Large Set is obtained by relaxing the correlation function from the small set. It depends on m; if m = 0 mod 4 and even then M = $2^{3m/2}$or m = 2 mod 4 then M $= 2^{3m/2} + 2^{3m/2}$. The correlation function values are given by

$$\left\{-{}^{1}/_{N}, {}^{\left(-1 \pm 2^{m/2}\right)}/_{N}, {}^{\left(-1 \pm \left(2^{m/2}+1\right)\right)}/_{N}\right\}$$

C. Walsh-Hadamard codes

Walsh functions are generated by mapping codeword rows of special square matrices called Hadamard matrices. These matrices contain one row of all zeros, and the remaining rows each have equal numbers of ones and zeros. Walsh functions can be constructed for block length $\mathrm{N} = 2^{\mathrm{n}}$ The Hadamard matrix of the desired length can be generated by the following recursive procedure [1]

$$H_1 = [0], H_2 = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} H_4 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 \end{bmatrix}$$

$$H_{2N} = \begin{bmatrix} H_N & H_N \\ H_N & \overline{H_N} \end{bmatrix}$$

Where N is a power of 2.

IV. OUTAGE PROBABILITY ANALYSIS

In multi-path fading environments due to shadowing environment and multiple access interferences, SNR of the received signal no longer remains a deterministic linear variable. Due to the random nature of SNR, bit-error and symbol-error rate also become random. Consequently, outage probability and Bit-Error Probability (BEO) become important parameters for QoS analysis in wireless communication.

The outage probability is defined for SNR [9] as

$$P_{outage} = p(\varphi < \varphi_{th}) \int_{0}^{\varphi_{th}} p(\varphi)\, d\varphi \qquad (15)$$

Where SNR φ is defined as a log-normal random variable,i.e., $\varphi = 10^{\varphi\, db/10}$, where is Gaussian distributed with mean $\mu_{db}$and variance ${\sigma_{db}}^2$ and φ_{th} denotes the minimum threshold SNR required for preventing an outage. The Gaussian PDF of SNR is given by

$$f_{\varphi}(\varphi) = \frac{1}{\sqrt{2\pi}\sigma\varphi} e^{-\frac{1}{2\sigma^2} ln^2} \left(\frac{\varphi}{\mu}\right) \qquad (16)$$

where $\mu = 10^{\mu_{db}/10}$ and $\sigma = 10^{\mu_{db}/10}$

The resulting CDF after integrating PDF is given by

$$F_{\varphi}(\varphi) = \int_{\varphi}^{\infty} f_{\varphi}(x)\, dx = Q\left[\frac{1}{\sigma} \ln\left(\frac{\varphi}{\mu}\right)\right] \qquad (17)$$

Where Q (.) is Gaussian Q function.

Substituting $\varphi \approx \frac{1}{{\varphi_I}^{-1}} + {\varphi^{-1}}_N$,

φ_I and φ_N being interference and noise powers respectively,

The outage approximation is obtained as,

$$P_{outage} = Q\left[\frac{1}{\sigma} \ln\left(\frac{{\varphi^{-1}}_{th} - {\varphi^{-1}}_N}{\mu}\right)\right] \qquad (18)$$

By converting Q function to complementary error function using the expression $erfc(m) = 2Q(\sqrt{2}\mathrm{m})$,
Outage probability obtained is given by

$$P_{outage} = 0.5 erfc \left\{\frac{\mu - \varphi_{th}}{\sqrt{2}\sigma}\right\} \qquad (19)$$

The outage probability provides a more accurate sense system performance using instantaneous bit-error rates in a random variable based channel environment.

V. RESULTS

MIMO multicarrier spread spectrum code-division multiple access (CDMA) as shown in Figure 1.(a) and Figure 1(b) is implemented with 2Tx-2Rx antenna configurations using Maximum Ratio Combiner (MRC) receiver. Spreading codes that exhibit good correlation values like Kasami, Gold and Walsh-Hadamard are used for spreading the information sequence. The number of subcarriers and spreading factor SF (viz code length L) is variable based on the requirement. Unless otherwise stated, cases with fully loaded systems are considered. BPSK with Gray encoding is applied for data symbol mapping. AWGN radio channel is implemented.

In the first case, we examine the system's performance in terms of outage probability P_{outage} by varying spreading factor (code length L) L= 4, 16, 64,256 for the number of subcarriers (N_C) $N_C = 4$.

In the second case, we examine the system's performance in terms of outage probability P_{outage} by varying number of subcarriers (N_c), N_c= 4, 16, 64 keeping spread factor SF constant at $L = 64$.

The simulation parameters used in the system are summarised in Table I.

TABLE I DESIGN PARAMETERS FOR THE SIMULATION

Design Parameter	Notation	Value
Bitrate No. of subcarriers	R_d N_c	1.28 MHz 4,16,64
Code length	L	4,16,64,256
No. of transmitters/ receivers	$N_t\ /N_r$	02
Cyclic prefix	CP	25%
Modulation order	M	2
Subcarrier spacing	S_c	5 kHz
Channel(s)		AWGN
Modulation		BPSK,
Coding		Walsh- Hadamard, Gold, Kasami

A. Outage Probability Analysis of the System for Varying Spreading Factor (Code Length L)

We examine the system's performance in terms of outage probability P_{outage} using different types of spreading codes like Walsh-Hadamard, Gold and Kasami for spreading the information sequence. Other simulation parameters used in the system are as summarised in Table I. The plot of outage probability P_{outage} as a function of mean Eb/No(μ_{db}) dB for varying SF L and various spreading codes is shown in the Figure 3, 4 and 5.

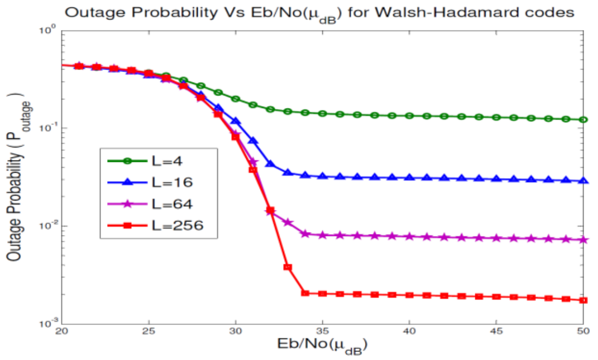

Fig. 3 Outage Probability versus Eb/ No($\boldsymbol{\mu}_{\mathbf{db}}$) for different values of Spreading factor using Walsh- Hadamard codes.

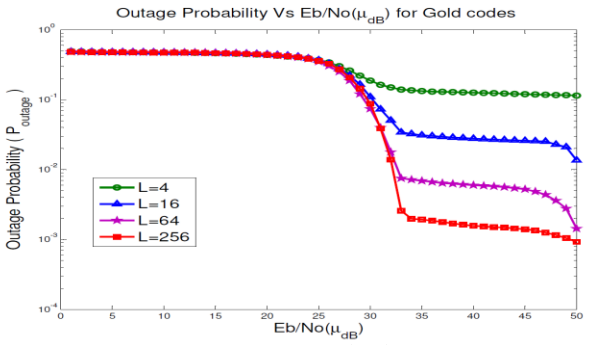

Fig. 4 Outage Probability versus Eb/No($\boldsymbol{\mu}_{\mathbf{db}}$) at different values of Spreading factor using Gold codes

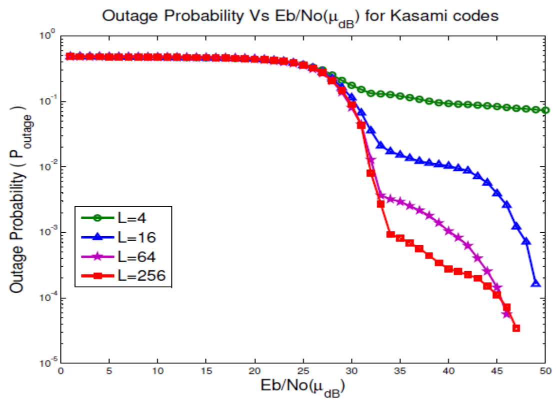

Fig. 5 Outage Probability versus Eb/No($\boldsymbol{\mu}_{\mathbf{db}}$) at different values of Spreading factor using r Kasami codes

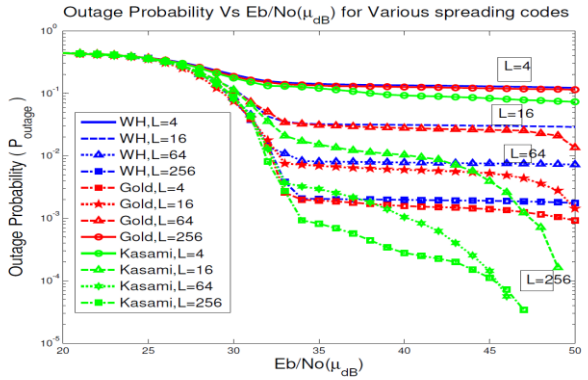

Fig. 6 Comparison of Outage Probability versus Eb/No($\boldsymbol{\mu}_{\mathbf{db}}$) at different values of spreading factor for different codes used

From Figure 3, 4 and 5 it is observed that the outage probability reduces as the average value of Eb/No improves for all values of spreading factor L. Under similar load conditions, it is noted that outage probability decreases with an increase in the value of spreading factor L for all the spreading codes considered. Comparison plot of outage probability versus Eb/No(μ_{db}) at different values of spreading factor for different codes used is as shown in Figure 3. It is observed that under similar load conditions, Kasami sequences show improved outage performance due to improved peak isolation and low cross-correlation than Gold codes and Walsh- Hadamard codes. It is further seen that Gold codes perform better than Walsh- Hadamard codes regarding outage probability.

B. Correlation Functions for Different Spreading Codes

In multiple-access applications selection of suitable spreading code is very important since they are the powerful safeguard against unauthorised access. To examine the system performance using robust and highly scalable spreading sequences, different types of spreading codes like Kasami, Gold codes and Walsh- Hadamard codes are used Autocorrelation Function (ACF) and Cross-correlation Function (XCF) properties of the spreading codes are analysed. Correlation functions are metrics used for performance evaluation of sequences ACF describes the self-interference due to a multipath communication channel and the XCF describes the interference among users that access the wireless channel.

Figure 7, 8, 9 shows the Autocorrelation characteristics of Walsh-Hadamard, Gold and Kasami respectively. Figure 7 is the plot of ACF for Walsh-Hadamard code for 30 lags. It is observed that the ACF crosses the desired 50% boundary multiple times; moreover, the overall ACF values are high.

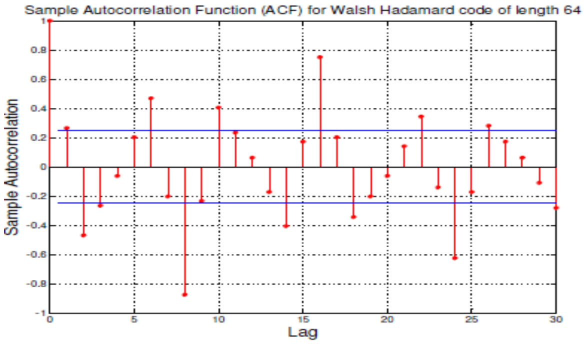

Fig. 7 Autocorrelation Function (ACF) for Walsh- Hadamard codes of length 64

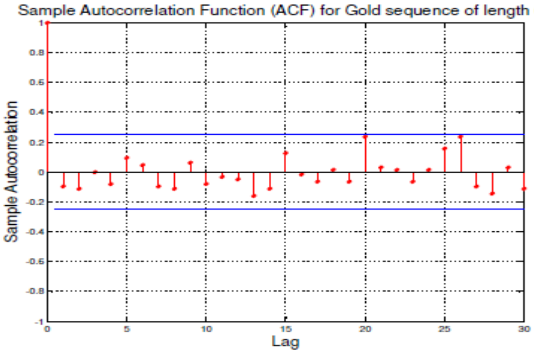

Fig. 8 Autocorrelation Function (ACF) for Gold codes of length 64

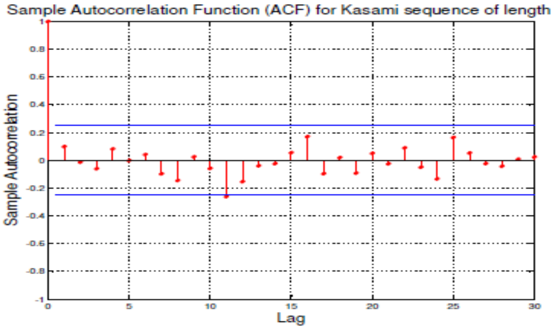

Fig. 9 Autocorrelation Function (ACF) for Kasami codes of length 64

In Figure 8 and Figure 9, the ACF of Gold and Kasami code is plotted for the same no. of lags. It clearly shows that the average of ACF of both the codes is less than 25%; which is within the desirable range. Further, it is observed from Figure 9 that Kasami codes have the best ACF compared to others since ACF has the maximum value at the origin and low values of phase time shifts. This provides better peak isolation and has less self-interference due to the multipath communication channel.

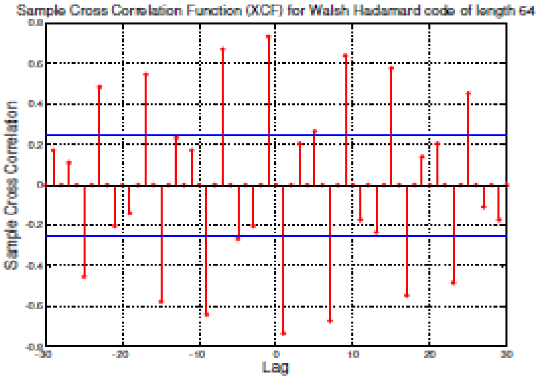

Fig. 10 Cross-correlation Function (XCF) for Walsh- Hadamard codes of length 64

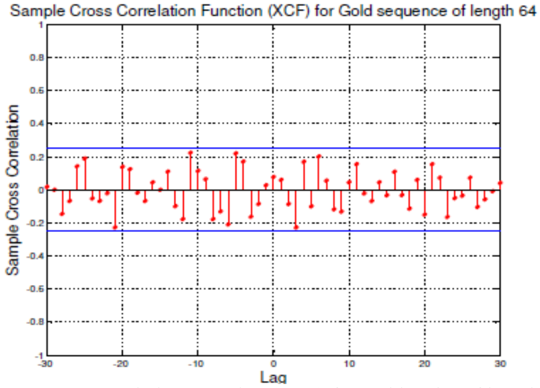

Fig. 11 Cross-correlation Function (XCF) for Gold codes of length 64

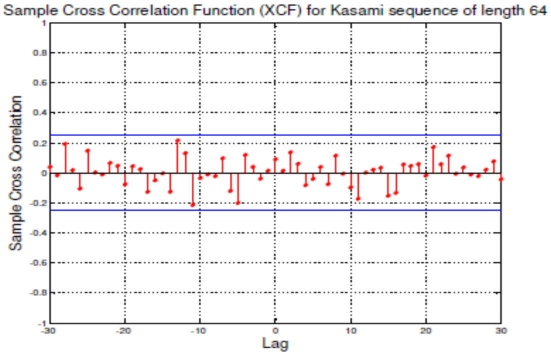

Fig. 12 Cross-correlation Function (XCF) for Kasami codes of length 64

Figure 10, 11, 12 shows cross-correlation characteristics of Walsh-Hadamard, Gold and Kasami respectively. The XCF magnitudes for Figure 12 are much lower than Figure 10 and Figure 11.The low XCF suggests that system with Kasami sequences has less interference among the users that access the wireless channel.

C. Outage Probability Analysis of the System for a Variable Number of Subcarriers (N_C)

For the system shown in Figure 1.(a)(b), performance in terms of outage probability by varying number of subcarriers (N_c), N_c= 4, 16, 64 keeping spread factor SF constant at $L = 64$ is studied. Spreading codes values like Walsh-Hadamard, Gold and Kasami are used to spread the information sequence.

The user density directly depends on no. of subcarriers N_c each subcarrier is allotted a part of the entire bandwidth. Thus, bandwidth efficiency increases because multiple users utilise same bandwidth simultaneously Figure 13 shows allotment of spectrum to each subcarrier for three cases, As subcarrier density increases, the capacity of the system also increases, however, it also leads to increase in multi-user interference (MUI).

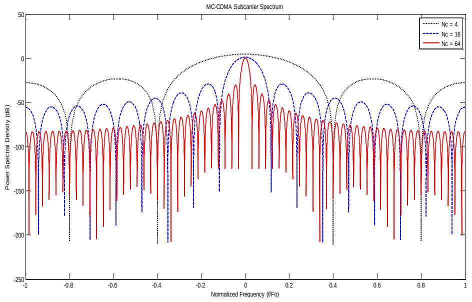

Fig. 13 Subcarrier spectrum for cases of Nc = 4; 16; 64

Comparison plot of outage probability versus Eb/No(μ_{db}) at different values subcarriers N_c for different codes used is as shown in Figure 14. It is observed that under similar load conditions, a number of subcarriers N_c increases, outage probability increases for a system using Walsh-Hadamard, Gold and Kasami spreading codes. Further, it also leads to a rise in multi-user interference (MUI). However, we observed from Figure 14 that Kasami sequences show better outage performance due to improved peak isolation and low cross-correlation than Gold codes and Walsh- Hadamard codes. It is further seen that Gold codes perform better than Walsh- Hadamard codes in terms of outage probability for varying subcarriers.

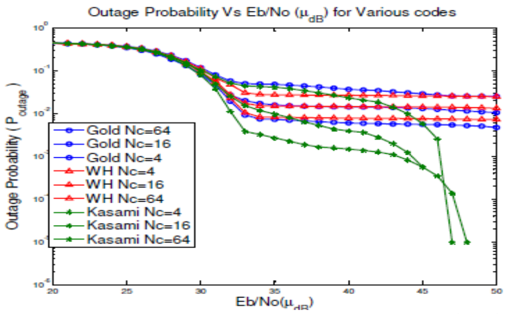

Fig. 14 Comparison of Outage Probability versus Eb/No($\boldsymbol{\mu_{db}}$) at the different number of subcarriers $\boldsymbol{N_c}$ and for different codes used

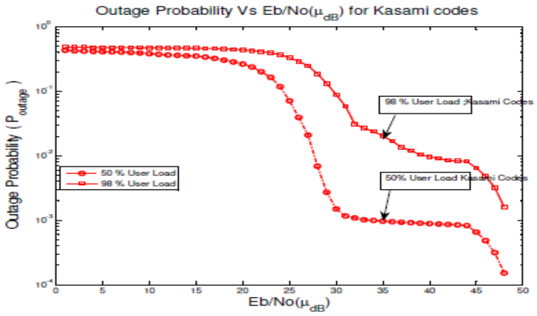

Fig. 15 Comparison of Outage Probability versus Eb/No (µdb) at 98% (Full load) and 50% (Low load) of maximum user capacity using Kasami codes

The outage probability P_{outage} as a function of the mean of Eb/No dB for Kasami codes at different load conditions is shown in Figure 15. The simulation is performed for two conditions: at the low-load and full-load condition. For Nc = 1024 subcarriers, 50 % load implies approximately 512 simultaneous users and 98% load suggests around 1000 simultaneous users. The outage probability reduces as the average Eb/No improves. It is also noted that the improvement in outage probability provided by Kasami sequences is more significant at low-load conditions than at full-load condition.

VI. CONCLUSION

In this paper, we study the outage probability of MIMO multicarrier spread spectrum code-division multiple access (CDMA) system with different types of spreading. System's performance is firstly evaluated in terms of Outage Probability by varying spreading factor (code length L) L= 4, 16, 64,256 for the number of subcarriers (N_C) $N_C = 4$. In the second case spread factor SF is kept constant at $L = 64$ and outage probability P_{outage} is analysed for varying number of subcarriers (N_c), N_c= 4, 16, 64. Compared to commonly used Walsh-Hadamard codes and Gold codes for both cases Kasami sequences illustrate improved correlation properties providing better peak isolation and localisation of users in high density. These properties help enhance the outage performance with reduction of ISI at low as well as high user load conditions.

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