Analysis on Multiple Access Capability of Hybrid Spread Spectrum System with Optimal Sequences - A Review of Performance Parameters Tradeoff

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***Abstract*—The performance analysis of hybrid direct-sequence/frequency-hopped spread spectrum multiple-access communication system over additive white Gaussian noise channels in asynchronous environment is reviewed. Binary phase shift keying is considered as base modulation for data signals. Random binary signature sequences as spreading codes and hopping patterns are employed. Several numerical results and graphs help in determining the optimal tradeoff between various performance parameters of the hybrid spread spectrum multiple access (H−SSMA) system. Multiple access capability of the system is examined with respect to transmission of maximum simultaneous signals and corresponding error probability. It is devised that under the identical bandwidth expansion and same modulation scheme along with random signature sequences and hoping pattern, the multiple access capability of hybrid spread-spectrum system is considerably better than frequency-hopped spread spectrum (FH−SS)system. But under same conditions, direct−sequence spread spectrum (DSSS) system performance is superior to H-SSMA system. Generation and performance analysis of different types and lengths of pseudo-random binary sequences are discussed in necessary detail, for use in spread spectrum multiple access scenario. Impact of code length, number of available hopping frequencies with respect to total number of users, signal to noise ratio at the particular receiver, variation in hopping speed with respect to data rate and tolerable error probability for the total number of possible simultaneous transmissions is determined, to achieve optimum performance of the H-SSMA system.**

***Index Terms*—DS-FH SSMA Systems, CDMA, Optimal Sequences, Correlation Properties of Spreading Sequences, Probability of Error, , SNR, System Performance Parameters.**

I. Introduction

In wireless Multiple Access communication systems, many users share a common transmission medium. Simultaneous sharing of channel access causes interference between transmitting signals. Various methods are practically in use for separating these signals in time(TDMA), frequency (FDMA) or code (CDMA) domains. In Code Division Multiple Access (CDMA) pseudo−random codes are used for spread modulation. Spread Spectrum multiple-access scheme (SSMA)is a well known form of CDMA, developed for use in variety of applications. In SSMA systems, transmitting signals use the complete available spectrum. Separation between signals is achieved through the orthogonal spreading codes or frequency hopping patterns. There are numerous methods of generating these codes [30]−[4]. Performance of such codes have been analyzed in multiple access environment [5]−[8]. The two principal forms of spread−spectrum CDMA are direct−sequence CDMA (DS/CDMA) and frequency−hopping CDMA (FH/CDMA). These are quite popular because of their multiple−access capabilities and interference combating effectiveness. In direct sequence, a high−rate binary code (referred as chip sequence) is phase modulated with the data signal to make the spreading signal [9], [10]. In frequency hopping a high−rate binary code (referred as frequency−hopping pattern) is used to dictate the carrier signal to hop across the entire spectrum [11], [12]. In H−SSMA, a DS spread modulated signal is hopped over frequencies according to a designated frequency−hopping pattern, hence, H−SSMA combines the advantages of these two schemes but at the cost of complexity of transmitter and receiver. This aspect is not studied in this paper, as it is a complete domain of separate knowledge. Authors have been proposing these hybrid schemes for ultimate performance in multiple access communication systems [13]−[15]. Literature supports the concept of multiple access phenomenon which states that under certain conditions, more number of users than available number of frequencies can be accommodated in a system [16].

In this paper the analysis are reviewed for the multiple access performance of direct sequence/frequency hopped (DS-FH) SSMA systems. Multiple access feature of a communication system is defined as "the optimum number of simultaneous transmission of signals that can be endured around a receiver while maintaining a certain error probability for the successful reception of a specified signal". While considering the multiple access capability of the system, it is considered essential to analyse the average error probability at the output of correlation receiver, based on conditional error probability of certain number of transmission collisions (hit) and then averaging over distribution of aggregate hits. In this work, Additive white Gaussian noise (AWGN) channels are considered for communication in asynchronous multiple-access scheme. Binary Phase Shift Keying (BPSK), as the most commonly used base modulation technique is employed. Effects of different hopping rates and multiple code lengths for data modulation are analysed. Moreover, Results are restricted to widely used random signature sequences and hopping patterns. Tradeoffs between different important system parameters are presented for analysing optimum performance of the system as per desired requirements.

Remainder of this paper is organized in the following way; Section II explores the system model in detail. Then section III describes the concept of average error probability for aforementioned system characteristics. Section IV comprises of case wise numerical results.

II. System Model

As review analysis, the system model has been obtained from literature. Detailed discussion on the system model with respect to signal analysis is available in [17], [18]. Hence, brief introduction about the H-SSMA transmitter and receiver is presented here in necessary detail. Transmitter of DS/FH SSMA is shown in figure 1, where i_{th} user's data bits $b_i(t)$ are phase modulated and then spread by i_{th} code sequence$a_i(t)$. $[+1, -1]$ valued code sequences of period N comprise of rectangular shape pulses with duration T_c. After modulation and spreading, the signal $c_i(t)$ is frequency hopped over q number of frequencies, according to the i_{th} frequency hopping sequence $f_i(t)$ during every T_h, i.e. hopping time. Here it is assumed that more than unit number of data bits transmitted during each hop. The i_{th} user's signal lastly takes the form as $s_i(t)$ and passes through the AWGN channel.

$$s_i(t) = \sqrt{2P} b_i(t)\psi(t)a_i(t)cos\big((2\pi[f_c + f_i(t)]t + \theta_i + \alpha_i(t)\big) \tag{1}$$

Here P is the power of each transmitted signal, $\psi(t)$ denotes the rectangular shape waveform and f_c is the center frequency. Furthermore, θ_i is the angle of phase derived by the i_{th} modulator−spreader. Code pulses $\alpha_i(t)$ are introduced by frequency hopper.

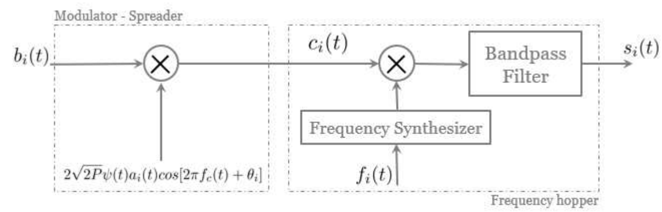

Fig. 1. H-SSMA System - Transmitter Model

Upon reception the signal r_t is fed into baseband filter at receiver end.

$$r_t = n_t + \Sigma_{i=1}^{K} s_i(t - \tau_i) \tag{2}$$

where n_t is noise added by the channel. The initial baseband filter is tuned at center frequency and has bandwidth W. After passing the received signal through baseband filter, the frequency de−hopper acquire frequency hopping pattern synchronization for i_{th} signal and deduce a resembling waveform as of frequency hopper, with phase $\beta i(t)$. The second baseband filter has bandwidth B, which removes the unwanted signals, like high frequency components. After de−hopping, the received signal passes through the de−spreader and demodulator section of the receiver, to get the desired form of signal, i.e. $\hat{b}_i(t)$.

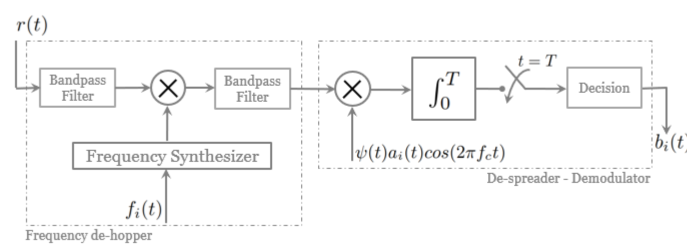

Fig. 2. H-SSMA System - Receiver Model

The signal $b_i(t)$ was initially transmitted by H−SSMA transmitter and passed through the channel with K other signals, simultaneously, thus experienced interference which caused the error in received signal. Before evaluating the average error probability at the output of H−SSMA receiver as shown in figure 2, it is essential to describe the probability of hit from other users, which is given by [19], as:

$$P = \frac{1}{q}(1 - \frac{1}{N_b}) \tag{3}$$

Where:

- Nb = T_h/T : Number of data bits transmitted per hop
- T_h : Duration of each hop
- q = : Number of frequency bins available with users

Nb = 1, refers to the intermediate frequency hopping with respect to speed of hopping. Whereas Nb = 100 is considered as Slow FH as compare to Nb = 10.

As already mentioned that we are focusing particularly on asynchronous multiple access system while employing random signature sequences. such sequences are described in a way that for all K users, independently and identically distributed binary elements taking values of $+1$ and -1 with equal provability, i.e. $\frac{1}{2}$. An important reason to select the asynchronous multiple access system employing random signature sequences is that the throughput of H-SSMA systems in asynchronous form is not substantially different by using either random or deterministic signature sequences. Important parameters included in error probability equation (upper bound) are discussed here while avoiding the detailed derivation which is available in [17]. Following equation is considered an upper bound of P_e while assuming that all collisions are full hits (i.e. for entire T_h).

$$P_e \ \leq \ \Sigma_{i=0}^{K} \left(\binom{K-1}{i}\right) \ P^i (1-P)^{K-1-i} \ P_f \tag{4}$$

Here P is defined by equation xyz and P_f is the conditional error probability given that i full hits are observed from other users, and is defined as:

$$P_f(i) = Q \ \ [SNR(i+1)] \tag{5}$$

and

$$SNR(i) = \left[(\frac{2E_b}{N_o})^{-1} + (\frac{n_\psi (i-1)}{N}) \right]^{-0.5} \tag{6}$$

where SNR(i) is the average signal to noise ratio at the output of receiver for binary DS/SSMA [10] and Q is the complementary error function. n_ψ has a value of $\frac{1}{3}$ while considering rectangular chip waveforms. After detailed discussion over H-SSMA system and deducing an expression of probability of error, next section describes the generation and performance of code waveforms which are assigned to the users for successful multiple access communication. Authors [20], [21] described another relation between signal to noise ratio and error probability which gives approximated results;

$$P_e \approx Q(SNR_{absolute}) \tag{7}$$

This section is concluded here with the statement that performance of H-SSMA system can be optimized while effectively analyzing the tradeoffs between different performance parameters of network. Detailed discussion on these tradeoffs is made part of section$-$IV.

III. Optimal Codes for Spread Spectrum

As discussed in earlier section that DS-SSMA and FH-SSMA employ code waveforms for spreading and hopping, respectively. In DSSS information bits are code spread over a wider bandwidth, thus reducing the chances of interference and making the transmit signal noise resilient. In FHSS the message signal is modulated onto a carrier frequency which hops across many sub-frequencies (termed as frequency bins 'q') within a wider spectrum using a random hopping pattern. The advantage of FHSS is that signal observes a different channel and a dissimilar set of interfering signals during every hop, which helps in avoiding the problem of deteriorated communication at one frequency over a specific time (T_h). The number of frequency bins over which the transmit signal hops, is selected as power of 2. Hopping is achieved by digital frequency synthesizers which selects the frequency as per assigned hopping sequence, generated by pseudo-random noise (PN) code generators [22], [23], [24]. However, practically, it is hard to find truly random sequences in which the bit pattern never repeats.

PN sequences (codes) are being used for minimizing interference in wireless communication since long. The core property of these sequences is orthogonality that is a measure of correlation between them. In many applications, it is assumed for analysis that these sequences are randomly generated through linear feedback shift registers (LFSRs). Whenever users simultaneously transmit data in same frequency bin, it causes destruction of data in that hop. Forward error control coding can be used to minimize the loss of data caused by frequency hits. Therefore, in presence of suitable forward error correction (FEC) scheme, it is feasible to tolerate several simultaneous transmissions [16]. Thus, a much greater number of users than frequency bins, are accommodated in CDMA environment. There are many civil as we as military applications in which frequency hopped orthogonal communication is based on various kinds of these sequences. Researchers have been working on analysing the optimal performance of different types of codes [25]$-$[29].

There are many kinds of PN codes used in spread spectrum, e.g. Gold Codes, Kasami Codes, Walsh Hadamard codes, Barker codes and many more. In this paper, generation of Gold codes through linear feedback shift registers (LFSRs) is discussed for orthogonal communication between signals.

A. Gold Codes

Robert Gold [30] provided a concept of generation of sequences which have been widely used. These sequences possess desired correlation properties therefore considered suitable for multiuser CDMA systems. A periodic binary sequence of 0 and 1, generated by shift registers connected in a linear feedback fashion and has maximum possible period given the number of states in the shift register is called maximal length sequence or simply m sequence [31]. This sequences of 0 and 1 is then replaced by 1 and -1, respectively. Conventionally, such sequences are also called binary sequences since they are two valued. Examples of m-sequences generated through polynomials of degree n are given in Appendix. The Gold sequences are generated by modulo-2 addition of two m sequences, clocked simultaneously.

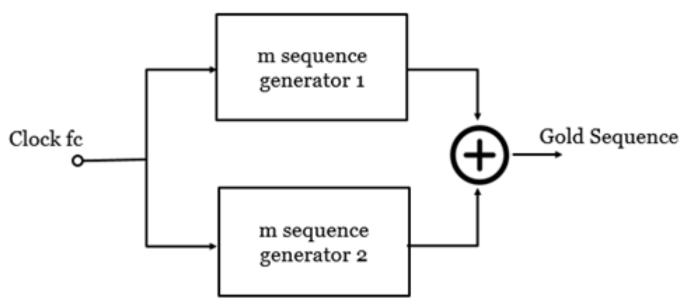

Fig. 3. Block diagram of Gold sequence generator

Block diagram of Gold sequence generator is shown in figure [3], where two m sequence generators are connected in parallel. Such sequence generators are set of shift registers, driven by n degree polynomial, where N = 2^n- 1 is the period of generated sequence and n is number of shift registers in the circuit. Polynomials are representation of the shift registers and their feedback phenomenon. There are certain preferred polynomial pairs for each degree of n, used to generate the desired Gold sequences [33]. These preferred pairs are selected on the basis of code length (N). Moreover, codes generated through these polynomials and relevant LFSRs, possess certain correlation properties which make their use advantageous in multiple access environment. For example, n=5 means the code length (N) is 31 and preferred pair of polynomials are give in table 1. When circuit of LFSRs is governed by the binary representation of these polynomials and their reciprocals, the codes of desired correlation properties are obtained. Detail on generation of these sequences can be found in [5], [8], [24], [31] and useful correlation properties are available in [32]$-$[34]. Without going into details of generation and correlation properties of these sequences, it is considered important to discuss here some useful mathematical relations of these sequences, with respect to some important parameters of H$-$SSMA system.

B. Gold Codes and Desired SNR

Gold sequences possess desired correlation properties which are suitable for multiple access scenario. In hybrid system DS spread modulated signal is frequency hopped according to the designated sequence. Therefore, while exploiting some advantages of DS and FH techniques, better performance can be achieved in a hybrid match. A H$-$SSMA system combines the anti$-$multipath feature of DSSS with reasonably good anti$-$partial band effectiveness of FHSS. However, suitable code length (N), required number of frequency hopping bins (q), desired signal to noise ratio (SNR) limit and threshold of error probability and number of simultaneous users (K) are vital parameters to achieve secure and reliable communication.

C. Correlation of Sequences

Let two sequences be x and y of period N, where x = (x_j) and y = (y_j) are elements considered for analyzing correlation between them. These sequences consist of $+1$ and -1 values. The non-periodic cross correlation property for X and Y is given by;

$$C_{x,y}(t) = \begin{cases} \sum_{j=0}^{N-1-t} x_j y_{j+1} & 0 \leq t \leq N \\ \sum_{j=0}^{N-1-t} x_j y_{j+1} & 1-N \leq t \leq 0 \\ 0, & l \geq N \end{cases} \tag{8}$$

Here t is an integer, denoting the number of cyclic shifts (-1 for one step right, $+1$ for one step left) in a sequence [33]. If $x = a^{(k)}$ and $y = a^{(i)}$, where ($a^{(k)}$: 1 $\leq$ k $\leq$ K) is a set of K binary signature sequences, then $C_{x,y}$(t) can be denoted $C_{k,i}$(t). Average interference function (SNR_i), for i_{th} correlation receiver, can be deduced [8] with the help of above shown correlation property between sequences, as;

$$SNR_i = \left(\left[(6N^3)^{-1} \, \Sigma_{k=1}^{K} \, C_{k,i} \right] + \frac{N_o}{2\, E_b} \right)^{-0.5} \tag{9}$$

Where the average interference parameter $C_{k,i}$ is given by;

$$C_{k,i} = \Sigma_{t=1-N}^{N-1} \, 2C_{k,i}(t)^2 + C_{k,i}(t) \, C_{k,i}(t+1) \tag{10}$$

Hence, $C_{k,i}$ gives values of average interference parameters of specified Gold sequences [30] which are used to find signal to noise ratio at i_{th} correlation receiver. There is a close approximation of equation 10 in analysis and design of asynchronous H$-$SSMA systems, for SNR using random binary sequences.

$$SNR_i \approx \left(\frac{N_o}{2E_b} + \frac{K-1}{3N}\right)^{-1} \quad (11)$$

This approximation is quite accurate for common values of K, N and $\frac{E_b}{N_o}$.

IV. Results and Analysis

Multiple access capability of a communication system is characterized by the maximum number of users, system can support, in terms of simultaneous transmissions. In this paper, Gold codes are adopted for orthogonal communication. These sequences are generated through preferred pairs of polynomials and have been considered optimal with respect to their correlation properties and subsequent use in spread spectrum multiple access systems. Table I contains the preferred pairs of polynomial and related parameters. Column 5 contains average interference values of different sequences obtained through equation 10. These values are based on correlation characteristics of relevant sequences, generated through corresponding pairs. Case wise results of some examples and subsequent analysis are presented in this section.

TABLE I
Preferred Pairs of Polynomials, Initial States and Corresponding Correlation Values

n	N	Preferred Pairs	Initial States	Corr-Values
5	31	100101 , 101001	11001 , 01001	3596
		110111 , 111011	00011 , 01101	3608
		111101 , 101111	11110 , 10010	3792
7	127	10001001 , 10010001	0010000 , 1001101	281326
		10001111 , 11110001	0000101 , 1111111	286726
		10011101 , 10111001	0001100 , 1000101	300126
		10100111 , 11100101	0010111 , 0110001	286230
		10111111 , 11111101	1110001 , 0101010	270166
		11101111 , 11110111	1110010 , 0110101	294310
		11010011 , 11001011	1110111 , 1000111	299614
		10000011 , 11000001	1101101 , 0010010	289582
		11010101 , 10101011	0000101 , 1101100	290918

A. Case 1

In this case orthogonality is maintained between signal S, T and U through the sequences, generated by polynomials of degree 3, which corresponds to the period 31. Users adopt the relevant sequences for maintaining the orthogonality among transmitting signal. However, complete interference cannot be avoided, therefore average interference is used to analyze the damage(error) caused by collisions(hits). Hence, the interference values are calculated using 10, and corresponding signal to noise ratio for each signal is obtained using 9.

$$SNR_S = \left[\left(6N^3\right)^{-1} \ ](r_{S,S}+r_{S,T}+r_{S,U})+\frac{N_o}{2E_b}\right)\right]^{-0.5} \quad (12)$$

From equation 9, we can observe the SNR for first signal of period 31 can be obtained by using the sum correlation value 3596:

- $(r_{S,S}) = 0$ (as per condition k $\neq i$)
- $(r_{S,T}) = 1706$
- $(r_{S,U}) = 1890$
- $\frac{E_b}{N_o}$ = 13dB

While putting all the values in (12), The SNR$_S$ becomes 4.7079. In the same way SNR$_T$ and SNR$_U$ are calculated as 4.7044 and 4.6517 respectively. Using these SNRs, their corresponding error probabilities can also be approximated by equation 7.

- SNR$_S$ $\approxeq 1.238 \times 10^{-6}$
- SNR$_T$ $\approxeq 1.300\ x\ 10^{-6}$
- SNR$_U$ $\approxeq 1.659\ x\ 10^{-6}$

Probability of error is a close approximation which depicts the behaviour and performance of the system. Obtained error probabilities are reasonably low, that can be tolerated in presence of any suitable forward error correction (FEC) scheme.

B. Case 2

To support more users we require more number of orthogonal sequences. In this case the sequences are generated for more users, to further analyse the multiple access capability of the system. Here, n = 7, which corresponds to the period 127. Again using the same equation, to calculate SNR for each signal. we consider the V as first user out of 9. Calculating SNR for this user yields:

$$SNR_V = \Big[(6N^3)^{-1} \ \ (r_{V,V} + r_{V,2} + r_{V,3} + r_{V,4} + r_{V,5} + r_{V,6} + r_{V,7} + r_{V,8} + r_{V,9} + r_{V,10}) + \frac{N_o}{2E_b}\Big]^{-0.5} \quad (13)$$

From equation 12, we have:

- $(r_{V,V}) = 0$
- $(r_{V,2}) = 31746$
- $(r_{V,3}) = 31078$
- $(r_{V,4}) = 30090$
- $(r_{V,5}) = 29106$
- $(r_{V,6}) = 33878$
- $(r_{V,7}) = 34338$
- $(r_{V,8}) = 30942$
- $(r_{V,9}) = 31350$
- $(r_{V,10}) = 28798$

- $\frac{E_b}{N_o}$ = 13dB

While putting all the values as sum correlation in (9), the SNR_V becomes 4.5696. In the same way SNR for remaining users which are assigned the remaining sequences can be calculated. Using these SNRs, their corresponding error probabilities can be approximated in the same way as in case 1.

TABLE II
SNR VALUES OF RELATED SIGNALS AND THEIR CORRESPONDING ERROR PROVABILITY

Signal	SNR Value	Approximated Error Probability
SNR_2	4.5488	2.812×10^{-6}
SNR_3	4.4983	3.561×10^{-6}
SNR_4	4.5507	2.682×10^{-6}
SNR_5	4.6135	2.013×10^{-6}
SNR_6	4.5200	3.092×10^{-6}
SNR_7	4.5002	3.397×10^{-6}
SNR_8	4.5379	2.949×10^{-6}
SNR_9	4.5328	2.949×10^{-6}

In the same way using relevant preferred polynomials, more sequences of longer periods N can be generated to support greater number of users while maintaining certain error probability.

C. Case 3

As discussed earlier that error provability is one of the performance parameters in multiple access communication systems. If it is further relaxed or conversely an increased value of $\frac{E_b}{N_o}$ is used, more number of users can be accommodated. In this case, it is assumed that Gold sequences are generated through a product of pair of polynomials of degree n and used in asynchronous H-SSMA communication system, where BPSK is adopted as base data modulation. Equation 4 is employed to determine the maximum number of users under certain conditions. Let the code length (N) be 31 and threshold of probability of error be 1×10^{-3}. All other system parameters vary, which are given in table 3 to analyze their impact on the system. Number of available frequency bins are q, number of bits per hop is N_b is 100, whereas $\frac{E_b}{N_o}$ is varied over a common range for obtaining the maximum supportable users (K).

Analysis: Results shows that more number of users are accommodated than available number of frequencies for various common values of $\frac{E_b}{N_o}$. Even setting the common threshold value of error probability considerably enhances the multiple access capability of the system.

D. Case 4

Impact of code length is also an important factor in multiple access capability of the H-SSMA system. In this case keeping the same error probability threshold and values of N_b, as of previous case, while setting the $\frac{E_b}{N_o}$ as 10 dB for the system, maximum supportable users are graphically represented for various code lengths and number of available frequencies.

TABLE III
MULTIPLE ACCESS CAPABILITY

$\frac{E_b}{N_o}$ (dB)	q	K
8	4	9
	8	17
	16	33
	32	66
10	4	19
	8	36
	16	71
	32	141
12	4	25
	8	48
	16	95
	32	189

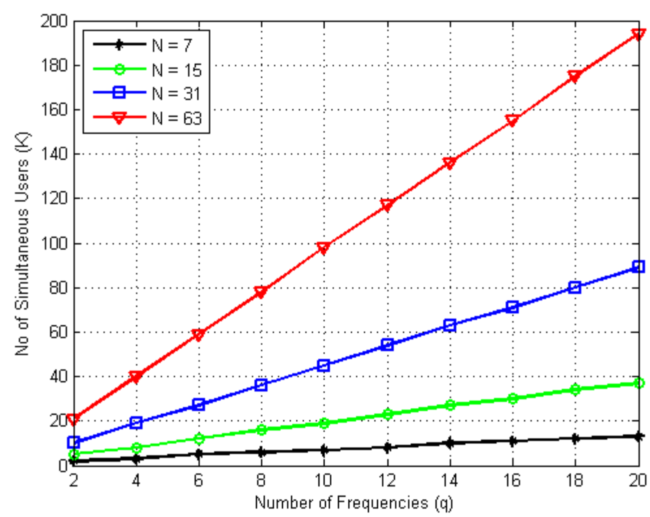

Fig. 4. K as a function of q for various Code Lengths

In the same way effect of varying error probability threshold, while keeping other parameters intact, performance of the system can be viewed.

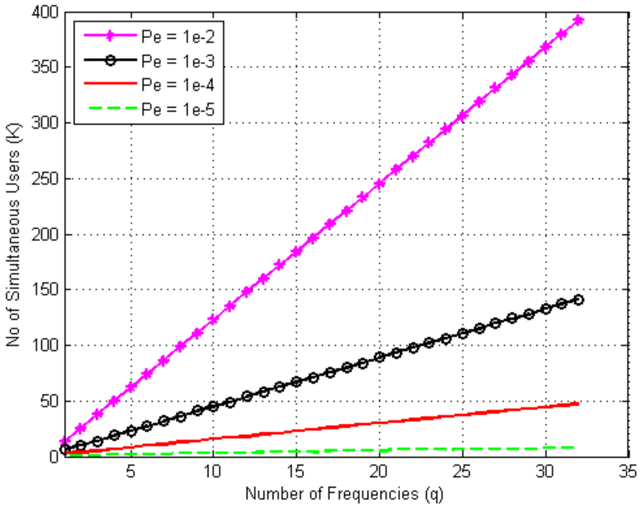

Fig. 5. Effect of Various Error Probability Thresholds

Analysis: Graph 4 clearly shows the considerable effect of another parameter, i.e. code lengths, over the various number of available frequency bins. The requirement of bandwidth increases with the length of code. This graph helps in establishing the tradeoff between the parameters as per desired environment and requirement. Moreover, impact of relaxing and tightening the error probability threshold is depicted in 5, from where it can be analyzed that selection of desired P_e threshold can considerably vary the multiple access performance of the system.

E. Case 5

Lets discuss the hopping speed comparison, where H-SSMA system is analyzed for different values of N_b over varying available number of frequency bins q, while keeping all the other parameters constat as per previous cases:

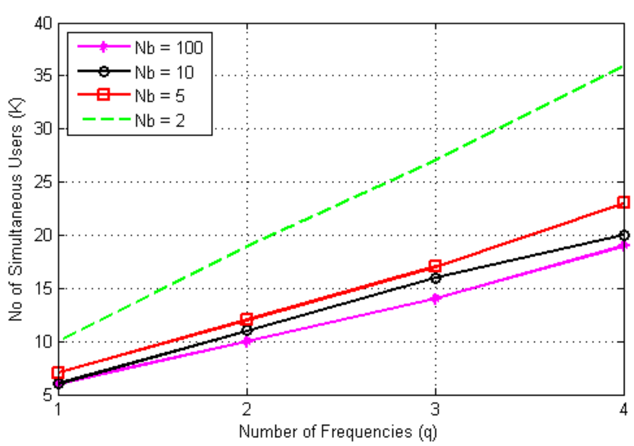

Fig. 6. K as a function of q for varying N_b

Analysis: Graph clearly shows that performance of H-SSMA enhances by increasing the hopping speed, remaining in slow frequency hopping domain (i.e. $N_b > 1$).

F. Case 6

In this case H-SSMA system is compared with pure DS-SSMA and pure FH-SSMA. The parameters N = 1 and available frequency bins q = 700 are a case of pure FHSS system and conversely if available frequency bins q = 1 and N = 700, the system is termed as pure DSSS. The available number of frequency bins (q) and code length N are served as spreading bandwidth for un−coded pure FHSS system and pure DSSS, respectively.

TABLE IV
COMPARISON OF MULTIPLE ACCESS SYSTEMS

System	N	q	K
Pure FHSS	1	700	14
Hybrid SSMA	7	100	63
Pure DSSS	700	1	117

Analysis: Evaluating the system in the same way as of previous cases through 4 and setting the $\frac{E_b}{N_o}$ as 10 dB, it is observed that 14 and 117 simultaneous users are supported by pure FS/SS system and pure DS/SS systems respectively. It can be seen that for any fixed bandwidth spread, pure FS/SS system gives poor performance whereas pure DS/SS systems provides the best results. The performance of H-SSMA remains in between both of these systems with 63 users for the same bandwidth spread.

G. Case 7

In this case H-SSMA system is analysed for multiple access feature while varying different network parameters.

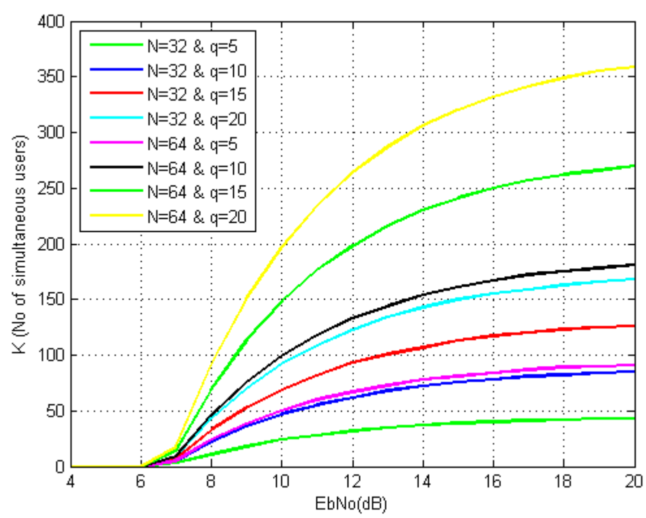

Fig. 7. Multiple Access Capability of System for varying different Network Parameters

Analysis: Finally a comprehensive pictorial representation is obtained for analysing the impact of variations in different network parameters.

V. Conclusion

In this paper asynchronous hybrid spread spectrum multiple access system (DS/FH SSMA) is examined for maximum supportable number of users while meeting a certain threshold of error probability. Analysis are carried out while adopting Binary PSK as data modulation scheme with random binary signature sequences and hopping patterns. Case wise results and analysis show that many users can be accommodated in H-SSMA system by maintaining the orthogonality between simultaneous signals through the use of optimal Gold codes. Tradeoffs between different parameters of H-SSMA system (N,q,K,N_b, SNR, threshold of P_e) can be established, based on obtained results, for optimum performance in desired environment.

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APPENDIX

Randomly generated binary (1,0) sequences have been used in communication and computing technologies since decades. Generally it is hard to find completely random sequences, therefore such sequences are termed as pseudo-random binary sequences generated through linear feedback shift registers (LFSRs). Possible sequences for different values of n can be obtained through all polynomials of degree n which dictates the connection formation of LFSRs. Polynomials, generate maximal length sequences or simply m sequences possess inherited property of period N = $2^n - 1$, are of prime interest with respect to desired correlation properties for multiple access systems.

A. Example 1: n=3

Possible sets of polynomials and relevant property of m sequences are presented as follows;

x^3+x^2+x+1	x^3+x^2+1	x^3+x+1	x^3+1
1: 110	1: 101	1: 110	1: 011
2: 011	2: 010	2: 111	2: 101
3: 001	3: 001	3: 011	3: 110
4: 100	4: 100	4: 001	4: 011
5: 110	5: 110	5: 100	5: 101
6: 011	6: 111	6: 010	6: 110
7: 001	7: 011	7: 101	7: 011
8: 100	8: 101	8: 110	8: 101

Comments: The period of first polynomial (column 1) is not N, the initial loading is repeated at 5th state, hence cannot be termed as m−sequences generator polynomial. Both next polynomials (column 2 and 3) have maximum periods (N), therefore, referred as *primitive polynomials*. The last polynomial is also categorised as non m-sequence generator because the initial loading is repeated at 4th state. Hence, the first example deduced that when n=3, only two m-sequence generator polynomials can be obtained among all the possible set of polynomials of degree n.

B. Example 2: n=4

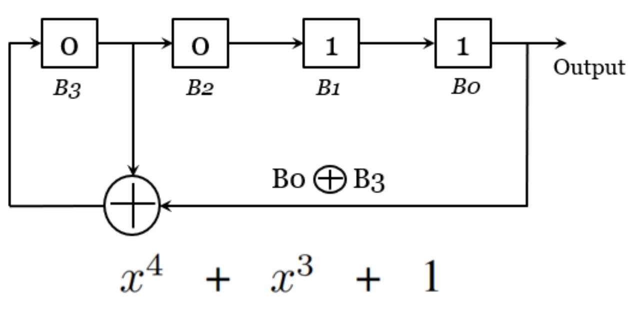

Fig. 8. LFSR - Feedback Connection Formation

Figure 8 shows one of the polynomials from example 2 for n=4, describing feedback connections of LFSR of n registers. As shown in figure, bit 0 is xored with bit 3 in fee dback path. *Output is always taken from bit 0 side*. Possible sets of polynomials and relevant property of m sequences are presented as follows:

x^4+x^3+1	x^4+x+1	x^4+x^2+1	$x^4+x^3+x^2+1$	x^4+x^3+x+1
1: 0011	1: 1101	1: 1001	1: 0101	1: 0101
2: 1001	2: 1110	2: 1100	2: 0010	2: 1010
3: 0100	3: 1111	3: 1110	3: 1001	3: 0101
4: 0010	4: 0111	4: 1111	4: 1100	4: 1010
5: 0001	5: 0011	5: 0111	5: 1110	5: 0101
6: 1000	6: 0001	6: 0011	6: 0111	6: 1010
7: 1100	7: 1000	7: 1001	7: 1011	7: 0101
8: 1110	8: 0100	8: 1100	8: 0101	8: 1010
9: 1111	9: 0010	9: 1110	9: 0010	9: 0101
10: 0111	10: 1001	10: 1111	10: 1001	10: 1010
11: 1011	11: 1100	11: 0111	11: 1100	11: 0101
12: 0101	12: 0110	12: 0011	12: 1110	12: 1010
13: 1010	13: 1011	13: 1001	13: 0111	13: 0101
14: 1101	14: 0101	14: 1100	14: 1011	14: 1010
15: 0110	15: 1010	15: 1110	15: 0101	15: 0101
16: 0011	16: 1101	16: 1111	16: 0010	16: 1010

Comments: The polynomial $x^4+x^3+x^2+x+1$, representing all feedback connections is not shown in this example which repeat the initial loading at 6th state. In example 1, polynomial of degree 3, in first column is representing all feedback connections. It is well known concept that *polynomial representing all feedback connections cannot produce the m-sequence*. The first two polynomials (column 1 and column 2) are repeating the initial loading at N, therefore, termed as *primitive polynomials*. However, remaining three polynomials in column 3 to 5, are categorised as non m-sequence generators, repeat the initial loading at 7, 8 and 7 respectively. Hence, this example conclude that when n=4, again only two m-sequence generator polynomials can be obtained among the possible set of polynomials.

TABLE V
M-SEQUENCES OF DIFFERENT DEGREES OF N

n (no. of shift registers)	N (period)	m-sequence polynomials
3	7	2
4	15	2
5	31	6
6	63	6
7	127	18
8	255	16
9	511	48

Table V shows maximal length shift register sequences and related parameters, for some initial degrees of n. Polynomials of higher degrees can be checked for m-sequences, in the same way as described in examples.