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INTERFERENCE MITIGATION BASED ON CARRIER INTERFEROMETRY CODES IN THE DOWNLINK LOW EARTH ORBIT SATELLITE CHANNEL

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ABSTRACT

The multi-carrier code division multiple access (MC-CDMA) system employs the Hadamard-Walsh (HW) code in the low earth orbit (LEO) satellite systems. It has been used as spreading code to maintain the multi-access interference (MAI) in the downlink LEO satellite channel. However, due to the non-orthogonality of the HW codes, these interferences are observed at the MC-CDMA satellite receiver. As a result, the LEO satellite system performance is degraded. In this paper, we propose to employ the orthogonal Carrier Interferometry (CI) code with MC-CDMA in the downlink LEO satellite channel. A new system is called CI/MC-CDMA which is used to mitigate the MAI. Moreover, the performance of the CI/MC-CDMA satellite system in terms of bit error rate (BER) is analyzed and simulated. To confirm the analysis, the system is compared to the HW/MC-CDMA system. It has been shown that CI/MC-CDMA satellite system outperforms HW/MC-CDMA.

Keywords:
1st Carrier Interferometry (CI) codes.
2nd LEO Satellite Systems.
3rd Multi-carrier Code Division Multiple Access (MC-CDMA).

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1 INTRODUCTION

In recent years, multicarrier code division multiple access (MC-CDMA) is accepted technology for LEO satellite systems [1]. Specifically, when the bandwidth of the transmitted signal is more than the coherence bandwidth of the channel leading to frequency selective fading channel [2], [3]. Many studies have been done for MC-CDMA techniques which provide improved robustness concerning DS-CDMA techniques in the frequency-selective multipath channel [4].

In the MC-CDMA system, each user is assigned a unique orthogonal code, where each user's data symbol is spread by that code. The number of spreading symbols is transmitted simultaneously on N narrow-band subcarriers. To provide access to all users from the same satellite, we combine all of the signals and transmit over frequency-selective LMS channel trying to establish the communication link between satellite and mobile terminal. This signal will be distorted by multipath interference (MPI). This makes it difficult for the MC-CDMA receiver to recover the desired signal. To mitigate such interference at the receiver side, few methods have been suggested and employed [5,6].

In the mobile wireless communication system, CI codes are employed as spreading codes for the MC-CDMA system [7]. It is introduced in frequency-selective Rayleigh fading channels. However, the CI codes have many advantages compared to other codes, for example, the CI codes can be designed for any length N (N∈I). Also, it is capable of supporting greater than N users. In [8], CI codes are proposed for the MC-CDMA system, and applied in downlink frequency-selective mobile wireless fading channels. This confirmed that CI/MC-CDMA system provides improved performances in terms of probability- of- error compared with HW/MC-CDMA system. In [9], carrier interferometry spreading codes are proposed for DS-CDMA systems to reduce the multi-beam interference in LEO satellite systems. Moreover, The CI codes are proposed for the MC-CDMA system over a hybrid Satellite/Underwater Acoustic Channel.

In this paper, we propose to apply CI/MC-CDMA in downlink frequency-selective LEO satellite systems. This will facilitate the MC-CDMA receiver to separate subcarrier components from the received signal by performing an FFT operation and accumulating them in the frequency domain.

This work demonstrates the performance improvement achievable through applying CI codes in the MC-CDMA system, and transmission over frequency-selective LEO satellite channel. The rest of this paper is organized as follows. In section II the CI/ MC-CDMA system model is given. Section III presents the channel model. Section IV presents the Performance Analysis. Simulation results and conclusions are provided in section V.

2 CI/ MC-CDMA SYSTEM MODEL

The transmitter for the u^{th} user in the MC-CDMA system is shown in Fig. 1. We assume BPSK modulation, i.e.,$a_k \in \{+1, -1\}$ with equal probability. The incoming data symbols of each user are converted from serial to parallel. The parallel data symbols are spread by a unique orthogonal code. A Synchronous MC-CDMA transmission system employing two different orthogonal spread codes (WH & CI) is considered. In the MC-CDMA system, each transmitter applies a unique orthogonal code to maintain orthogonality between different users. Each spreading symbol is modulated by N orthogonal subcarriers using N point IFFT. The output of N point IFFT is converted to the serial data stream, and cyclic prefix (CP) is added to the final form. The output of the n^{th} point of IFFT ($n = 0,1, \dots \dots . N-1$) is represented as:

$$S_n[i] = \sum_{\mathrm{u=1}}^{\mathrm{U}} \sum_{\mathrm{m=0}}^{\mathrm{N-1}} \mathrm{A}\ C_m^u a_u[\mathrm{i}]. e^{j\left(\frac{2\pi}{N}mn\right)} \tag{1}$$

Where $\mathrm{A} = \sqrt{\frac{E_s}{N}}$ is a constant that ensures symbol energy of unity ($E_s = 1$). The spread code C_m^u with length N corresponding to the u^{th} user is:

$$C_m^u = \sum_{m=0}^{N-1} e^{j\beta_m^u} \tag{2}$$

For CI codes $\quad \beta_m^u = \frac{2\pi}{N}\ .u.m \quad (3)$

And for Hadamard-Walsh codes $\quad \beta_m^u = 0\ or\ \pi \quad (4)$

The pass-band representation of the transmitted signal for u^{th} user is:

$$s_u(t) = Re\left\{\mathrm{A}\ a_u[\mathrm{i}] \sum_{m=0}^{N-1} C_m^u\ e^{j(2\pi f_m t)}\ \mathrm{g}(t - mT)\right\} \tag{5}$$

where $\mathrm{g}(t)$ is pulse shaping filter with duration $T = T_s + T_{cp}$, where T_s is symbol duration, and T_{cp} cyclic prefix duration. The frequency of m^{th} subcarrier $f_m = f_c + m\Delta f$, where f_c is the carrier frequency, and subcarrier separation $is\ \Delta f = 1/T_s$.

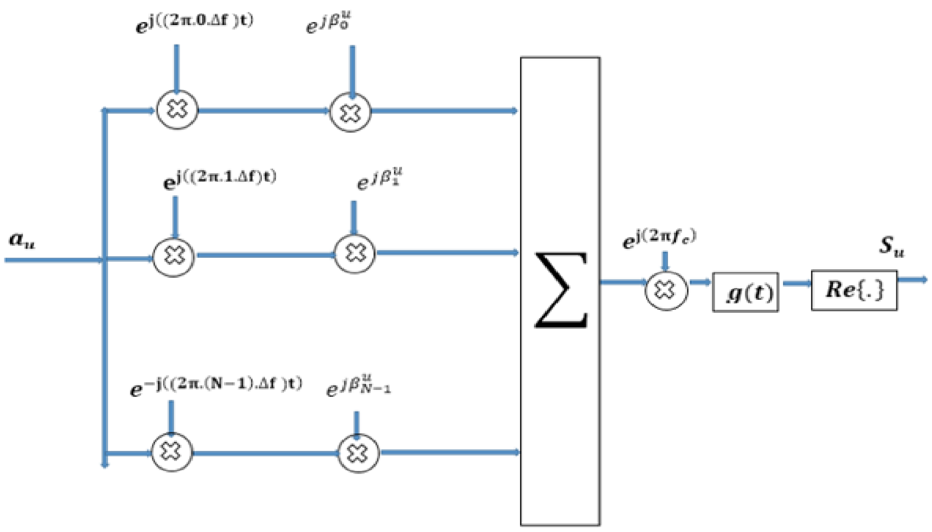

Fig. 1. MC-CDMA transmitter model for user u^{th}.

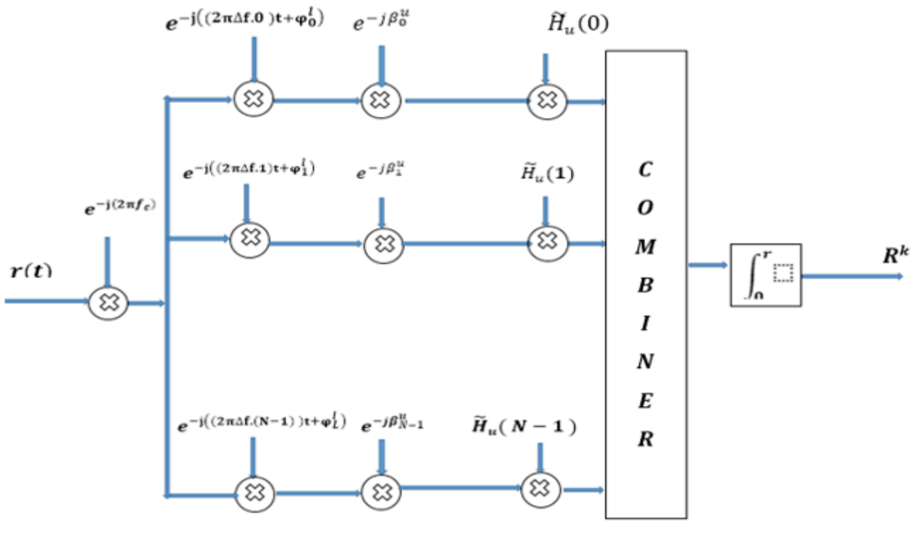

Fig. 2. MC-CDMA Receiver structure model for user u^{th} .

The total transmitted signal considering all U users' for MC-CDMA system is

$$\mathrm{s(t)} = \mathrm{Re}\left\{\mathrm{A}\sum_{\mathrm{u=1}}^{\mathrm{U}}\sum_{\mathrm{m=0}}^{\mathrm{N-1}} a_u[\mathrm{i}].\, C_m^u.\, e^{j(2\pi(\mathrm{f_c}+\mathrm{m}\Delta f)\mathrm{t})}\ \mathrm{g}(t-mT)\right\} \tag{6}$$

The wideband MC-CDMA signal $\mathrm{s(t)}$ of (6) is transmitted over frequency-selective downlink LEO satellite channel.

The signal arriving at the receiver is:

$$r(t) = \mathrm{Re}\left\{ \mathrm{A} \sum_{l=1}^{L} \sum_{u=1}^{U} \sum_{m=0}^{N-1} \mathcal{R}_m^l \, a_u[\mathrm{i}].\, C_m^u.\, e^{\mathrm{j}\left((2\pi \mathrm{f_c} + \mathrm{m}\Delta\mathrm{f})\mathrm{t} + \varphi_m^l\right)} \mathrm{g}(\mathrm{t} - \mathrm{nT} - \tau_m^l) \right\} + \mathrm{n(t)} \tag{7}$$

where $\mathcal{R}_m^l$, φ_m^l and τ_m^l are fading gain coefficients, phase offset, and time delay parameters for $l^{th}\ path$ of m^{th} subcarrier, respectively. The line of sight (LOS) component is given by $l = 1$ and multipath components are given by $l = 2 \ldots \ldots .. L$. The additive white Gaussian noise (AWGN) is presented by $\mathrm{n(t)}$ with power spectral density $\frac{N_o}{2}$. The MC-CDMA receiver model is illustrated in Fig. 2.

3 CHANNEL MODELING

In this study, Loo's statistical channel model is used for the land mobile satellite (LMS) channel [10]. The channel model parameters were taken from linear regression fits of experimental measurement results of real-world LMS channels in the environment of rural areas [11]. The channel model for land mobile satellite systems is usually modeled as composite fading distributions to describe more accurately the amplitude fluctuation of the signal envelope. Although some mathematical models, such as the Loo model have been developed to describe the satellite channel. It provides a significantly less computational burden than other channel models. In this model, the amplitude of LOS is characterized by the Nakagami distribution, and the multipath part is the Rayleigh distribution. The fading channel of the satellite links can be modeled as.

$$\mathcal{R}(t) = A(t)\, e^{(j\alpha(t))} + Z(t)\, e^{(j\beta_0)} \tag{8}$$

Where $\alpha(t)$ is the stationary random phase process with uniform distribution over [0,2π), while β_0 is the deterministic phase of the LOS components. The independent stationary random process $A(t)$ and $Z(t)$, which are also independent of $\alpha(t)$, are the amplitudes of the scatter and the LOS components, following Rayleigh and Nakagami distributions, respectively.

$$p_A(a) = \frac{a}{b_o} \exp\left(\frac{-a^2}{2b_o}\right), \qquad a \geq 0 \tag{9}$$

$$p_Z(z) = \frac{2m^m}{\Gamma(m)\ \Omega^m}\ \ z^{2m-1}\ \exp\left(\frac{-m\, z^2}{\Omega}\right),\ \ z \geq 0 \tag{10}$$

Where $2b_o = E[A^2]$ the average power of the scattering components, $\Gamma(.)$ is the gamma function, $m = \frac{(E[Z^2])^2}{Var[Z^2]} \geq 0$ is the Nakagami parameter with Var [.], and $\Omega = E[Z^2]$ is the average power of the LOS component.

The case of $0 < m > \infty$ is associated with suburban and rural areas with partial obstruction of the LOS component. The received signal envelope $|\mathcal{R}(t)|$ for the mobile satellite channel has probability density function (PDF) defined by:

$$p_{\mathcal{R}}(r) = \left(\frac{2b_o m}{2b_o m + \Omega}\right)^m \frac{r}{b_o} \exp\left(\frac{-r^2}{2b_o}\right) \ {}_1F_1\left(m, 1, \frac{\Omega r^2}{2b_o(2b_o m + \Omega)}\right), \tag{11}$$

for r ≥ 0

where ${}_1F_1(.,.,.)$ is the confluent hypergeometric function. To take care of propagation effects regardless of transmitted signal characteristics, the most general approach is wideband modeling which is proposed. Therefore, we propose to extend narrowband Abdi's channel to wideband and employ it in our simulation. A block diagram of the channel model is presented in Fig. 3.

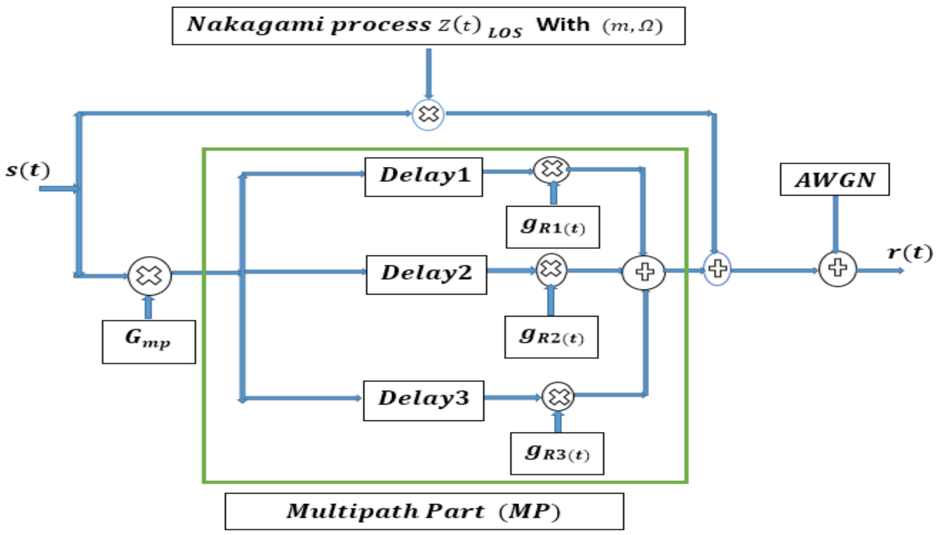

Fig. 3. LEO satellite channel model

In this particular case, the wideband LMS channel is the tapped delay-line model, where each tap is described by a narrowband model. This channel model is defined as a time-varying impulse response consisting of four paths. The first path represents the amplitude of the LOS component, following Nakagami distribution $Z(t)$. The remaining three paths represent multipath part following Rayleigh distribution $g_{R(i-1)}$(t) for ($i = 2,3,4$). The multipath part parameters are determined by the channel delay profile (CDP) given in Table I, where P_i represents the average power of taps, and τ_i (μsec) is channel delay.

Table I Channel Delay Profile (CDP)

i	2	3	4
P_i	0.704	0.225	0.071
τ_i (μsec)	0.1	0.2	0.3

One way of incorporating the effect of the elevation angle in a statistical LMS channel model is to use empirical expressions for the parameters of the envelope PDF in terms of the elevation angle [11]. We use least-square polynomial fits of preliminary wideband measurement data to calculate these parameters:

$$b_o(\theta) = -4.794 \text{ x } 10^{-8}\ \theta^3 + 5.578 \text{ x } 10^{-6}\ \theta^2 - 2.134 \text{ x } 10^{-4}\ \theta + 3.271 \text{ x } 10^{-2} \quad (12)$$

$$m(\theta) = 6.3739 \text{ x } 10^{-5}\ \theta^3 + 5.8533 \text{ x } 10^{-4}\ \theta^2 - 1.597 \text{ x } 10^{-1}\ \theta + 3.5156 \quad (13)$$

$$\Omega(\theta) = 1.4428 \text{ x } 10^{-5}\ \theta^3 - 2.3798 \text{ x } 10^{-3}\ \theta^2 + 1.2702 \text{ x } 10^{-1}\ \theta - 1.4864 \quad (14)$$

The G_{MP} the parameter shown in the figure is used to control multipath power. Requiring that the overall average power of the MP part is equal to unity, we have that

$$G_{MP}(\theta) = \sqrt{2b_o(\theta)} \quad (15)$$

4 THE MODULES ANALYSIS

In this section, we provide an analytical comparison of the performance of traditional HW/MC-CDMA and CI/MC-CDMA in downlink frequency-selective LEO satellite channels. The received signal $r(t)\ in\ (7)$ is down-converted after CP removal. The receiver employs fast Fourier transform (FFT) to separate N orthogonal subcarriers, then the output of FFT q point (q=0,1,…N-1) is projected over the set of orthogonal subcarriers N, to form

$$\mathrm{R(q)} = \mathrm{A}\sum_{\mathrm{u=1}}^{\mathrm{U}}\sum_{\mathrm{m=0}}^{\mathrm{N-1}} H_u(q)\,.\,a_u\,.\,C_m^u + \frac{N_o}{2} \quad (16)$$

Where $H_u(q)$ is the frequency response of the LMS channel for u^{th} user, which is represented by:

$$H_u(q) = \sum_{\mathrm{l=1}}^{\mathrm{L-1}} \mathcal{R}_u^l\ e^{-j\left(\frac{2\pi}{N}l.q\right)} \quad (17)$$

The frequency response of the MMSE equalizer for u^{th} user is:

$$\widetilde{H}_u(q) = \frac{\left(H_u(q)\right)^*}{|H_u(q)|^2 + \frac{N_o}{2}} \tag{18}$$

The output after multiplying each FFT point by each equalizer output is:

$$D_u(q) = \widetilde{H}_u(q).\ \left[\mathrm{A}\sum_{\mathrm{u=1}}^{\mathrm{U}}\sum_{\mathrm{m=0}}^{\mathrm{N-1}} H_u(q)\ .a_u\ .C_m^u\ + \frac{N_o}{2}\right] \tag{19}$$

To recover the original data, we must multiply the $D_u(q)$ by spreading code that we used at the transmitter for each u^{th} user

$$X_u(q) = D_u(q).\ (C_m^u)^H \tag{20}$$

The final decision variable of the combiner for u^{th} user is:

$$Y_u = \sum_{\mathrm{q=0}}^{\mathrm{N-1}} X_u(q) \tag{21}$$

$$Y_u = \sum_{\mathrm{q=0}}^{\mathrm{N-1}} \left[A\ \widetilde{H}_u(q)\ H_u(q)\ \ a_u + A\sum_{\substack{\mathrm{k=0}\\ k\neq u}}^{\mathrm{U}} \widetilde{H}_u(q).H_k(q)\ \ a_k\ C_m^k\ \ (C_m^u)^H + \widetilde{H}_u(q).(C_m^u)^H.\frac{N_o}{2}\right] \tag{22}$$

The final decision variable includes three terms

1) First-term represents the desired signal power

$$P_{desired\ signal} = \ (A.a_u)^2\sum_{q=1}^{N-1}\widetilde{H}_u(q).\ \ H_u(q) \tag{23}$$

2) The second term represents the signal power of multi-access interference from the remaining $(U-1)$.

$$P_{MAI} = \sum_{q=1}^{N-1}\widetilde{H}_u(q).\ \ H_u(q)\left(A\sum_{\substack{\mathrm{k=0}\\ k\neq u}}^{\mathrm{U}}.\ \ a_k.C_m^k\ .(C_m^u)^H\right)^2 \tag{24}$$

1. For BPSK modulation $a_k = +1\ or - 1$ then

$$P_{MAI} = A^2(U-1)\sum_{q=1}^{N-1} \widetilde{H}_u(q).\ H_u(q)\,(C_m^k.\,(C_m^u)^H)^2 \tag{25}$$

3) The third term represents AWGN with variance $\frac{N_o}{2}$.

$$P_{noise\ signal} = \frac{N_o}{2}\sum_{\mathrm{q=0}}^{\mathrm{N-1}} \widetilde{H}_u(q).\,((C_m^u)^H)^2 \cong \frac{N_o}{2} \tag{26}$$

$A^2 = 1$ at each q point

$$\mathrm{SINR(q)} = \frac{\widetilde{H}_u(q).\ H_u(q)}{(U-1)\,\widetilde{H}_u(q).\ H_u(q)E\left[Re\left(C_m^k\,.\,(C_m^u)^H\right)^2\right] + \frac{N_o}{2}} \tag{27}$$

where $E[Re(C_m^k\,.\,(C_m^u)^H)^2]$ is average signal Interference power from other users' code.

$$P_q = E\left[\frac{Re(C_m^k\,.\,(C_m^u)^H)^2}{k} \neq u\ \right] = E\left[cos^2\left[\frac{2\pi}{N}(k-u)m\right]/k \neq u\right] \tag{28}$$

If CI codes are employed as spreading code in MC-CDMA, the P_q is:

$$P_q = E\left[cos^2\left[\frac{2\pi}{N}(k-u)m\right]/k \neq u\right] = \frac{1}{2} \tag{29}$$

The instantaneous signal to interference noise ratio (SINR) for CI/MC-CDMA is:

$$\mathrm{SINR}_{\frac{CI}{MC}-CDMA}(\mathrm{q}) = \frac{\widetilde{H}_u(q).\ H_u(q)}{\frac{1}{2}(U-1)\,\widetilde{H}_u(q).\ H_u(q) + \frac{N_o}{2}} \tag{30}$$

Therefore, the total signal power of multi-access interference for CI/MC-CDMA is

$$P_{\frac{\mathrm{CI}}{\mathrm{MC}}-\mathrm{CDMA}}(\mathrm{\ q}) = \frac{1}{2}\,(U-1)\,\widetilde{H}_u(q).\ H_u(q) \tag{31}$$

and for Walsh codes, the P_q *is*

$$P_q = E\left[cos^2\left[\frac{2\pi}{N}(k-u)m\right]/k \neq u\right] = 1 \tag{32}$$

The instantaneous signal to interference noise ratio (SINR) for HW/MC-CDMA is:

$$\mathrm{SINR}_{\frac{HW}{MC}-CDMA}(\mathrm{q}) = \frac{\widetilde{H}_u(q).\ H_u(q)}{(U-1)\ \widetilde{H}_u(q).\ H_u(q) + \frac{N_o}{2}} \tag{33}$$

Therefore, the total power of multi-access interference for HW/MC-CDMA is

$$P_{\frac{\mathrm{HW}}{\mathrm{MC}}-\mathrm{CDMA}}(\mathrm{q}\,) = (U-1)\ \widetilde{H}_u(q).\ H_u(q) \tag{34}$$

By comparing (30) and (33). It is clear that for CI/MC-CDMA system leads to better performance in teams of bit error rate. Because

$$P_{MAI}(CI\ codes) = \frac{1}{2}\ P_{MAI}(HW\ codes) \tag{35}$$

5 SIMULATION RESULTS AND DISCUSSION

We are simulated CI/MC-CDMA and HW/MC-CDMA systems over downlink frequency-selective LEO satellite channels. We are assuming spreading code length and the number of subcarriers are the same ($N = 32$) for both systems to transmit up to 32 active users. Also, we assume that the interferences from the adjacent beam and neighborhood satellites are negligible. For all users, the Monte Carlo method was run for more than 10^5 OFDM symbols. The probability of error for half load (16 users) and full load (32 users) of two systems at different elevation angles as shown in Figs. 4 and 5, respectively. By comparing Figs. 4 and 5, we show that:

1) CI /MC-CDMA demonstrates much better performance in terms of probability of error.
2) The performance of the CI/MC-CDMA system in terms of elevation angle is improved by 10°.

Also, we have observed the elevation angle improvement for half and full-load CI/MC-CDMA system, if we take $SNR = 20\ dB$, and compare it with BER for both systems at common points. For example, BER=0.0004 and 0.005 in Figs. 4 and 5, respectively. In Fig. 6, it is shown that at the low load system the performance of both systems is almost the same.

6 CONCLUSION

The simulation results show that system performance for half load HW/MC-CDMA is the same as in full load CI/MC-CDMA at the same elevation angle. It means that the CI/MC-CDMA system capacity is improved by 50%. Moreover, the simulation results show that the CI/MC-CDMA system has better interference mitigation than WH/MC-CDMA system at higher elevation angles. For example CI/MC-CDMA full load system at 40° elevation angle has much BER improvement compared with WH/MC-CDMA.

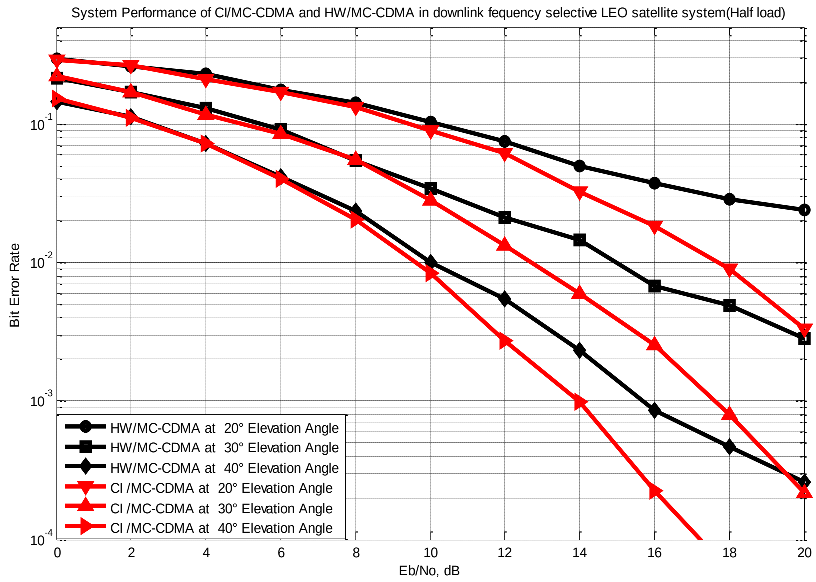

Fig.4. Simulation results for CI / MC-CDMA and HW / MC-CDMA systems over downlink LEO satellite channel (Half load)

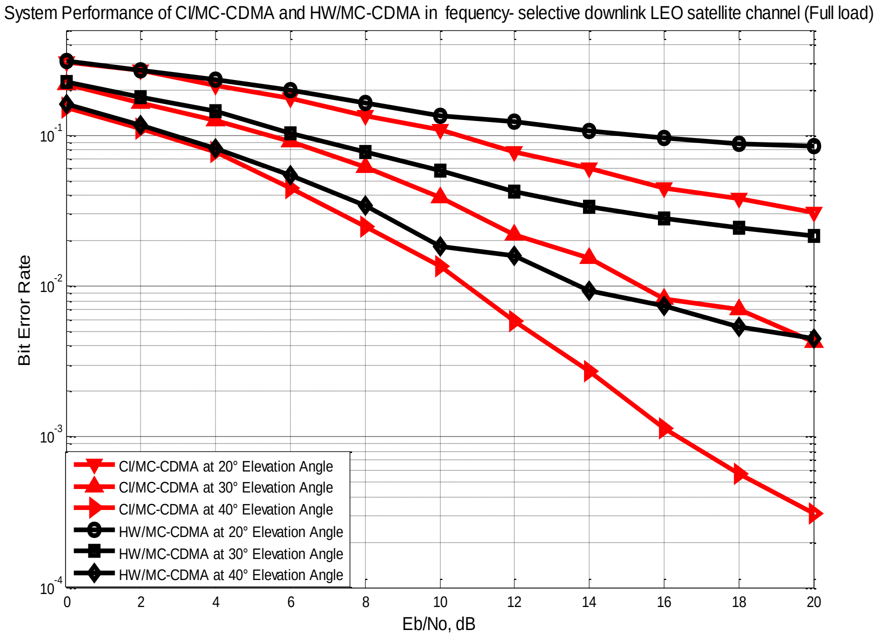

Fig.5. Simulation results for CI / MC-CDMA and HW / MC-CDMA systems over downlink LEO satellite channel (Full load)

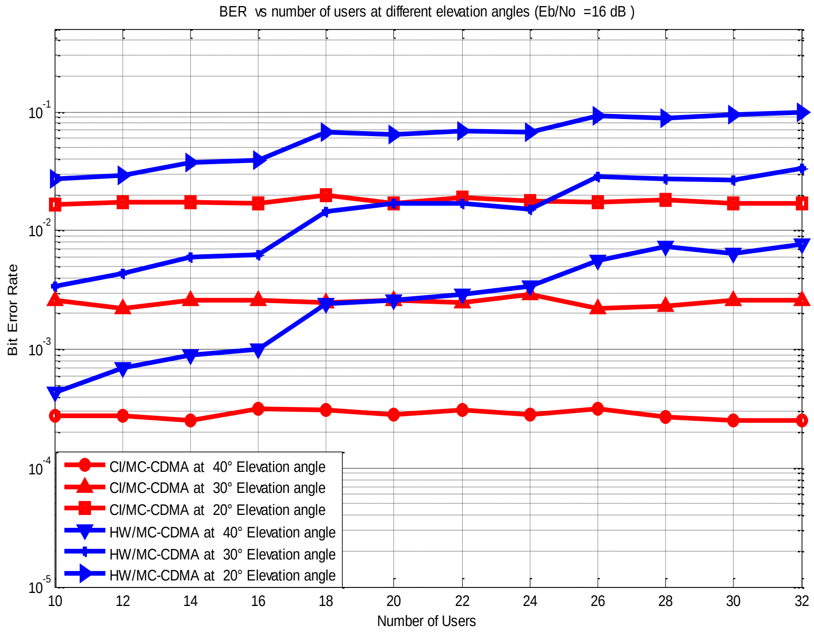

Fig. 6. BER at 16 dB vs number of users at different elevation angles.

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التقليل من ظاهرة التداخلات في أنظمة إستقبال الأقمار الاصطناعية ذات المدار المنخفض باستخدام نظام التشفير المتعامد

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الملخص

يستخدم نظام-Multi-Carrier code division multiple access (MC CDMA)في أنظمة الاقمار الصناعية ذات المدار الارضي المنخفض (low earth orbit satellite). هذا النوع من الانظمة تستخدم (HW) Hadamard Walsh codeكنوع من انواع التشفير وذلك للحد من تقليل ظاهرة تداخل الإشارات المستقبله عند محطات الاستقبال الارضية عبر الاقمار الاصتناعية. وبسبب عدم الاعتمادية (non-orthogonality) لشفرات Walsh codes المستخدمة حاليا في نظام MC-CDMAلوحظ وجود بعض التشويش عند محطات الاستقبال الارضية وخاصة القريبة من بعضها. والنتيجة هي انخفاض مستوي أده هذة الانظمة من حيث نقاءة الاشارات المستقبلة من الاقمار الاصطناعية. ولهذا جاءت فكرة تطبيق نوع جديد من انواع التشفيرالمتعامدة (Orthogonality codes) ولأول مرة في هذة انظمة الاقمار الاصتناعية ذات المدار المنخفض. هذا النوع من التشفير يسمي Interferometry codes له عدة مزايا نذكر بعض منها علي سبيل المثال تقليل من ظاهرة التدخلات بين المستخدمين في نظام الشبكات الأرضية (terrestrial networks). وبتالي جاءت فكرة استخدام هدا النوع من نظام التشفير في انظمة الاقمار الاصتناعية ذات المدار المنخفض. وقد تم تحقيق ذلك عن طريق تحليل هذة الانظمة رياضيا وقياس معدل الخطأ في البت Bit error rate (BER) عند محطات الاستقبال باستخدام برامج Math lab ومقارنة مستوي ادائها بانظمة MC-CDMAا التي تستخدم HW codes. واثبت النتائج المتحصل عليها مدي فاعيلة هذا النوع من التشفير في انظمة الاقمار الاصتناعية ذات المدار المنخفض.

الكلمات الدالة:
انظمة الاقمار الاصتناعية ذات المدار المنخفض.
الشفرات المتعامدة و الغير متعامدة.

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