A NOVEL CHAOTIC-COLLABORATIVE-CDMA SCHEME UNDER RAYLEIGH FADING

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ABSTRACT
The paper describes the mathematical model of a novel scheme 2x-Mod (1)-Chaotic-Collaborative-CDMA (2XM1-CCCDMA) and analyzes its bit-error-rate (BER) performance under Rayleigh fading. The row elements of an NxN matrix of mutually orthogonal chaotic sequences generated by the 2x-Mod(1) one-dimensional (1D) chaotic-map is used as the ‘shared-spreading-sequences’ for a group of collaborating users. The i\(^{th}\) row of the NxN matrix determines the spreading sequence for the collaborating users of the i\(^{th}\) group in 2XM1-CCCDMA. The proposed scheme also utilizes a chaotic-pilot for the synchronization of the users at group level and addresses the capacity and security requirements for imminent wireless systems. The simulation results show the performance comparison of BER with conventional and collaborative CDMA schemes. The proposed scheme eliminates the constraints in security and user-capacity outperforming existing multi-user-detection (MUD) schemes and espouses a fourfold increase in the number of users with good BER performance under Rayleigh fading.

Keywords: chaotic communication, collaborative code division multiple access, synchronization, 1D-chaotic map, rayleigh fading, multi-user detection, multiple-access interference, chaos-based communication systems, multi-access systems.

1. INTRODUCTION
Chaotic communication aims at providing security for information transmitted through various communication channels. Wireless communication system generations including the forthcoming 5th generation (5G) strive for faster data transfer with higher security. Chaos based code-division-multiple-access (CDMA) has been used as the multiple access scheme over the years and aims at fulfilling these requirements. The major aspect of chaotic-CDMA schemes is the level of security and capacity they provide under worse channel scenarios. Variations of multi-user chaotic-CDMA schemes are researched to accommodate the rising number of users and their data transmission through adverse channel conditions.

The chaos based communication system, initiated by Shannon in 1947, recognises that a signal similar to noise with a wave form of maximal-entropy has an optimized channel capacity [1]. The practical implementation was accomplished by Chua in 1980 by implementing a practical chaotic-electrical circuit [2]. Chaotic maps have high sensitivity, to their initial conditions, which give them the potential to generate a large number of (theoretically, infinite) signals with low cross correlation. This characteristic makes them eligible candidate for multi-user spread spectrum communication schemes [3]-[6].

The collaborative-CDMA is a grouped CDMA scheme that increases the capacity by making a small number of users share the same pseudo-random-noise (PN) sequences to spread their data. It supersedes the multi-user detection (MUD) schemes using group pseudo de-correlating detector and layered space time MUD [7] [8]. Binary sequences can be obtained from chaotic-trajectories generated by non-linear ergodic maps [9]. Hence, chaotic sequences are a better replacement to PN codes in CDMA systems because of their better cross-correlation properties [10].

Robust synchronisation mechanisms are needed in such chaos based DS-CDMA systems and have turned out to be an active area of research [11] [12]. A synchronisation analysis of the DSSS systems using chaotic sequences has been made [13]. Also, the synchronisation of multiple groups with a chaotic pilot has been investigated using AWGN channel under multiple-access-interference (MAI) limited environments in which mutually orthogonal chaotic sequences spread the users’ data within a group [14].

A pilot based channel estimation technique has been studied for non-coherent CDMA over fading channels. An optimal receiver is designed with a maximum-likelihood decoder and the parameters such as coding rate and data-to-reference-power-ratio that optimizes the system performance are provided in [15]. The effects of frequency flat-fading on non-coherent synchronization of a chaos-based DS-CDMA system have been studied. The bit error rate of the system with a chaotic pilot has been investigated and the performance evaluated with noise, inter user interference and flat fading [16]. A comprehensive survey of the complete set of wireless radio frequency communication systems based on chaos and the challenges in implementing chaos systems, its synchronization and coherent techniques are addressed in [17].

Consequent to investigating several such techniques, the proposed scheme addresses the effect of Rayleigh fading in a novel 2XM1-CCCDMA system that achieves good BER for an increased number of users. The various users within a group share the same chaotic sequences which in turn allow more number of users than that of the spreading length in existing systems. The proposed scheme also achieves better synchronization in
Rayleigh fading and can be integrated into less complex wireless systems.

The ensuing sections of the paper are as follows: Section 2 describes the issues in conventional multiuser schemes. Section 3 explains the system model and mathematical realization. Section 4 discusses the simulation results. Section 5 presents the conclusion and scope for future work.

2. THE ISSUES IN CLASSICAL MULTI-USER SCHEMES

The MAI and traditional MUD make the BER performance worse in many grouped-CDMA systems. (i) Overloading of users cannot be ousted in future communication systems and therefore robust methods are needed to confront them. In all wireless systems, the MAI increases with an increase in the number of users. In effect, the number of spreading sequences has to be increased in accordance with the growing number of simultaneous users. But, the number of users within group is restricted in the conventional grouped CDMA systems. Various collaborative CDMA schemes [8] achieve a maximum of 90 users per cell-sector, with three users sharing a PN sequence in an AWGN channel. (ii) An opponent can imitate the transmission by knowing the bit timings. This can be eliminated using the properly defined set of chaotic sequences. (iii) Synchronizing the systems under severe fading conditions is also very difficult. The proposed system increases the user capacity and addresses the above mentioned issues by utilizing a unique set of chaotic sequences generated by well defined parameters of the 2x-Mod(1) 1D map, under Rayleigh fading conditions.

3. SYSTEM MODEL AND MATHEMATICAL REALIZATION

3.1 2XM1-CCCDMA multiuser system design

The baseband model for the proposed 2x-Mod (1) system is shown in Figure-1. In a wireless environment, the propagating multipath signals are added constructively or destructively causing large fluctuations in their dynamic range in a short span of time. The information is also spread all over irrespective of the intended receiver. These phenomena in wireless channels make the communication challenging. The Rayleigh fading model is widely used as it aptly represents the practical fading phenomenon in such scenarios.

The chaotic sequences are generated by the rule,

\[ x_0 = x; \quad x_{n+1} = (2x_n) \mod 1, \ \forall n \geq 0 \]  

\( \text{Figure-1. Baseband model for the proposed 2XM1-CCCDMA scheme.} \)
A unique initial condition is used to generate the chaotic sequence for the $i^{th}$ element of the $N \times N$ spreading matrix. The generated sequences of length $1 \times N$ ($N$ is the order of the spreading matrix) are made orthogonal using the 1D-Bernoulli orthogonal-chaotic sequence generation or by the orthogonal chaotic vectors generator using Gram-Schmidt Ortho-normalization process. The $i^{th}$ row constitutes the spreading sequences for the $i^{th}$ group in the 2XM1-CCCDMA scheme. The $G^{th}$ group users share the same orthogonal chaotic sequence to spread their data. In each group $T$ users are combined to form a complex codeword which is then spread using the respective $G^{th}$ orthogonal chaotic sequence.

The transmit signal $s_i(t)$ is:

$$s_i(t) = \sum_{k=1}^{G} \sum_{l=1}^{T} V_{gl}(t) D_{kl}(t)$$  \hspace{1cm} (2)

Where, $K = G \times T$ is the total number of users and $k = 1, 2, 3, K, G$ and $l = 1, 2, 3, K, T$. At the transmitter, the total number of users ($K$) is divided into $G$ groups with $T$ users sharing an orthogonal chaotic sequence. Users, with encoded message $V_{1T}$ within a group, will use the same chaotic-spreading sequence $D_{CG}$. The $k^{th}$ user signal is:

$$s_{k}(t) = V_{k}(t) D_{kl}(t) = \begin{cases} -1 \cdot D_{kl}(t), & \text{for } V_{k}(t) = -1 \text{ and } t \in [(i-1)T_r, iT_r] \\ +1 \cdot D_{kl}(t), & \text{for } V_{k}(t) = +1 \text{ and } t \in [(i-1)T_r, iT_r] \end{cases}$$  \hspace{1cm} (3)

Where, $i^{th}$ represents the $i^{th}$ transmitted bit. For the synchronization part, a chaotic pilot sequence modulated by ‘ones’ is considered which has been generated from the same chaotic map.

$$S_{00}(t) = +1 \cdot D_{C0}$$ \hspace{1cm} (4)

The received signal $r(t)$ is:

$$r(t) = \left( \sum_{k=1}^{G} \sum_{l=1}^{T} h_{kl} V_{kl} \cdot D_{kl} \right) \sqrt{2A \cos(\omega_r I t + \phi)} + \xi_i(t)$$  \hspace{1cm} (5)

Where, $\phi$ is the phase difference between the carriers at transmitter and receiver, $I = \sqrt{2} \cos(\omega_r I t)$, the pilot amplitude $A = \sqrt{\frac{2E}{T_r}}$ and $h_{kl}$ is the channel gain coefficient of the $k^{th}$ user.

At the receiver, the complex codeword has been decoded to extract the groups’ information. The chaotic-collaborative-spreading technique improves the bit error performance of 2XM1-CCCDMA in the Rayleigh fading scenario. The pilot sequence determines the starting position of the spreading of the individual user groups. As the received pilot is synchronized with its counterpart generated at the receiver, it can determine the starting position of the individual user groups. The proposed scheme thus increases the capacity and provides better security, due to its correlation properties inherited from chaotic-codes, in flat fading channel conditions.

The de-spread received signal forms an output signal vector $Z_G$ obtained as:

$$Z_G = RH_G + \xi_i(t)$$  \hspace{1cm} (6)

Inverse cross-correlation matrix multiplication of the de-correlator output gives the vector $a_G$

$$a_G = R^{-1}Z_G = h_G + R^{-1} \xi_i(t)$$  \hspace{1cm} (7)

The individual elements of $a_G$ are sent to the bank of $G$ ML-detectors to estimate the $T$ co-spread users’ data.

The final estimates of group data obtained with minimum Euclidian distance are given by:

$$b_G = \arg \min_{b \in D} \left\{a_G - \sum_{l=1}^{T} h_{lg} V^{(l)}_g \right\}^2$$  \hspace{1cm} (8)

Where, $q \in [1, M^T]$ and $M^T = 2^T$ is the data combinations to search the $T$ co-spread users.

4. PERFORMANCE ANALYSIS AND SIMULATION RESULTS

The total output noise is Gaussian distributed and the probability of bit error each group conditioned on channel-fading-realization $h_G$ is given by

$$P_e(v_G \mid h_G) = Q(\sqrt{\Gamma_{c_G}})$$  \hspace{1cm} (9)

Where, $Q(x)$ is the standard error integral and $\Gamma_{c_G}$ is the signal-to-interference plus noise ratio (SINR).

Now, by calculating the probability of bit error over all the instances of the fading distribution of the $G^{th}$ user, the average error probability is obtained as:

$$P_e(v_G) = \int_0^\infty P_e(v_G \mid h_G) \Psi(\Gamma_{c_G}) d\Gamma_{c_G}$$  \hspace{1cm} (10)

Where, $\Psi(\Gamma_{c_G})$ is the probability density function of SINR based on fading channel magnitude of the $G^{th}$ group. The SINR at the output of the de-correlator $\Gamma_{c_G}$ can be obtained from the single group case, $\Gamma_0$, without MAI or noise given by $\Gamma_{c_G} = \frac{E(|a_G|^2)}{N_0}$.
\[
\Gamma_G = \frac{\left( \frac{a_G}{T} \right)^2}{\sigma^2 \left( \frac{a_G}{T} \right)^2} = \left( \frac{a_G}{T} \right)^2 \Gamma_{c_G} \left( 1 - U_G^T R_G U_G \right) \quad (11)
\]

Where, \( U_G \) is the \( G \)th column of \( R \) devoid of the diagonal elements and \( R_G \) is obtained by separating the \( G \)th row and column elements from \( R \). Since, chaotic sequences are employed \( R_G \) will consist of random correlation values and therefore statistical-average is used rather than fixed-cross-correlations. Averaging \( \left( \frac{d}{d_0} \right)^2 \) over all the fading distribution gives the average probability of error \( P_e(v_G) \). In the proposed scheme, modifying the formula for the standard BPSK probability-of-error, by substituting \( \Gamma_{c_G} \) by \( \Gamma_{c_0} \) with a weighted ratio of \( \left( \frac{d}{d_0} \right)^2 \) (where, \( \overline{d}^2 \) is the average-squared-error-distance per bit obtained by averaging over all the composite symbols and \( d_0^2 = 4 \)), the final BER is obtained as,

\[
P_e(v_G) = \frac{1}{2} \left[ 1 - \left( \frac{\overline{d}^2}{d_0^2} \right)^2 \Gamma_{c_0} \right]
\quad (12)
\]

In Figure-2, the BER performance of the proposed 2XM1-CCCDMA scheme is compared to that of the conventional CDMA and collaborative CDMA in Rayleigh flat fading channel under perfect channel-estimation (\( \sigma^2 (\epsilon) = 0 \)). A processing gain (or spread-length) of 31 is chosen with the total number of groups \( G \) = 30 and the collaborating users \( T = [2, 4] \) so that it accommodates a total of \( K = 60 \) and 120 users (\( G \times T = [30 \times 2, 30 \times 4] \) respectively). Conventional CDMA with 30 users and collaborative CDMA with 60 and 90 users are also generated.

Figure-2. User capacity and BER performance of 2XM1-CCCDMA in Rayleigh flat-fading channel with 1D chaotic sequences of spread length 31.

The results show that the performance of 2XM1-CCCDMA is superior to the other schemes as it supports \( K=120 \) users with an overloading ratio of \( \frac{K}{N} = 133\% \) when compared to the lesser BER performance of other schemes with \( K=90, 60 \) and 30 users. There is significant increase in the total number of users with added security utilizing chaotic codes. The performance variation can be better understood with respect to the theoretical analysis using (10).
In Figure-3, the BER performances of the schemes have been compared with a processing gain of 15. In this case, the performance is analyzed with $G = 14$, $T = [2, 4]$ such that $K = 28$ and 56 users respectively. The performances of conventional CDMA with 14 users and collaborative CDMA with 28 and 52 users have been compared.

The results clearly show that 2XM1-CCCDMA outperforms the other schemes with an overloading ratio of $\frac{K}{N} = 107\%$. However, there is a small degradation in the performance compared to the first case as the spreading length is reduced. As in conventional CDMA systems, the proposed scheme also gives the performance directly related to the length of the spreading sequences.

5. CONCLUSIONS

The mathematical model of a 2XM1-CCCDMA scheme is described under Rayleigh flat fading channels and compared to high capacity grouped-CDMA schemes. The proposed scheme demonstrates acceptable BER performance as the number of users per group is increased. A large number of secure-spreading sequences generated by a 2x-Mod (1) chaotic map have been made available, which in turn increases the total number of users. By the use of 1D-chaotic-coding it also provides security and eliminates MAI without the knowledge of channel parameters. The simulations reveal a fourfold increase (approximately) in the user capacity when compared to the existing schemes. Even though there is an SNR degradation of approximately 2dB for the additional users within a group, most wireless systems accept this degradation in signal-to-noise ratio taking into account the total number of users. More investigations on implementation of 3D-chaotic maps can be taken into account for future research.

REFERENCES

Transactions on Communications. doi: 10.1109/TCOMM.2013.071013.130225.


