Design and Simulation of a Cooperative Communication System Based on DCSK/FM-DCSK

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Abstract — Frequency modulated differential chaos shift keying (DCSK/FM-DCSK), a joint modulation and spread spectrum technique, is a promising modulation technique for low-cost and low-complexity wireless transmission applications. The noise performance of DCSK/FM-DCSK is superior to most conventional modulation schemes in multipath-channel environment. Cooperative communication, on the other hand, is receiving increasing attention due to its efficiency in sharing single-antenna mobiles or network nodes with other antennas to achieve combating fading via transmitting diversity. By combining these two aspects of advantages, a novel chaotic communication system is proposed in this paper, aiming to achieve combating multipath and fading effects. Simulation results show that significant performance improvement can be achieved by the proposed system in comparison with non-cooperative systems. It is found that the choice of some key parameters, such as the spread spectrum factor and the relay selective strategy, affect the system performance prominently. It reveals that the combination of the DCSK/FM-DCSK framework with a cooperative strategy is of great practical value for certain wireless communication networks.

I. INTRODUCTION

Chaotic communication systems offer a promising solution to spread-spectrum communication applications. Although the noise performance of most chaotic digital modulation schemes over AWGN channels is generally under that of conventional modulation schemes, the performance degradation of chaotic modulation schemes is smaller under certain propagation conditions where coherent reception is impossible. In particular, frequency-modulated differential chaos shift keying (DCSK/FM-DCSK) technique offers robustness against multipath interference and channel imperfections [1][2]. This advantage can be verified in single input and multiple output (SIMO) and ultra wideband (UWB) transmission environments [3][4]. Thus, DCSK/FM-DCSK demonstrates itself as a promising modulation technique for many low-cost and low-complexity wireless transmission applications, such as wireless sensor networks (WSN) and low-data-rate wireless personal or body area networks (WPAN, WBAN) [5][6].

On the other hand, cooperative communications can provide transmit diversity for most wireless networks operate in multiuser mode. In cooperative communications, terminals share their antennas to achieve uplink transmit diversity. Since one user’s signals can be relayed by other users’ independent fading paths to the destination, this approach achieves spatial diversity through all partners’ antennas, which enhances the ability of combating fading in wireless communication systems [7]. In WSN, WPAN and WBAN, which are complicated applications requesting low-cost, low power and various demands of QoS, a communication system that combines DCSK/FM-DCSK modulation with cooperative communication strategy is advantageous. This approach has great potential for improving link performance through only increasing overheads of network algorithms while keeping all terminal conditions unchanged.

II. THE SYSTEM MODEL

A. Principles of DCSK and FM-DCSK

Figure 1 shows a block diagram of the DCSK/FM-DCSK system. The difference between FM-DCSK and DCSK is that the generator in the carrier, and FM-DCSK contains an FM modulator [8].

![Block diagram of the DCSK/FM-DCSK system (a) transmitter, (b) receiver](image)

As can be seen, the binary DCSK/FM-DCSK system transmits a reference and its repeated or reverse according to the digital information “1” or “0”. Due to the difficulty of exact recovery and complete synchronization of chaotic carriers, demodulation of the binary DCSK/FM-DCSK employs a simple differential coherent approach. The detection consists of multiplying the received signal by its...
$T/2$ delayed version, integrating the results between $T/2$ and $T$, and then making a decision of this integral value by using a zero threshold: if the integral value is greater than zero, “1” is detected; otherwise, “0” is chosen.

The theoretical noise performance of the differentially coherent DCSK/FM-DCSK system was derived in [8]:

$$BER = \frac{1}{2^B} \exp \left( -\frac{E}{2N_0} \sum_{\ell=0}^{B-1} \sum_{i=0}^{\ell} \frac{1}{i!} \cdot \left( j + BT - 1 \right) \right)$$  \quad (1)

Equation (1) shows that the noise performance of differentially coherent FM-DCSK is as good as that of noncoherent binary FSK for the case of $BT=1$. In this case, the superior multipath performance of FM-DCSK cannot be exploited, however, so $BT>1$ is adopted in this paper.

### B. Cooperative Communication

Cooperative communication is a valid method to mitigate multipath fading. The cooperative scheme is illustrated by Fig. 2. This is a three-node model. The information bits are divided into two parts, to be sent in two phases. In the first phase, user1 broadcasts $N_1$ bits, and the partner (user2) receives and decodes it. If the $N_1$ bits from user1 can be successfully decoded by user2 in the first phase, $N_2$ bits will be retrieved from $N_1$, encoded again, and then transmitted by user2 in the second phase; else the $N_2$ bits are transmitted by user1 in the second phase. In the destination, $N_1$ and $N_2$ bits are jointly decoded by the transmitting user. The level of cooperation is defined as $N_2/N$. The same process is carried out when user2 is transmitting data and user1 is acting as relay. This is a coded cooperation method [9]. It is because AF brings up amplified noise and DF brings up error propagation. Fig. 2 shows the situation where the users can decode signals from each other.

![Figure 2. Cooperative scheme](image)

### C. DCSK/FM-DCSK CC model

The implementation of DCSK/FM-DCSK cooperative communication (CC) system is shown in Fig. 3. The two users cooperate by dividing the transmission of their $N$-bit code words into two successive time segments, or frames. In the first frame, each user transmits its own $N_1$ bits through DCSK/FM-DCSK modulation to all available relays and the destination. Each partner as one relay also receives and decodes the user's transmitted data. If the partner successfully decodes the user's transmitted data, then $N_2$ bits encoded by the user itself are transmitted to the second frame. Whether or not the decoding by the relay is successful it can always be implemented by CRC check.

![Figure 3. The transmitter of the DCSK/FM-DCSK CC system (with CRC)](image)

Next, to describe the mathematical formulation of the above-described model, the impulse response of the multipath channel is represented as [10]

$$h_{i,j}(t) = \chi(t) \sum_{k=1}^{N_k} \alpha_{i,j}^k \cdot \delta(t - t_k)$$  \quad (2)

where $N_k$ is the number of multipath components that can be resolved at the receiver, $\alpha_{i,j}^k$ is the gain between $i$ and $j$ of the $k$th path, $t_k$ is the delay, $\chi(t)$ models the distortion of the multipath components due to the frequency selectivity of the interaction with the propagation environment.

The cooperation process is described as follows:

**Phase 1:**

$$Y_{k,r}(t) = X_{s,r}(t) \otimes h_{s,r}(t) + N_{s,r}(t)$$  \quad (3)

If the relay decodes $Y_{s,r}(t)$ correctly, then

$$Y_{r,d}(t) = X_{s,d}(t) \otimes h_{s,d}(t) + N_{s,d}(t)$$  \quad (4)

else

$$Y_{s,d}(t) = X_{s,d}(t) \otimes h_{s,d}(t) + N_{s,d}(t)$$  \quad (5)

**Phase 2:**

where $Y_{k,r}(t)$, $Y_{s,r}(t)$, $Y_{r,d}(t)$ and $Y_{s,d}(t)$ are the models of the received signals at the destination, the relay during is $[0,T/2]$, $Y_{s,d}(t)$, $Y_{r,d}(t)$ are the received signals at the destination during $[T/2,T]$, $N(t)$ is the additive channel noise in the receiver, and $\otimes$ denotes the convolution operation.

### III. PERFORMANCE ANALYSIS

The performance of the above-proposed system is investigated in this section. For simplicity of illustration, consider the scenario of two users both transmitting data to a single destination. Assume that the channels between the two
users (inter-user channels) and from each user to the destination (uplink channels) are mutually independent and subject to rayleigh multipath slow fading.

There are four possible cooperative situations for the transmission in the second phase, as illustrated by Fig. 4.

<table>
<thead>
<tr>
<th>The first phase</th>
<th>The second phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>User1</td>
<td>User1</td>
</tr>
<tr>
<td>User2</td>
<td>User2</td>
</tr>
</tbody>
</table>

Figure 4. Four cooperative cases for the second phase

The performance is over a multipath channel, one has

\[ \gamma_{p,q} = \sum_{i=1}^{L} p_i \frac{\Omega_{p,q}^i}{\Omega_{q}} (\alpha_{p,q}^i)^2 \]  

(6)

where \( p_i = 1 \) if the \( i \)th bin is occupied with an arrival, \( L \) is the number of resolvable paths, and \( \alpha_{p,q}^i \) is the fading coefficient magnitude of the \( i \)th path between users \( p \) and \( q \). Also,

\[ \Gamma_{p,q} = E[\gamma_{p,q}] = E \left[ \sum_{i=1}^{L} p_i \frac{E_{b,p} \alpha_{p,q}^i}{\Omega_{q}} \right] \]

(7)

where \( \Omega_{p,q}^i \) is the expectation of \( \alpha_{p,q}^i \), for \( \alpha_{p,q} \) is independent samples of rayleigh-distributed random variable, and users \( p \neq 1 \) and \( q \neq 0 \).

Take Case 1 (see Fig. 4) for example. When both users successfully decode each other's first frame, each user's bits are divided between the two user channels. In this case, the unconditional PEP [9] is

\[ P(d) = \frac{1}{\pi} \int_{0}^{\pi/2} \left( 1 + \frac{d_1 \Gamma_{1,0}}{\sin^2 \theta} \right)^{-1} \left( 1 + \frac{d_2 \Gamma_{2,0}}{\sin^2 \theta} \right)^{-1} d\theta \]

(8)

where \( d_1 \) and \( d_2 \) are the portions of the error event bits transmitted through user1's and user2's channels, respectively. An alternative form of the \( Q \) function and the well-known MGF [11] are used in (8). Thus, if \( d_1 \) and \( d_2 \) are both non-zero, then full diversity order of two is achieved when both partners successfully receive signals from each other. The probability and performance under one case are:

\[ P(\Theta = 1) = (1 - P_1)(1 - P_2) \]

\[ P_b(\gamma, \Theta) \leq \frac{1}{N} \sum_{d=0}^{N} c(d)P(d | \gamma, \Theta) \]

(9)

where \( P_1 \) and \( P_2 \) are the error probabilities of the first frame for user1 and user2, respectively, and \( N \) is the number of input bits.

The other three cases can be easily analyzed in the same way. Thus, the end-to-end error probability is

\[ P_b = \sum_{i=1}^{4} P_i(\Theta)P(\Theta = i) \]

(10)

IV. SIMULATION RESULTS

To evaluate the performance of the DCSK/FM-DCSK CC system, simulations were carried out over rayleigh multipath fading channels. The parameters include a multipath number of three, a power delay profile of \([0.4, 0.4, 0.2]\), and delays of \([0, T/(2\beta), T/\beta]\), where the \( \beta \) is the spread spectrum factor. The encoder generator polynomial is \([15, 17]\) in the first phase and \([13, 15]\) in the second phase. From [2], it is known that the performance of FM-DCSK is better than conventional spread-spectrum communication methods. Therefore, the following simulations are performed under DCSK and FM-DCSK modulations.

Figure 5 shows the BER results for DCSK CC and FM-DCSK CC systems with the same average SNR uplink multipath channels, where the level of cooperation is 50%, the spread-spectrum factor is 16, and both user-uplink channels have equal average SNR.

From Fig. 5, one can see that the performance of FM-DCSK CC is still better than that of DCSK CC over a multipath channel, as concluded in [2]. This indicates that the cooperation communication theory can be used in FM-DCSK and DCSK systems to improve their BER performance.

Observing Fig. 6 and Fig. 7, it can be seen that the spread spectrum factor distinctly affects the system performance. As the spread spectrum factor increases, the performance actually is improved over the multipath fading channel, which shows that the proposed system can achieve good
error performance by sacrificing some spectral resources under a multipath fading environment, just as the conventional DCSK/FM-DCSK system. But it is noted there is an optimal spread spectrum factor, not the bigger the better.

Because the $N_1$ bits can always be correctly decoded, the cooperative performance is determined only by the second phase. It shows that $d_{R,D} \leq d_{S,D}$ in general, but in the DCSK CC system, there is an additional area as compared to FM-DCSK, which can be found through simulations. Left of Fig. 8 shows the relay selective strategy for DCSK, while the right is for FM-DCSK. Although the performance of FM-DCSK is better than that of DCSK, the available relay is less than that of DCSK under the same transmitting power. Why did this happen? Because the relay selective strategy depends on the modulation method. This has been proved through our recent research, which will be reported elsewhere soon.

V. CONCLUSION

In this paper, a system combining DCSK/FM-DCSK with cooperative communication strategy is proposed. Through performance analysis and simulation, it is shown that the proposed wireless communication system can effectively enhance the system performance over multipath and fading channels. Based on either DCSK or FM-DCSK, the proposed cooperative mechanism can achieve about 2.5 dB gain for $BER=10^{-4}$ in contrast to the non-cooperative schemes. For the proposed cooperative communication system based on DCSK/FM-DCSK, it is found that the choice of some key parameters, such as the spread-spectrum factor and relay’s position, is important in affecting the system performance. The FM-DCSK cooperative communication system is more sensitive to the spread-spectrum factor as compared to DCSK; it begins to have gains in factor 4 while DCSK in 8, but the latter has more available relays than the former. These characteristics imply that the chaotic modulation method has flexibility in meeting application specifications. A more realistic multiuser scenario will be further investigated in the near future.

References


