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An Efficient Transmission Scheme for DCSK Cooperative Communication Over Multipath Fading Channels

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ABSTRACT Differential-chaos-shift-keying cooperative communication (DCSK-CC) has attracted a great deal of attention in the past five years, because it can overcome the negative effect of wireless multipath fading. However, the conventional DCSK-CC system suffers from a major disadvantage of low data rate due to the resource consumption in cooperation. To address the issue, this paper proposes an efficient cooperative scheme, called partial-sequence CC (PS-CC) scheme, for the DCSK-CC system. In the PS-CC framework, the source and relays only transmit a partial chaotic sequence corresponding to one bit to the destination, while consuming the same transmission energy as DCSK-CC. To validate the feasibility of the DCSK PS-CC system, this paper carries out the error performance, diversity order, and data rate analyses under different cooperative conditions over multipath fading channels. Both numerical and simulated results show that the proposed PS-CC system outperforms the DCSK-based non-cooperative system and DCSK-CC systems over the range of signal-to-noise ratio under study. Moreover, the proposed system can enhance data rate and reduce the computational overhead of the relays as compared with the DCSK-CC system. In addition, it will be demonstrated that the DCSK PS-CC system preserves its advantages in typical ultra-wideband (UWB) channels. Overall, the PS-CC appears to be a desirable cooperative scheme for those applications featured by high-data-rate, low-power, and low-complexity, such as wireless sensor networks using the transmitted reference UWB technique.

INDEX TERMS User cooperation, partial-sequence cooperative communication (PS-CC), differential chaos shift keying (DCSK), multipath Rayleigh fading channel.

I. INTRODUCTION Modern communication applications, including indoor, mobile radio and wireless local networks (WLAN), are extremely vulnerable to multipath fading and distortion effects. One technique to tackle this problem is using a chaotic carrier to spread a digital signal over a wide bandwidth spectrum for modulation [1]. The chaos-based technique offers excellent error performance in the case that communication channel suffers from multipath propagation and distortion, or the communication channel is time-varying [1]. Among those chaos-based modulations, differential-chaos-shift-keying (DCSK) is considered as one promising technique for implementation without synchronization or channel estimation, which only requires frame or symbol rate sampling [2]. Also, there is no need to involve extra spreading and despreading circuit when realizing DCSK-based systems [3]. Therefore, DCSK has drawn considerable interest since its inception [4]–[11]. Because of the inherent wide-band property, DCSK can be seamlessly combined with ultra-wideband (UWB) and applied to...
wireless personal area networks (WPANs) and wireless sensor networks (WSNs) [12]–[17].

Another effective technique to mitigate the signal corruption arisen from multipath fading propagation is spatial diversity [18]. Allowing multiple antennas to transmit redundant signal information can greatly reduce the effect of multipath propagation. However, multiple antennas are hard to deploy in DCSK due to the variation of its carrier in different bit periods. This deployment is also impractical considering the cost, size, and power of the device in many wireless-communication applications. To overcome this limit, in [19] and [20], it has been proposed to use a DCSK-based cooperative communication (DCSK-CC) system and demonstrated that the near-far effect can be effectively avoided in DCSK-CC system as compared to conventional CDMA system, which is of great significance to energy-constrained networks such as WSNs [21].

In the DCSK-CC system [19], [20], each transmission period is split into two phases: in the first phase, the source broadcasts message to the destination and relays; in the second phase, the relays retransmit the processed signal to the destination according to a given cooperative protocol, e.g., the amplify-and-forward (AF) protocol or selective decode and-forward (SDF) protocol [20]. In other words, in the DCSK-CC system, the chaotic sequence corresponding to a given bit is sent repeatedly from the source and relays in different phases. Noticeably, this cooperative technique possesses relatively low bandwidth efficiency since some channel resource is allocated to the relays for transmission and thus the overall data rate is dramatically reduced [21]. In addition, it will be shown in this paper that with more relays involved, the DCSK-CC system has worse error performance than DCSK non-cooperative (DCSK-NC) system in the low-SNR region.

Aiming to mitigate the aforementioned adverse effects, this paper proposes an efficient DCSK-CC scheme, called DCSK partial-sequence CC (PS-CC). In the new system, the source only extracts a PS instead of a whole DCSK-based chaotic sequence to broadcast in the first phase. The relays then process and transmit the received PS to the destination in the second phase. In this transmission mechanism, the transmitted data rate can be remarkably increased and hence the system throughput is enhanced. Meanwhile, the computational overhead of the receiver is reduced for processing fewer samples as compared to the existing DCSK-CC scheme. Theoretical analyses and simulations show that the proposed PS-CC system is superior to the DCSK-CC system in error performance over multipath Rayleigh fading channels. To validate its feasibility in practical applications, this paper also compares the performance of PS-CC, DCSK-CC, and DCSK-NC systems over typical UWB channels, which demonstrates that the proposed PS-CC system can retain its performance advantage. As a consequence, the PS-CC system provides a very good transmission solution for low-power and low-complexity wireless applications, such as WLANs, WPANs, and WSNs.

The remainder of this paper is organized as follows. The DCSK PS-CC system framework is proposed in Section II. The BER performance and diversity order of the proposed DCSK PS-CC system are analyzed in Section III. Numerical results are reported in Section IV, and concluding remarks are given in Section V.

II. SYSTEM MODEL

This section first reviews the basic principles of DCSK modulation and then describes the proposed DCSK PS-CC system.

A. DCSK MODULATION

In DCSK modulation, the binary information to be sent is mapped to a differential chaotic wideband signal in order to alleviate the negative effect of multipath fading. By sampling the waveform output from the chaos generator, one can obtain a DCSK-based chaotic sequence corresponding to each bit. Every bit is specified by two chaotic segments of the same length. Fig. 1 shows the block diagram of the binary DCSK system, where the modulation unit transmits a chaotic-reference segment in the first half of the symbol duration, and repeats or reverses the segment in the second half of the symbol duration, depending on bit information “1” or “0”. Let $\beta$ denote the length of each chaotic segment. Then, the spreading factor is yielded as $2\beta$. During the $l$-th bit duration, the transmitted signal can be expressed as

$$s_k = \begin{cases} c_k, & k = 2\beta(l - 1), \ldots, (2l - 1)\beta, \\ (2b_l - 1)c_k - \beta, & k = \beta(2l - 1)\beta, \ldots, (2l)\beta, \end{cases}$$

(1)

where $c_k$ denotes the $k$-th chaotic sample, $b_l$ denotes the $l$-th transmitted bit, and $b_l \in \{0, 1\}$. Utilizing the discrete-time baseband equivalent model, the received signal $r(t)$ over a multipath fading channel can be written as

$$r_k = \sum_{i=1}^{L} a_i s_{k-i} - \tau_i + n_k,$$

(2)

where $r = \{r_k\}$ is the received chaotic signal, $L$ is the number of fading paths, $a_i$ is the independent Rayleigh-distributed fading gain of the $i$-th path, $\tau_i$ is the time delay of the $i$-th path, and $n_k$ is the Gaussian distributed random noise with spectral density of $N_0/2$. At the receiver, using a
correlation-based detection, the received signal can be demodulated by
\[ z = \sum_{k=\beta+1}^{2\beta} r_k r_{k-\beta}. \]  

Note that we use \( T \) to denote the bit duration period of 2\( \beta \) chaotic samples.

**B. MULTI-RELAY DCSK PS-CC SYSTEM**

User cooperation diversity has the potential to be successfully applied in wireless ad hoc networks. In cooperative systems, there are several inter-user channels that are independently subjected to multipath block fading. In this paper, we assume that the channel state remains constant during each cooperative period, as in [20] and [22]. Two cooperative protocols, AF and SDF, are considered in this paper. As can be seen from [21], these two protocols are good in terms of implementation, but with the disadvantage of low data rate.

Consider a cooperative system consisting of one source, one destination and \( n \) relays. In the conventional DCSK-CC, a chaotic sequence corresponding to a bit is transmitted repeatedly to the destination and relays in different time slots. Thus, the overall data rate is reduced. To overcome this weakness, we propose a novel DCSK-CC system, called **DCSK PS-CC system**, as illustrated in Fig. 2. In the DCSK PS-CC system, a chaotic sequence corresponding to one bit is denoted by \( s = \{c_1, c_2, \ldots, c_{2\beta}\} \). Similar to time division multiple access (TDMA) to avoid interference, the PS-CC scheme is divided into two steps. First, let \( s_0 \) denotes the PS of length \( 2\beta/(m+1) \) to be sent, where \( m \) is a non-negative integer. The PS, to be broadcasted to the destination and the relays in the first phase, is formulated via successively extracting the first sample from each subsegment of length \( m+1 \) in \( s \). Second, each relay processes the received "corrupted" signal of \( s_0 \). Let \( s_j \) denote the retrieved signal by the \( j \)-th relay according to AF or SDF strategy. These retrieved signals will be respectively sent to the destination by their corresponding relays in different time slots in the second phase. It should be noted that the value of \( m \) should be determined properly. The impact of \( m \) on the system performance will be investigated in Section IV.

Based on the above description, the received signal at the destination is given by
\[ r_k = \sum_{i=1}^{L_0} \alpha_i s_{0,k-\tau_i} + \sum_{i=1}^{L_1} \alpha_i s_{1,k-\tau_i} + \ldots + \sum_{i=1}^{L_n} \alpha_i s_{n,k-\tau_i} + \sum_{j=0}^{n} \xi_j, \]  

where \( L_j \) denotes the number of Rayleigh fading paths from the \( j \)-th relay to the destination, \( s_{j,k-\tau_i} \) denotes the \( k \)-th sample in signal \( s_j \) delayed by \( \tau_i \). \( \xi_j \) is the Gaussian-distributed random noise between user and destination, \( j = 0, 1, \ldots, n \).

Because the PS is transmitted instead of a whole chaotic sequence, in contrast to (3), the received signal of length \( 2\beta/(m+1) \) at the relays is demodulated by
\[ z = \sum_{k=\beta/(m+1)}^{2\beta/(m+1)} r_k r_{k-\beta}. \]  

In general, fewer samples bearing at the receiver leads to lower computational overhead. Hence, comparing (3) with (5), one can observe that the DCSK PS-CC system enables lower relay computational overhead than the DCSK-CC system. Fig. 3 presents the transmission mechanisms of the DCSK PS-CC system and the conventional DCSK-CC system. As seen, the DCSK PS-CC spends less transmission time than the DCSK-CC system in transmitting each bit. Thus, the DCSK PS-CC system has higher data rate as compared to the DCSK-CC system. In the following section, it will be showed that if \( L_j \) is constant (i.e., \( L_j = L \) and the

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1 Strictly speaking, in the multi-relay DCSK-CC system, each transmission period consists of two phases, i.e., the broadcasting phase and the cooperative phase. The broadcasting phase includes only one time slot, while the cooperative phase includes \( n \) time slots. In particular, the \( j \)-th time slot is allocated to the \( j \)-th relay, which will be utilized to forward message to the destination.

2 To simplify the description, the subscript "\( j = 0 \)" is used to denote the source, while "\( j > 0 \)" is used to denote the \( j \)-th relay. For example, the first polynomial in (4) represents the received signal (excluding the noise) from source to destination.
inter-user channel is good enough, the DCSK PS-CC system can achieve the diversity order of \((n+1)L\).

### III. PERFORMANCE ANALYSIS

In this section, we will first discuss the BER evaluation of DCSK-NC system over multipath fading channels, based on which the BER formulas of DCSK PS-CC system will be analyzed. To simplify the analyses, we assume that i) the time delay \(\tau_i\) is much shorter than the bit duration, i.e., \(\tau_i \ll 2\beta\), such that inter-symbol interference (ISI) can be ignored, ii) the number of paths \(L_j\) is kept constant (i.e., \(L_j = L\)), iii) the channel attenuation \(\alpha_i\) and phase shifts are known at the receivers, and iv) the maximal ratio combiner (MRC) is adopted at the receivers.

#### A. THEORETICAL BER FOR DCSK-CC SYSTEM

As one of the most typical diversity-reception techniques, MRC has attracted much attention in the past decade. Using this technique, the received SNR \(\bar{\gamma}_b\) for a given bit at the receiver is expressed as

\[
\bar{\gamma}_b = \sum_{i=1}^{L} \gamma_i = \frac{E_b}{N_0} \sum_{i=1}^{L} \alpha_i^2, \tag{6}
\]

where \(L\) is the number of fading paths, \(\gamma_i = \alpha_i^2 \frac{E_b}{N_0}\) is the instantaneous SNR of the \(i\)-th path, and \(E_b\) is the transmit energy per bit, defined by

\[
E_b = 2\beta \mathbb{E}((c_k)^2). \tag{7}
\]

Then, the probability density function (PDF) of the received SNR becomes

\[
f(\gamma_b) = \frac{1}{\bar{\gamma}^L (L-1)!} \gamma_b^{L-1} e^{-\frac{\gamma_b}{\bar{\gamma}}}, \tag{8}
\]

where \(\bar{\gamma} = \mathbb{E}\{\gamma_i\}\) is the average received SNR per path. The conditional BER for DCSK as a function of the received instantaneous SNR is given by [23]

\[
\text{BER}(\gamma_b) = \frac{1}{2} \text{erfc}\left(\frac{4}{\gamma_b} + \frac{2\beta}{\bar{\gamma}}\right). \tag{9}
\]

Combining (8) and (9), the average BER can be obtained by integrating the corresponding conditional BER, as

\[
\text{BER} = \int_0^{\infty} \text{BER}(\gamma_b) f(\gamma_b) d\gamma_b. \tag{10}
\]

In the DCSK-NC system, assuming that the energy per bit is set to be one, and each path has the identical power, i.e., \(\bar{\gamma} = \frac{E_b}{N_0}/L\). For fair comparison, in the \(n\)-relay DCSK-CC system, the energy of each transmitter for one bit is assigned to be \(1/(n+1)\). As a result, the overall energy is \(1/(n+1) + n/(n+1) = 1\), the same as that in the DCSK-NC system. In the DCSK-CC system, the total number of chaotic samples transmitted to the destination is \(2\beta(n+1)\), since the source and each relay transmit \(2\beta\) samples. From the above description, the global spreading factor of the DCSK-CC system is equivalent to \(2\beta(n+1)\). Thus, the BER of DCSK-CC system with \(n\) relays can be evaluated by using (8)-(10) with the parameters \(L(n+1)\) replacing \(L\) in (8), \(2\beta(n+1)\) replacing \(2\beta\) in (9), and \(\bar{\gamma} = (E_b/N_0)/(L(n+1))\).

#### B. THEORETICAL BER FOR DCSK PS-CC SYSTEM

The DCSK PS-CC system also considers a network with one source, one destination, and \(n\) relays. At the source transmitter, each bit is firstly modulated by DCSK as a chaotic sequence of length \(2\beta\). Afterwards, the transmitter extracts \(2\beta/(m+1)\) samples from \(2\beta\) samples to transmit. For a given bit, the overall length of the chaotic samples transmitted to the destination in the PS-CC system becomes \(2\beta(n+1)/(m+1)\). Therefore, the global spreading factor of the system can be defined as \(2\beta(n+1)/(m+1)\), and this parameter will be used in the BER calculation.

1) BER WITH A PERFECT \(S \rightarrow R\) CHANNEL

In the PS-CC system, the destination receives \((n+1)\) partial sequence signals from one source and \(n\) relays. Each channel includes \(L\) independent fading paths. For fair comparison, similar to the DCSK-CC system, the transmission energy per user is assumed to be \(1/(n+1)\). The overall received SNR at the destination is

\[
\gamma_b = \frac{E_b}{N_0} \sum_{i=1}^{(n+1)L} \alpha_i^2. \tag{11}
\]

The power of each path is uniformly allocated as

\[
E((\alpha_i^2)) = \frac{1}{(n+1)L}. \tag{12}
\]

The PDF of the received SNR can be expressed as

\[
f(\gamma_b) = \frac{1}{\gamma^{(n+1)L}((n+1)L-1)!} \gamma_b^{(n+1)L-1} e^{-\frac{\gamma_b}{\gamma}}, \tag{13}
\]

where \(\bar{\gamma} = (E_b/N_0)/(L(n+1))\). Using (9) and (13), one can easily obtain the averaged BER of the proposed system.

2) BER UNDER PRACTICAL CONDITIONS

Without loss of generality and to consider more practical channel conditions, the BER expressions of the PS-CC system will be derived under different inter-user distances and different relaying protocols, respectively. Unless otherwise mentioned, we consider a three-node \((n = 1)\) PS-CC system here.\(^3\) In this case, the transmission energy for the source and relays are \(P_{SD} = P_{RD} = 0.5\).

We first evaluate the BER with different inter-user distances under the error-free relaying protocol (i.e., a perfect \(S \rightarrow R\) channel). In fact, the path loss is of great importance to determine the error performance of DCSK PS-CC system. Let \(d_{SR}, d_{SD}, d_{RD}\) denote the distances from source to relay (\(S \rightarrow R\)), source to destination (\(S \rightarrow D\)), and relay to destination (\(R \rightarrow D\)) links, respectively. Taking the path-loss

\(^3\)Note also that the new results can be easily extended to the scenario of \(n > 1\).
gain $1/d^2$ into account, the received SNR at the destination becomes
\[
\gamma_b = \frac{E_b}{N_0} \sum_{i=1}^{L} \gamma_{SD,i} + \sum_{i=1}^{L} \gamma_{RD,i} = \frac{E_b}{N_0} \sum_{i=1}^{L} \alpha_i^2 (1/d_{SD,i}^2 + 1/d_{RD,i}^2). \tag{14}
\]

Also, the average SNR is
\[
\bar{\gamma} = \frac{P_{SD} \cdot 1/d_{SD}^2 + P_{RD} \cdot 1/d_{RD}^2 (E_b/N_0)}. \tag{15}
\]

For the one-relay PS-CC system, one can further obtain
\[
f(\gamma_b) = \frac{1}{\bar{\gamma}^{2L}(2L-1)!} \gamma_b^{L-1} e^{-\bar{\gamma}}. \tag{16}
\]

Substituting (14)-(16) into (10), the average BER formula can be obtained, which is relevant to $d_{SD}$ and $d_{RD}$.

Secondly, we evaluate the BER expressions with AF and SDF relaying protocols, respectively. When AF is adopted, the relay directly forwards a scaled version of the received signal to the destination in the second phase. The received SNR with AF is the same as that given in (14). Moreover, the average received SNR at the destination is [24]
\[
\bar{\gamma} = \bar{\gamma}_{SD} + \frac{\bar{\gamma}_{SR} \cdot \bar{\gamma}_{RD}}{\bar{\gamma}_{SR} + \bar{\gamma}_{RD} + 1}, \tag{17}
\]

where $\bar{\gamma}_{SR}$, $\bar{\gamma}_{SD}$, and $\bar{\gamma}_{RD}$ denote the average received SNR of $S \rightarrow R$, $S \rightarrow D$ and $R \rightarrow D$ links, respectively. Assuming that $S \rightarrow R$ and $S \rightarrow D$ channels suffer from the $L$-path fading, one has
\[
\bar{\gamma}_{SR} = \bar{\gamma}_{SD} = \bar{\gamma}_{RD} = \frac{1}{2L} (E_b/N_0). \tag{18}
\]

Using (10), (14), (17), and (18), one can calculate the average BER of the AF-based PS-CC system.

Finally, we derive the BER expression when SDF is adopted. In the SDF-based PS-CC system, if the relay can decode the received signal correctly, it re-generates a chaotic signal of length $2\beta/(m + 1)$, and then forwards the signal to the destination. Otherwise, it remains idling. Thus, one can write the BER in the SDF case as follow:
\[
BER_{SDF} = BER_{SR} \cdot BER_{SD} + (1 - BER_{SR}) \cdot BER_{RD+SD}, \tag{19}
\]

where $BER_{SR}$, $BER_{SD}$, $BER_{RD+SD}$ represent the BER of the relay, the destination with one signal from source, and the destination with two signals from source and relay, respectively. If the relay fails to detect the received signal, $BER_{SR}$ is equal to $BER_{SD}$ with the received SNR expressed by
\[
\gamma_b = \sum_{i=1}^{L} \gamma_{SD,i} + \sum_{i=1}^{L} \gamma_{RD,i}. \tag{20}
\]

The $BER_{SR}$ and $BER_{SD}$ can be evaluated by using (8)-(10) with the following parameters:
\[
\bar{\gamma} = \frac{E_b \cdot P_{SR}}{N_0 \cdot L}, \tag{21}
\]
\[
f(\gamma_b) = \frac{1}{\bar{\gamma}^{L}(2L-1)!} \gamma_b^{L-1} e^{-\bar{\gamma}}. \tag{22}
\]

where $P_{SR}$ denotes the transmit power from the source to the relay, $P_{SR} = 1/n$. If the relay decodes correctly, the BER can be estimated similarly using the following parameters:
\[
\gamma_b = \frac{E_b \cdot P_{SR} + P_{SD}}{N_0 \cdot 2L}, \tag{23}
\]
\[
f(\gamma_b) = \frac{1}{\bar{\gamma}^{2L}(2L-1)!} \gamma_b^{L-1} e^{-\bar{\gamma}}. \tag{24}
\]

Based on the above results, one can finally calculate the BER of the SDF-based PS-CC system by exploiting (19).

### 3) DIVERSITY-ORDER ANALYSIS

According to [18], which provides a pair-wise-error-probability (PEP) expression of the binary-phase-shift-keying (BPSK) CC system, the diversity-order analysis of DCSK PS-CC system is performed in this subsection. Let $\gamma_\mu$ denote the instantaneous received SNR of the $i$-th path in the $R_j \rightarrow D$ link, where $j = 0, 1, \ldots, n$, $i = 1, 2, \ldots, L$, $\mu = (j + 1)i$, and $S = R_0$. It is obvious that $\gamma_\mu$ follows the exponential distribution with mean $\Gamma_\mu = E(\gamma_\mu)$, which characterizes the quality of each channel.

In a multipath Rayleigh fading channel, the PEP of DCSK PS-CC system is given as
\[
P(b_l \rightarrow \tilde{b}_l | \gamma_b) = P \left( b_l \rightarrow \tilde{b}_l \bigg | \sum_{\mu=1}^{\Omega} \gamma_\mu \right), \tag{26}
\]

where $\tilde{b}_l$ represents the error bit after demodulation, which is the complement of the transmitted bit $b_l$, and $\Omega = (n + 1)L$. According to (9), the conditional BER of the proposed system is rewritten as
\[
P(b_l \rightarrow \tilde{b}_l | \gamma_b) = \frac{\gamma_b}{2(1 + \beta \cdot \Omega \cdot E((\alpha_\mu^2))}, \tag{27}
\]

where $E((\alpha_\mu^2))$ is the expectation of the square of the channel fading gain. If
\[
\frac{\beta \cdot \Omega}{2\gamma_b} E((\alpha_\mu^2)) \ll 1, \tag{28}
\]

then
\[
P(b_l \rightarrow \tilde{b}_l | \gamma_b) = \frac{1}{\pi} \int_{0}^{\pi/2} \exp \left( -\frac{\sum_{\mu=1}^{\Omega} \gamma_\mu}{4 \sin^2 \theta} \right) d\theta. \tag{29}
\]

Thus, substituting the moment-generating function [25, eqs. (3.5-1)-(3.5-3)] and [26, eq. (17)] into (29), one can obtain the unconditional averaged BER of the multi-relay PS-CC system over multipath Rayleigh fading channels, yielding
\[
P(b_l \rightarrow \tilde{b}_l) = \frac{1}{\pi} \int_{0}^{\pi/2} \prod_{\mu=1}^{\Omega} \left( 1 + \frac{\Gamma_\mu}{4 \sin^2 \theta} \right)^{-1} d\theta. \tag{30}
\]
Note that if one maximizes \( \sin^2 \theta = 1 \), the upper bound of (30) is reduced to

\[
P(b_l \rightarrow \tilde{b}_l) = \frac{1}{2} \prod_{\mu=1}^{\Omega} \left( 1 + \frac{1}{1 + 4 \Gamma_{\mu}} \right).
\]  

(31)

Since \( \Gamma_{\mu} = E(\gamma_{\mu}) = E((a_{\mu}^2)(E_b/N_0)) \), one has

\[
P(b_l \rightarrow \tilde{b}_l) = \mathcal{O} \left( \frac{1}{E_b/N_0} \right)^\Omega = \mathcal{O} \left( \frac{1}{\text{SNR}} \right)^\Omega.
\]  

(32)

Thereby, the diversity order of the PS-CC system is equal to \( \Omega \) in this case.

4) DATA-RATE COMPARISON

It is reasonable to assume that the transmission time of one bit is proportional to the number of transmitted samples. Hence, we assume that the transmission time for a chaotic sequence of length \( 2\beta \) is \( T_s \). For simplicity, the processing time at relays is ignored. As seen from Fig. 3, since \( n \) relays are utilized to forward message in different time slots, the total transmission time for a given bit in the DCSK-CC system is

\[
T_{\text{DCSK-CC}} = (n+1)T_s,
\]  

(33)

while the total transmission time in the PS-CC system becomes

\[
T_{\text{PS-CC}} = \frac{T_s}{m+1} + \frac{T_s}{m+1}n = T_s(n+1)/(m+1).
\]  

(34)

With respect to the DCSK-CC system, the data rate of PS-CC system is enhanced by \( M \) times, where

\[
M = \frac{T_{\text{DCSK-CC}}}{T_{\text{PS-CC}}} = m + 1.
\]  

(35)

As shown in (35), the proposed PS-CC system can accomplish a larger data rate as \( m \) increases. However, the selection of \( m \) is limited by the practical channel condition, which will be further discussed in the next section.

IV. NUMERICAL RESULTS AND DISCUSSIONS

This section presents simulated and the numerical BER under several transmission scenarios. All channels being considered are \( L \)-path Rayleigh channels, in which the transmission power of different paths is allocated uniformly. In simulations, the spreading factor \( 2\beta \) of DCSK is set to be 60.

A. PERFORMANCE COMPARISON OF THREE DCSK-BASED SYSTEMS

To start, we analyze the performance of PS-CC system under the condition of ideal \( S \rightarrow R \) link. That is, the relays can perfectly decode all signals without error. Fig. 4 plots the simulated and the numerical BER results of the DCSK PS-CC, DCSK-CC, and DCSK-NC systems over multipath Rayleigh fading channels, with parameters \( n = 1, d_{SD} : d_{SR} : d_{RD} = 1 : 1 : 1, L = 2, \tau = (0, 1) \), and \( m = 1, 2, 3 \). One can observe that the proposed PS-CC system with \( m = 1 \) and DCSK-CC system achieve a gain of about 5 dB and 4 dB over the DCSK-NC system at a BER of \( 10^{-3} \), respectively. Moreover, Fig. 4 exhibits that the performance gain and data rate of the proposed system are further increased as \( m \) becomes larger, i.e., \( m = 2 \) and 3.

Note that although the PS transmission method enhances the data rate, it should not consist of over-less samples in order to avoid corrupting the cross-correlation of noisy sample functions, as in the transmitted reference (TR) UWB systems. Indeed, this problem can be mitigated greatly by inserting guard interval and using wide signal bandwidth [17]. Furthermore, shorting reference and information segments can improve the modulation efficiency of TR UWB systems [17].

As a further insight, Fig. 5 presents the BER curves of the three DCSK systems over multipath Rayleigh fading channels, where the number of relays in both DCSK PS-CC and DCSK-CC system is set to be \( n = 5 \). Referring to
this figure, the DCSK-CC system shows worse BER than the DCSK-NC system in the low-SNR region (i.e., $E_b/N_0 = 16 \text{ dB}$). Actually, a larger value of $n$ induces a smaller transmission power for each relay with a fixed overall transmission power $E_b$. Thus, the chaotic sample with less power in the DCSK-CC system shows weaker anti-noise ability as compared to the DCSK-NC system. In this scenario, the increase of diversity gain cannot sufficiently offset this degradation in the low-SNR region. However, it is interesting to see that the PS-CC system is superior to both DCSK-NC and DCSK-CC systems when the value of $m$ is equal to the number of relays (i.e., $m = 5$). Accordingly, the PS-CC system is an attractive alternative scheme for energy-constrained wireless communication applications, such as the WSNs [16].

B. SYSTEM PERFORMANCE WITH DIFFERENT VALUES OF CRITICAL PARAMETERS

1) DISTANCE RATIO

Fig. 6 shows the theoretical and simulated BER curves of the DCSK PS-CC system with different distance ratios over multipath Rayleigh fading channels, in which other parameters used are the same as those listed in Fig. 4. As expected, it illustrates that with the fixed $d_{SD}$ and $d_{SR}$ distances, the system with smaller $d_{RD}$ distance has better performance due to the path-loss gain induced. Also, the theoretical BER curves agree well with the simulated ones.

2) NUMBER OF FADING PATHS

The BER performance of the DCSK PS-CC system with different paths over multipath fading channels is shown in Fig. 7. Here, the parameters used are $n = 3$, $d_{SD} : d_{SR} : d_{RD} = 1 : 1 : 1$, and $m = 2$. Since more fading paths can provide higher diversity order, the PS-CC system with three-path fading outperforms the one with two-path fading, which is consistent with the numerical results.

3) NUMBER OF RELAYS

We also discuss the impact of number of relays (i.e., the value of $n$) on the performance of DCSK PS-CC system over multipath Rayleigh fading channels and present the results in Fig. 8. Although the performance gain by PS-CC system with one relay over DCSK-NC system can be up to 5 dB, the gain increases slowly as the value of $n$ further increases. The PS-CC system with four relays has a negligible gain over the one with three relays. On the contrary, the system with more relays has a slight performance loss in the low-SNR region, with higher complexity in hardware implementation. Therefore, the aforementioned issues should be carefully considered to choose a proper number of relays in practical applications.

C. SYSTEM PERFORMANCE WITH DIFFERENT RELAYING PROTOCOLS

To further justify the applicability of the proposed system, an imperfect $S \rightarrow R$ channel is used instead of an ideal
scenario. Assuming that the received signals are processed by either AF or SDF at the relays. Fig. 9 shows the BER curves of the PS-CC system with different relaying protocols over multipath Rayleigh fading channels, where the system-parameter setting is: \( n = 1, L = 2, \tau = (0, 1), d_{SD} : d_{SR} : d_{RD} = 1 : 1 : 1, \) and \( m = 1. \) As seen from this figure, the theoretical curves agree well with the simulated ones for both SDF and AF protocols. Besides, the SDF protocol exhibits a performance gain of about 2 dB over the AF protocol at a BER of \( 10^{-4}. \) However, the SDF suffers from higher hardware complexity with respect to the AF due to the requirement of demodulating and re-generating the received chaotic signals.

**D. PERFORMANCE COMPARISON OVER UWB CHANNELS**

The FM-DCSK-based system has already been proposed for WPAN applications within the IEEE 802.15.4a standard. The FM-DCSK UWB signal stands out as a feasible solution for UWB channels [13]. This section examines the performance of the proposed PS-CC system in UWB transmission environments with one relay [13]. By modifying the DCSK modulator to an FM-DCSK modulator in PS-CC system, the FM-PS-CC signal can be produced. Fig. 10 shows the signal structure output from an FM-DCSK modulator, where \( f_1(t) \) and \( f_2(t) \) are the chaotic-reference and information-bearing FM chaotic segments, respectively. If the data bit to be sent equals \( +1, \) \( f_2(t) = f_1(t); \) otherwise, \( f_2(t) = -f_1(t). \) In the PS-CC system, \( f_1(t) \) and \( f_2(t) \) denote the first and second fragments of a transmitted signal \( s_j, j = 0, 1, \ldots, n. \) Let \( T_b \) and \( T_c \) denote the duration of one bit and the duration of each FM chaotic segment, respectively. Note that the guard duration \( T_b/2 - T_c \) between two successive chaotic segments is provided in FM-DCSK-based modulation. In the simulation, we consider the IEEE 802.15.4a CM1 channel model and set the parameters as follows: \( T_b = 250 \) ns, \( T_c = 50 \) ns, the sampling frequency \( f_s = 8 \) GHz, and the center frequency \( f = 5 \) GHz. Fig. 11 compares the BER performance of the FM-DCSK-PS-CC, FM-DCSK-CC, and FM-DCSK-NC systems over UWB CM1 channels, where the system parameters are set as \( n = 1, d_{SD} : d_{SR} : d_{RD} = 1 : 1 : 1, \) and \( m = 1. \) Referring to this figure, the proposed FM-PS-CC system outperforms the FM-DCSK-CC and FM-DCSK-NC systems by 1 dB and 3 dB at BER of \( 10^{-5}. \) respectively.

**V. CONCLUSIONS**

To boost the data rate of conventional DCSK-CC system over multipath fading channels, an efficient PS transmission mechanism has been developed in this paper. We have not only derived the theoretical BER expression of the DCSK PS-CC system, but have analyzed its diversity-order and data-rate as well. Both analytical and simulated results have demonstrated that the proposed DCSK PS-CC system is superior to the conventional DCSK-CC and DCSK-NC systems in terms of data rate and error performance over multipath fading channels. Moreover, the proposed DCSK PS-CC scheme can dramatically reduce the computational overhead at the receiver terminals in comparison with the DCSK-CC one. Furthermore, we have formulated an FM-DCSK-PS-CC system and investigated its error performance over typical WLAN UWB channels. The results have indicated that the FM-DCSK-PS-CC system also obtains better performance as...
DCSK-based TR UWB systems. The proposed DCSK-PS-CC system is fairly suitable for compared to the FM-DCSK-CC and FM-DCSK-NC systems, increasing the coverage of a radio device. Consequently, the proposed DCSK-PS-CC system is fairly suitable for those energy-constrained multi-relay wireless applications that require high data-rate and low-complexity, such as DCSK-based TR UWB systems.

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