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作者:Jiang, B(Jiang, Bin);Wu, XW(Wu, Xiaowei);Bao, JR(Bao, Jianrong);Liu, C(Liu, Chao);Tang, XH(Tang, Xianghong);

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[Jiang, Bin] Hangzhou Dianzi Univ, Sch Commun Engn, Hangzhou 310018, Peoples R China.

[Jiang, Bin] Hangzhou Dianzi Univ, Sch Elect & Informat, Hangzhou 310018, Peoples R China.

[Wu, Xiaowei; Bao, Jianrong; Liu, Chao; Tang, Xianghong] Hangzhou Dianzi Univ, Sch Commun Engn, Hangzhou 310018, Peoples R China.

通讯作者地址:

Bao, JR (corresponding author), Hangzhou Dianzi Univ, Sch Commun Engn, Hangzhou 310018, Peoples R China.

电子邮件地址:jiangbin@hdu.edu.cn; 332129637@qq.com; baojr@hdu.edu.cn;liuchao@hdu.edu.cn; tangxh@hdu.edu.cn

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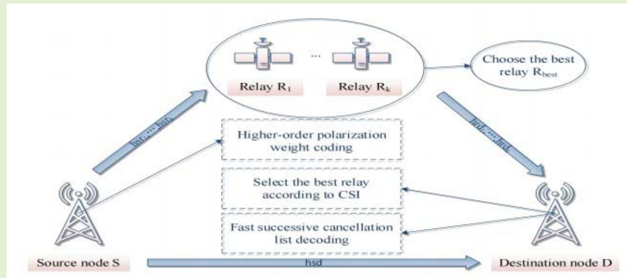
Optimized Higher-Order Polarization Weight Incremental Selective Decoding and Forwarding in Cooperative Satellite Sensor Networks

Bin Jiang, Xiaowei Wu, Jianrong Bao, *Senior Member, IEEE*, Chao Liu, and Xianghong Tang

***Abstract*—An optimized higher-order polarization weight (HPW) incremental selective decoding and forwarding (ISDF) scheme is proposed for cooperative transmissions in satellite sensor networks (SSNs). First, an HPW method is designed with subchannel power allocation in encoding to enhance the antiinterference. Second, a cooperative decision in the destination is used to avoid error propagation for better outage probability (OP) and bit error rate (BER) performance. It switches between direct and cooperative transmissions alternatively by channel state information (CSI). Finally, the HPW coding information, cyclic redundancy codes (CRCs), and four special frame structures of polar subcodes are jointly fast successive cancellation list (FSCL) decoded to improve efficiency and BER performance. Finally, we apply the optimized polarization encoding and decoding to the relay system to form a new ISDF relay system for better coding efficiency, BER, and OP performance. Simulation results show that the proposed scheme obtains approximately 0.8 and 1 dB performance gains at OP of 10^{-2} and BER of 10^{-6}, respectively, when compared with those of the current ISDF scheme. Therefore, the cooperative scheme possesses efficient decoding and cooperation, which endows it a promising candidate relay scheme in SSNs.**



***Index Terms*—Channel state information (CSI), cooperative decision, error propagation, outage probability (OP), polarization weight (PW).**

I. INTRODUCTION

SATELLITE sensor networks were supposed to provide advanced space sensor technologies, including modified IEEE 802.11 standard for intersatellite transmissions, distributed intensive computing for onboard signal processing, and reconfigurable satellite system-on-a-chip design [1]. Cooperative communications had been always recognized as an indispensable candidate to provide seamless connectivity for users around the world, especially in remote areas in lack of terrestrial networks [2]. Then an integrated satellite–terrestrial wireless sensor network used a terrestrial relay to assist transmissions [3]. However, the insufficient transmission power from a source satellite to a far destination earth station adversely affected the transmission efficiency. Cooperative communications mainly included amplify and forward (AF) [4], decode and forward (DF) [5], coded cooperation (CC), and so on [6]. Different from traditional point-to-point communications, they can improve efficiency and reliability on low outage probability (OP) and bit error rate (BER) occasions [7]. The AF amplified both signals and noises and it still improved the OP performance by an asymmetric bidirectional relay power and location selection [8]. In the DF, decoding and forwarding were used to combat white Gaussian noises, thereby reducing the OP [9]. Given correct decoding in relays and then forwarding, the OP of the DF was much better than that of the AF [10]. Moreover, the OP was also improved with the increased cooperative relay number. An adaptive DF utilized directional antennas to improve diversity gains and select the best transmission channel for better efficiency in the multirelay DF. However, even on false decoding occasions, the relay still forwarded messages and thus deteriorated the

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Bin Jiang is with the School of Communication Engineering and the School of Electronic and Information, Hangzhou Dianzi University, Hangzhou 310018, China (e-mail: jiangbin@hdu.edu.cn).

Xiaowei Wu, Jianrong Bao, Chao Liu, and Xianghong Tang are with the School of Communication Engineering, Hangzhou Dianzi University, Hangzhou 310018, China (e-mail: 332129637@qq.com; baojr@hdu.edu.cn; liuchao@hdu.edu.cn; tangxh@hdu.edu.cn).

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BER [11], [12]. Then, an selective decoding and forwarding (SDF) scheme was proposed with the channel state information (CSI) in relay channels to solve excessive error propagation, which selected optimal relays with the best CSI to forward messages [13]. Moreover, in slow-fading wireless channels, each relay selected message segments independently to avoid waiting for all relay decoding to the destination. So, a dynamic selective decoding and forwarding (D-SDF) scheme was proposed to accomplish these purposes [14]. However, the OP was still unsatisfactory. Subsequently, incremental selective decoding and forwarding (ISDF) [35] was proposed to reduce the OP by incremental transmission with errors that occurred in decoding and forwarding. Finally, the destination notified the source to retransmit the failure messages.

To further improve the cooperation efficiency, the CC was studied and combined with channel coding [15], such as low-density parity-check (LDPC) and polar codes [16]. In the early days, the LDPC and relay cooperation were combined together to improve channel utilization [17]. Subsequently, LDPC was used in the DF cooperation and decoded by the belief propagation (BP) algorithm to improve BER performance. However, the highly nonlinear operation of BP decoding led to high complexity [18], [19]. In 5G communications, polar codes were used for channel coding with both low coding complexity and good BER performance. It soon became the preferred error correction code for the CC systems [20] and it had been proven to exhibit better performance than those of LDPC codes under short code length [21]. The polar codes were constructed with the Monte Carlo method by sorting and selecting the channels of better CSI [22]. However, it had high complexity, because a large number of simulations were conducted to count the error probability of each subchannel. In practice, a transmission scheme with polar coding and a hybrid automatic request (HARQ) mechanism was widely used in the Internet of Things with higher coding gains than those of other counterparts [23]. The destination uses successive cancellation (SC) decoding to reduce the decoding complexity on single relay transmission scenarios. However, many issues such as low BER and OP performance still needed to be improved in the polar coded CC cooperation for different channels and modes [24].

To solve the problems of the above-mentioned schemes, an optimized higher-order polarization weight (HPW) ISDF scheme is proposed for better BER performance and low complexity. The HPW method is also adopted in polar coding with the cyclic redundancy code (CRC)-aided fast SC list (FSCL) decoding to reduce the forwarding error rate. Finally, the main contributions are represented as follows.

1) Adaptive relay selection with the CSI decision to determine relay cooperation for better efficiency.
   An optimized HPW-ISDF relay is proposed according to the exchanged mutual information among relays. Given excellent CSI, it directly transmits messages from the source to the destination for better transmission efficiency. Compared with the fixed ISDF, the proposed scheme identifies and timely stops forwarding error messages to improve the overall BER performance.
2) HPW coding with the higher-order basis and CRC to accomplish channel polarization and simplify coding.
   The scheme adopts HPW coding to polarize information according to the weight in the coding stage. The HPW coding only needs to consider the channel index and introduces a higher-order base β. It still preserves the feature of nested code construction for polar codes, and the construction is used to transmit signals in the proposed ISDF scheme. Then a CRC is added in the HPW, and the message bit and CRC are mapped to the free bit of the HPW code for transmission. Then, it reduces the contribution of different binary bits to the corresponding basis integrals. Compared with the traditional coding scheme, it effectively reduces the coding complexity, improves efficiency, and enhances the antiinterference performance.
3) FSCL decoding by an increment of four frame structures of polar subcodes to reduce BER significantly.
   The scheme adopts FSCL decoding in the decoding stage, four special frame structures, namely, freeze bit (R0), repeat code (Rep), single parity check (SPC) code, all source bits are 1 (R1), and the CRC segment are inserted in each coded frame in successive cancellation list (SCL) decoding. R0, Rep, SPC, and R1 are freeze bits, repeat codes, single parity check codes, and all source bits 1, respectively. They are precoded polar codes, once the special frame structures are detected. And the fast decoding is directly performed and the corresponding information is obtained by the proposed scheme. Therefore, it significantly improves decoding efficiency and reduces BER.
4) Incremental retransmission by the channel estimation of the HPW weight for better mutual information exchange and less error propagation.
   The proposed ISDF introduces incremental retransmission by switching between direct and cooperative transmission according to CSI. The destination D and relay R estimate the ideal channel with infinite close channel capacity according to the weight of HPW coding for effective and quickly obtaining the channel capacity. When the information transmission rate is larger than the channel capacity, the error signals will not be transmitted. It significantly improves the error propagation and thus reduces the OP compared with traditional decoding and forwarding.

The article is organized as follows. First, we briefly review the related work about relay cooperation in Section II. In Section III, the system model is introduced, and the proposed ISDF cooperation is established by the channel capacity among source, relays, and destination to arrange transmission mode. In Section IV, the process of the HPW method is performed using the higher-order base to sort and polarize channels. It obtains more efficient forwarding and lower complexity than those of traditional coding schemes. The detailed procedures of the proposed ISDF are introduced in Section V, and the performance is analyzed theoretically to highlight the advantages. In Section VI, the performance of the proposed scheme is verified by simulation results with theoretical analysis. Section VII summarizes the whole study.

II. Related Work

A location-based relay selection (OLB-RS) and region-aware relay selection (RA-RS) strategy was proposed to study the reliability-enhanced region (RER) [33]. The RA-RS solved the excessive feedback overhead of the OLB-RS and it obtained achievable reliability benefits. However, it was only highly dependent on the relay location.

To optimize the relay selection efficiency in satellite sensor networks (SSNs), the relay selection was modeled to the maximum weighted matching through node virtualization [34]. Moreover, an iterative algorithm was designed to acquire the optimal solution of the approximated convex problem by the Lagrangian dual method. But the nonconvex problem was difficult to be solved, along with the accuracy loss in conversion.

Partial relay selection (PRS) and full relay selection (FRS) were used to study relay selection under dynamic CSI [35]. The PRS was suitable for the situation without the relay-destination CSI. The FRS algorithm selected the relay with the highest end-to-end signal-to-interference-and-noise ratio (SINR), with better OP performance other than that of the PSR. However, the FRS required CSI among all channels and available relays, which increased overhead. Then a self-energy recycling (S-ER) algorithm was proposed [36]. And the energy generated by self-interference would be recovered at the relay for future use.

In summary, the above schemes did not consider error propagation. So, we use incremental retransmission to reduce error propagation, along with the optimized relay selection strategies.

III. System Model of the Optimized HPW-Based ISDF Transmission System

In this section, a three-node relay channel model is used to facilitate diversity analysis in cooperative communications. It consists of a source S, several relays R, and a destination D in half-duplex communications. When the source retransmission or relay cooperation is needed, each transmission needs to be divided into two time slots: the first and second slots. Assuming that R is the best relay selected, each channel is located in the Rayleigh fading channel. Given unchanged channel gain in transmission, each transmission link was independent of each other and every node obtained the ideal CSI by received signals [26]. The specific process of the signal transmission is shown in Fig. 1.

In previous ISDF and some other similar schemes, relay cooperation is adopted only when the retransmission of source S cannot meet the requirement of the information transmission rate adequately. They tend to use the source retransmission under a failed direct transmission. However, the channel capacity of the relay cooperation is usually better than that of the source retransmission. The power consumption of the relay transmission is lower than that of the source one after retransmission power allocation. But in the proposed ISDF scheme, relay cooperation is preferred, when the direct transmission does not meet the requirement of transmission, the relay cooperative forwarding mode is preferred to be chosen for better relay cooperation and average transmission power. Finally, a complete procedure of the cooperation performs in two successive time slots, and they are presented as follows.

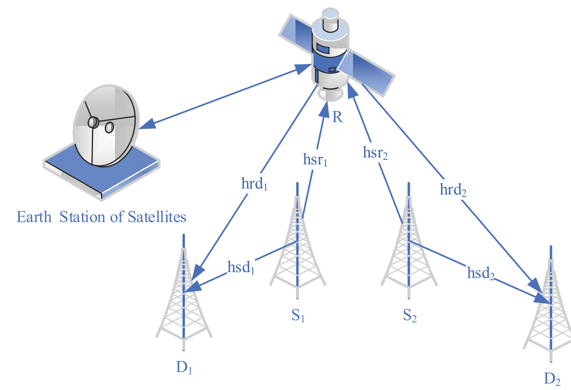

Fig. 1. Typical three-node relay channel model.

In the first time slot, the source S broadcasts signals to the relay R and the destination D by (1) and (2), respectively. Similar to [14], the received signals are represented as

$$y_r = \sqrt{P_s} h_{\mathrm{sr}} x_s + w_r \tag{1}$$

$$y_d^{(1)} = \sqrt{P_s} h_{\mathrm{sd}} x_s + w_d^{(1)} \tag{2}$$

where P_s is the transmission power of S. x_s is the signal to be transmitted. h_{sr} and h_{sd} are the channel coefficients of link S-R and S-D, respectively. They are independent cyclic symmetric complex Gaussian random variables with zero mean and variance of η_{sr}^2 and η_{sd}^2, as $h_{\mathrm{sr}} \sim CN(0, \eta_{\mathrm{sr}}^2)$ and $h_{\mathrm{sd}} \sim CN(0, \eta_{\mathrm{sd}}^2)$. w_r and $w_d^{(1)}$ are the additive white Gaussian noises (AWGNs) at the relays and destination, respectively, with zero mean and variance of N_0, denoted as $w_r \sim CN(0, N_0)$, $w_d^{(1)} \sim CN(0, N_0)$ in the first time slot.

Destination D evaluates the correctness of received signals by calculating whether the channel capacity is greater than the information rate. Then, it decides the transmission mode and notifies the source S and relay R by broadcasting feedback signals. If D correctly receives the signals from S, the noncooperative transmission is adopted, and S sends new messages in the second time slot. Otherwise, the retransmission or decoding and forwarding in the relay is executed according to whether the channel capacity is larger than the transmission rate r or not. If the retransmission by S is adopted, S retransmits the signals x_s to D in the second time slot by (3). The signals received in D are represented as

$$y_d^{(2)} = \sqrt{P_s} h_{\mathrm{sd}} x_s + w_d^{(2)} \tag{3}$$

where $w_d^{(2)}$ is the AWGN at D of the second time slot, with zero mean and the variances of N_0, as $w_d^{(2)} \sim CN(0, N_0)$.

If the relay decoding and forwarding mode is adopted in the second time slot [29]. The signals received by D are expressed as

$$y_d^{(2)} = \sqrt{P_r} h_{\mathrm{rd}} x_r + w_d^{(2)} \tag{4}$$

where P_r is the transmission power of R. x_r is the signal which is the result of y_r decoded by R; h_{rd} is the channel coefficient of link R-D, and a cyclic symmetric complex

Gaussian random variable with zero mean and variance of $\eta_{\rm rd}^2$, as $h_{\rm rd} \sim CN(0, \eta_{\rm rd}^2)$.

The D uses maximum ratio combination (MRC) [25] to combine all received signals in two slots as

$$y = a_1 y_d^{(1)} + a_2 y_d^{(2)} \tag{5}$$

where a_1 and a_2 are merging factors. It is selected by different ways of cooperation according to [25]. y is the final decision result of received signals.

The transmission system has four types of channel capacity for signal transmission: 1) direct channel capacity $C_{\rm DT}$; 2) retransmission channel capacity $C_{\rm DRT}$; 3) channel capacity $C_{\rm DF}$ of relay decoding and forwarding; and 4) source-relay channel capacity $C_{\rm R}$. Similar to [30], they are respectively expressed as

$$C_{\rm DT} = \frac{1}{2}\log_2\left(1 + \frac{P_s|h_{\rm sd}|^2}{N_0}\right) \tag{6}$$

$$C_{\rm DRT} = \frac{1}{2}\log_2\left(1 + 2\frac{P_s|h_{\rm sd}|^2}{N_0}\right) \tag{7}$$

$$C_{\rm DF} = \frac{1}{2}\log_2\left(1 + \frac{P_s|h_{\rm sd}|^2}{N_0} + \frac{P_r|h_{\rm rd}|^2}{N_0}\right) \tag{8}$$

$$C_{\rm R} = \frac{1}{2}\log_2\left(1 + \frac{P_s|h_{\rm sr}|^2}{N_0}\right). \tag{9}$$

To facilitate the subsequent calculation, we use (10) to calculate the probability density and then select the transmission mode. So, there is a variable configuration as follows. Let $\gamma_{\rm sd} \triangleq (P_s|h_{\rm sd}|^2/N_0)$, $\gamma_{\rm sr} \triangleq (P_s|h_{\rm sr}|^2/N_0)$, $\gamma_{\rm rd} \triangleq (P_r|h_{\rm rd}|^2/N_0)$. $h_{\rm sd}$, $h_{\rm sr}$ and $h_{\rm rd}$ are independent of one another, and they obey the distributions as $h_{\rm sd} \sim CN(0, \eta_{\rm sd}^2)$, $h_{\rm sr} \sim CN(0, \eta_{\rm sr}^2)$ and $h_{\rm rd} \sim CN(0, \eta_{\rm rd}^2)$, respectively. $\gamma_{\rm sd}$, $\gamma_{\rm sr}$, and $\gamma_{\rm rd}$ obey exponential distribution. The average values are $\bar{\gamma}_{\rm sd} \triangleq (P_s\eta_{\rm sd}^2/N_0)$, $\bar{\gamma}_{\rm sr} \triangleq (P_s\eta_{\rm sr}^2/N_0)$, and $\bar{\gamma}_{\rm rd} \triangleq (P_r\eta_{\rm rd}^2/N_0)$. The probability density function of the exponential distribution $\gamma_i (i \in \{sd, sr, rd\})$ can be written as

$$f_{\gamma_i}(\gamma) = \frac{1}{\bar{\gamma}_i}\exp\left(-\frac{\gamma}{\bar{\gamma}_i}\right), \quad \gamma \geq 0 \tag{10}$$

where $\Pr(\gamma_i > a) = \exp(-a/\bar{\gamma}_i)$ is obtained.

IV. Optimized HPW Incremental Selection Decoding and Forwarding Scheme

A. Traditional Polarization Weight (PW) Scheme

The PW scheme was first proposed in "3GPP RAN1 #86" as a method to generate the ordered subchannel sequence through reliability. The SNR-independent subchannel reliability order is estimated by computing the PW of each subchannel and storing the ordered index sequence $q_0^{N_{\max}-1}$ for the polar codes of the maximum code length $N_{\max}$. The assumption is $T(i) \triangleq B_{n-1}B_{n-2}\cdots B_0$ converts the decimal channel index i to the n-bit binary with the most significant bit on the left, $T(i, j) \triangleq B_j$, $i \in Z$, $B_j \in Z$, $j = [0, 1, \ldots, n-1]$ and $n = \log_2 N_{\max}$. According to [28], the power of the ith PW subchannel is expressed as

$$W_i = \sum_{j=0}^{n-1} T(i, j)\cdot\beta_j = \sum_{j=0}^{n-1} B_j \cdot \beta^j \tag{11}$$

where β is a constant weight base in the summation. The equation represents the PW of a subchannel W_i with the base β through the summation of (11).

In (11), the PW provides a construction of polar codes without channel parameters. The selection of β defines the performance of the PW, which affects the pulsewidth of each subchannel and ordered sequence. The interval of β converges to a constant close to $1.1892 \approx 2^{(1/4)}$ by comparing the partial order theory with the density evolution (DE)/Gaussian approximation (GA) generation sequence of an AWGN channel [28]. When $\beta = 2^{(1/4)}$ and the SCL list is 8, the PW and GA have the same BER performance. Therefore, the number of SCL lists cannot determine the performance of the PW.

B. HPW Scheme by the PW

An HPW method is proposed for efficient coding and reliability ranking because the PW does not meet the ideal requirements. The higher-order basis reduces the difference in the contribution of different binary bits to the corresponding basis integral. The HPW represents the PW variation between each channel on an additional higher-order basis and it provides a locally refined sequence of subchannels. According to (11), only one basis is present in the summation and the HPW represents the new basis by introducing the higher-order β. The HPW method can be represented as

$$W_i = \sum_{j=0}^{n-1}\sum_{\xi\in\Xi} B_j \times \beta^{\frac{1}{4^{\xi}}}. \tag{12}$$

To simplify the implementation and description in (12), the HPW equation of zero- and one-order bases are used as

$$W_i = \sum_{j=0}^{n-1} B_j \times \left(\beta_j + \frac{1}{4}\beta^{\frac{1}{4}j}\right). \tag{13}$$

Take (13), for example, let $\beta = 2^{(1/4)}$, and the length $N = 2^n = 16$. The β-expansion of the synthetic channel with index 3 of $B_3 = (0, 0, 1, 1)$ is $W_3 = 0 \cdot 2^{3/4} + 0 \cdot 2^{2/4} + 1 \cdot 2^{1/4} + 1 \cdot 2^{0/4} = 2.189\ldots$ Thus, the β-expansion of all synthetic channels can be expressed as $W = \{0.000\ \ 1.000\ \ 1.189\ \ 2.189\ \ 1.141\ \ 2.414\ \ 2.603\ \ 3.603\ \ 1.682\ \ 2.682\ \ 2.871\ \ 3.871\ \ 3.096\ \ 4.096\ \ 4.285\ \ 5.285\}$. By sorting W, the total order is obtained as $\{0\ \ 1\ \ 2\ \ 4\ \ 8\ \ 3\ \ 5\ \ 6\ \ 9\ \ 10\ \ 12\ \ 7\ \ 11\ \ 13\ \ 14\ \ 15\ \}$. The nested code construction of the HPW is shown in Fig. 2.

The HPW has the same reliability ranking as the GA. Meanwhile, in Fig. 3, the nested code construction (or nested frozen sets) for polar codes is preserved by the HPW. It is a very ideal method to design code structure with variable length, which still keeps the simple calculation of the PW and helps to reduce the complexity. The HPW completes the coding with only a simple formula, thereby significantly improving the coding efficiency. In addition, the nested frozen sets are obtained by the decoder in advance for facilitating fast decoding.

C. Proposed ISDF Transmission Using HPW Coding

First, HPW coding is performed on input signals. The destination D receives signals and calculates four channel

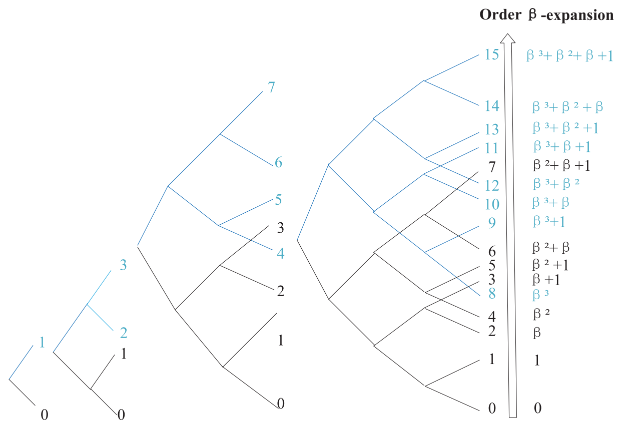

Fig. 2. Nested β-expansion structure ($\beta = 2^{(1/4)}$) for $N = 2, 4, 6, 8$.

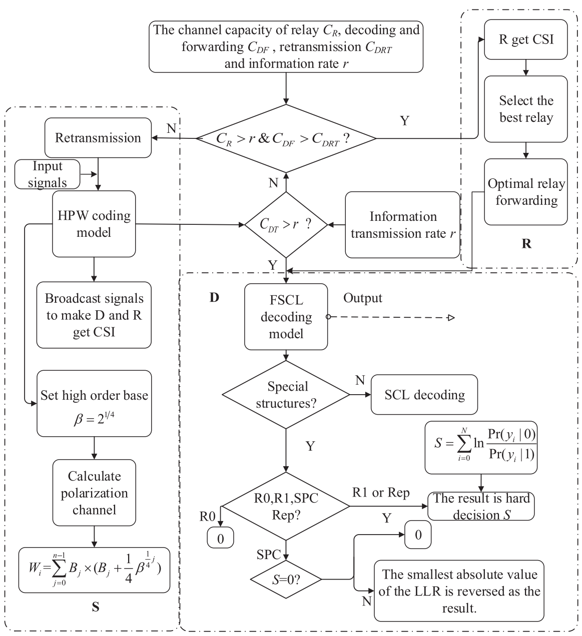

Fig. 3. Block diagram of the proposed ISDF system.

capacity $C_{\rm DT}$, $C_{\rm DF}$, $C_{\rm DRT}$, $C_{\rm R}$, and transmission rate r. Next, D compares different channel capacities and r to determine the transmission mode. If $C_{\rm DT}$ is larger than r, the system performs the direct transmission. The source S directly transmits the messages to D, and D executes FSCL decoding. Otherwise, the system employs the relays for the transmission. Else if C_R is larger than r and $C_{\rm DF}$ is larger than $C_{\rm DRT}$, the best relay is selected for transmissions. Otherwise, S performs the retransmission. The proposed ISDF system is shown in Fig. 3.

The transmission power of the source S and the best relay R is set $P_{\rm S} = P_{\rm R}$. The transmission rate is r bit/s, and the SNR in S is SNR $= (P_{\rm S}/N_0)$. If destination D can successfully receive the source messages in the first time slot, the transmission between S and D is not interrupted. The channel capacity of direct transmission mode $C_{\rm DT}$ is expressed as

$$C_{\rm DT} = \frac{1}{2}\log_2\left(1+\gamma^{\rm DT}\right) > r \tag{14}$$

Algorithm 1 Procedures of the Proposed ISDF Scheme

S broadcasts the HPW encoded signals x_s;
D and R obtain $h_{\rm sd}$, $h_{\rm rd}$, $h_{\rm sr}$ and calculate C_{DT}, C_{DF}, C_{DRT} and C_R;
if $C_{DT} > r$ **then**
  The direct transmission is chosen;
  D decodes signals by FSCL;
else
  D employs R for forwarding;
end if
if $C_{\rm R} > r$, $C_{DF} > C_{DRT}$ **then**
  R successfully forwarded the signals;
  D performs MRC to decode the signals;
else
  S retransmits x_s;
  D performs MRC to decode the signals;
end if
S is ready to transmit the next signals;
Return to the beginning.

where $\gamma^{\rm DT} = {\rm SNR}\cdot|h_{\rm sd}|^2$ represents the instantaneous SNR at D, $|h_{\rm sd}|^2$ is the channel gain of link S-D, the exponential distribution of parameter is $(1/\delta_{\rm sd}^2)$ and the selection threshold is set as T at D. Then, (14) is transformed to obtain the relationship between $|h_{\rm sd}|^2$ and T as $|h_{\rm sd}|^2 > (2^{2r} - 1/{\rm SNR}) = T$.

If the direct transmission is not selected, R should satisfy the requirements of $(1/2)\log_2(1+{\rm SNR}\cdot|h_{\rm sd}|^2) > r$, $|h_{\rm sr}|^2 > T$ and the DF forwarding scheme is adopted. Otherwise, retransmission in S is used to deliver signals.

D. Algorithm Flow of the Proposed ISDF Scheme

The procedures of the proposed ISDF are presented in Algorithm 1 and it is explained in detail as follows.

Step 1: The source S encodes the source messages according to the nested structure of HPW coding in the first time slot. They are transmitted through the HPW polarization channel. Then, S broadcasts the HPW encoded signals, the destination D and the relay R estimate the channel by the training sequence to obtain channel coefficients of $h_{\rm sd}$, $h_{\rm rd}$ and $h_{\rm sr}$ for channel quality evaluation. Subsequently, D calculates $C_{\rm DT}$, $C_{\rm DF}$, $C_{\rm DRT}$, and $C_{\rm R}$ by the above known information and it determines the transmission mode by comparing the channel capacity of different links. Finally, D sends the decision results to source S.

Step 2: The destination D calculates and judges whether $C_{\rm DT}$, $C_{\rm DRT}$ and C_R are larger than the transmission rate r by signals from S in the second time slot. S and R execute the following two steps, respectively, according to the judgment result of D.

1) If $C_{\rm DT} > r$, the direct transmission is chosen. Thus, D notifies S to send new messages in the next time slot, the relay keeps silent.

2) Otherwise, if the direct transmission is not selected, D employs R for forwarding.

Step 3: When the direct transmission is not selected, the best relay R compares $C_{\rm R}$ with r to determine the correctness of the relay decoding as follows.

1) If $C_R > r$, the best relay can decode correctly. Meanwhile, if $C_{DF} > C_{DRT}$, the feedback signals from D inform R to cooperate with the DF, and S keeps silent. If $C_{DF} < C_{DRT}$, D notifies S to retransmit signals and R keeps silent.

2) Otherwise, R cannot decode correctly, S retransmits the signals, and R keeps silent. If the retransmission fails, an interrupt occurred in the transmission, and the system transmits new signals in the next time slot.

With the above mentioned processes, $C_{DT} > r$ can be expressed as

$$\frac{P_s|h_{sd}|^2}{N_0} > 2^{2r} - 1 \tag{15}$$

where $\gamma_{th} \overset{\Delta}{=} 2^{2r} - 1$. Given that $\gamma_{sd} \overset{\Delta}{=} (P_s|h_{sd}|^2/N_0)$, (15) can be used to deduce the results under $\gamma_{sd} > \gamma_{th}$. $C_{DT} \leq r$ and $C_{DRT} > r$ can deduce $\gamma_{th}/2 < \gamma_{sd} \leq \gamma_{th}$. $C_{DRT} \leq r$ can derive $\gamma_{sd} \leq \gamma_{th}/2$. $C_R > r$ can deduce $\gamma_{sr} > \gamma_{th}$. $C_R \leq r$ can derive $\gamma_{sr} \leq \gamma_{th}$.

The total SNR in destination D after MRC is expressed as

$$\gamma_{DF}=\gamma_{sd} + \gamma_{rd} \tag{16}$$

where $\gamma_{sd} = \text{SNR} \cdot |h_{sd}|^2$ and $\gamma_{rd} = \text{SNR} \cdot |h_{rd}|^2$ represent the received SNRs of links S-D and R-D, respectively. The channel capacity of the cooperative DF transmission in (16) is derived as

$$C_{DF} = \frac{1}{2}\log_2(1 + \gamma_{DF}). \tag{17}$$

In summary, the amount of channel capacity transmitted for the proposed ISDF can be expressed as

$$C_{HISDF} = \begin{cases} C_{DT}, & \gamma_{sd} > \gamma_{th} \\ C_{DRT}, & \frac{\gamma_{th}}{2} < \gamma_{sd} \leq \gamma_{th} \\ C_{DRT}, & \gamma_{sd} \leq \frac{\gamma_{th}}{2} \ \& \ \gamma_{sr} \leq \gamma_{th} \\ C_{DF}, & \gamma_{sd} \leq \frac{\gamma_{th}}{2} \ \& \ \gamma_{sr} > \gamma_{th}. \end{cases} \tag{18}$$

Equation (18) specifically represents the channel capacity of the proposed scheme in different transmission modes, and the system performance analysis is also inseparable from it.

V. Performance Analysis

The proposed scheme adopts the HPW in the coding stage. It uses the higher-order base β in (12) to reduce the contribution difference in the corresponding basis integration. It also utilizes nested code construction of the HPW for channel polarization to ensure transmission stability and high efficiency. In the transmission phase, if the direct transmission is selected, the relay is not needed. Otherwise, the system gives priority to the best relay for forwarding. If the relay forwarding does not meet the threshold, the system will retransmit to reduce the OP. In addition, the FSCL decoding decodes the HPW to enhance the BER performance and reduce the complexity significantly.

A. BER Analysis of the HPW-Based ISDF Transmission Scheme

BER is an important indicator of transmission quality in satellite–terrestrial communications. The BER of the proposed ISDF is the accumulation of the BER of direct transmission, source S retransmission, and DF cooperative transmission by multiplying their probability of occurrence. For the proposed ISDF, the BER is expressed as

$$\begin{aligned} P_{HISDF}(e) = {} & \Pr\left(|h_{sd}|^2 > T\right) \times P_{DT}(e) \\ & + \Pr\left(T/2 < |h_{sd}|^2 \leq T\right) \times P_{DRT}(e) \\ & + \Pr\left(|\mathrm{h_{sd}}|^2 \leq \mathrm{T}/2, |\mathrm{h_{sr}}|^2 \leq \mathrm{T}\right) \times \mathrm{P_{DRT}}(e) \\ & + \Pr\left(|\mathrm{h_{sd}}|^2 \leq \mathrm{T}/2, |\mathrm{h_{sr}}|^2 > \mathrm{T}\right) \times \mathrm{P_{DF}}(e) \end{aligned} \tag{19}$$

where $P_{DT}(e)$, $P_{DRT}(e)$, and $P_{DF}(e)$ represent the BER in direct transmission, source S retransmission, and DF cooperative transmission, respectively. $[\Pr(|h_{sd}|^2 > T)$, $\Pr(T/2 < |h_{sd}|^2 \leq T)$, $\Pr(|h_{sd}|^2 \leq T/2, |h_{sr}|^2 \leq \mathrm{T})$, and $\Pr(|h_{sd}|^2 \leq T/2, |h_{sr}|^2 > \mathrm{T})$ are the probability on condition of $|h_{sd}|^2 > T$, $T/2 < |h_{sd}|^2 \leq T$, $|h_{sd}|^2 \leq T/2, |h_{sr}|^2 \leq \mathrm{T}$, and $|h_{sd}|^2 \leq T/2, |h_{sr}|^2 > T$, respectively.

For the instantaneous SNR, the conditional BER of the binary phase shift keying (BPSK) modulation [30] can be expressed as

$$P(e/\gamma) = Q\left(\sqrt{2\gamma}\right) \tag{20}$$

where the Q function is defined as $(1/\sqrt{2\pi})\int_x^{\infty} e^{-(t^2/2)}\mathrm{d}t$.

Given the same channel quality in (19), the BER of the proposed ISDF and ISDF is derived and equally represented as

$$\begin{aligned} P_{HISDF}(e) \leq {} & \Pr(|h_{sd}|^2 > T) \times P_{DT}(e) \\ & + \Pr(T/2 < |h_{sd}|^2 \leq T) \times P_{DRT}(e) \\ & + \Pr(|\mathrm{h_{sd}}|^2 \leq \mathrm{T}/2, |\mathrm{h_{sr}}|^2 > \mathrm{T}) \times \mathrm{P_{DF}}(e) \\ & + \Pr(|\mathrm{h_{sd}}|^2 \leq \mathrm{T}/2, |\mathrm{h_{sr}}|^2 \leq \mathrm{T}) \times \mathrm{P_{DF}}(e) \\ = {} & P_{ISDF}(e). \end{aligned} \tag{21}$$

According to (21), the BER of the proposed ISDF is lower than that of the traditional counterpart. The reason is that error data are transmitted when $|h_{sd}|^2 \leq T/2, |h_{sr}|^2 \leq T$ under the same channel quality. As a result, the BER of the proposed ISDF is lower than that of the original ISDF.

B. OP Analysis

OP is used to measure the frequency of interruption in communication, and it is an important index of communication reliability [29]. When r is larger than the channel capacity of direct transmission and retransmission, the interruption occurs. The direct transmission mode in the proposed ISDF scheme aims at the successful reception of the destination to prevent the occurrence of interruptions. The OP of the proposed ISDF

TABLE I
COMPLEXITY COMPARISON BETWEEN THE PROPOSED FSCL AND THE EXISTING SCL ALGORITHM

Computational SCL algorithm	SCL algorithm	Proposed FSCL
Addition computation	$L_s N$	$L_S N - \sum\limits_{t=0}^{n} (N_t^l - 1)$
Multiplication computation	$L_s(2N+1)$	$L_S(2N+1) - 3\sum\limits_{t=0}^{n} (N_t^l - 1)$
Comparison computation	$L_s N + L(L-1)/2$	$L_S N + (K - \log_2 L_S) L_S (L_S - 1) - \sum\limits_{t=0}^{n} N_t^l \frac{(L_S - L_{SC})(L_S - L_{SC} - 1)}{2}$

can be expressed as

$$P_{\text{HISDF}}^{\text{OUT}} = \Pr\left(|h_{\text{sd}}|^2 \le T/2, |h_{\text{sr}}|^2 > T, C_{\text{DF}} < r\right) + \Pr\left(|h_{\text{sd}}|^2 \le T/2, |h_{\text{sr}}|^2 > T, C_{\text{DRT}} < r\right) = P_{\text{HISDF1}}^{\text{OUT}} + P_{\text{HISDF2}}^{\text{OUT}}. \tag{22}$$

When $|h_{\text{sr}}|^2 > T$, $\gamma_{\text{DRT}} \le \gamma_{\text{DF}}$, the following is obtained:

$$P_{\text{HISDF1}}^{\text{OUT}} \le \Pr\left(|h_{\text{sd}}|^2 \le T/2, |h_{\text{sr}}|^2 > T, C_{\text{DRT}} < r\right). \tag{23}$$

Replacing (23) with (22), it yields

$$P_{\text{HISDF}}^{\text{OUT}} \le \Pr\left(|h_{\text{sd}}|^2 \le T/2, |h_{\text{sr}}|^2 > T, C_{\text{DRT}} < r\right) + \Pr\left(|h_{\text{sd}}|^2 \le T/2, |h_{\text{sr}}|^2 > T, C_{\text{DRT}} < r\right) = \Pr\left(|h_{\text{sd}}|^2 \le T/2, C_{\text{DRT}} < r\right) = P_{\text{ISDF}}^{\text{OUT}}. \tag{24}$$

By (24), the OP of the proposed ISDF is lower than that of the original one. When SNR tends to infinity, the approximate values of $P_{\text{HISDF1}}^{\text{out}}$ and $P_{\text{HISDF2}}^{\text{out}}$ can be derived as

$$P_{\text{HISDF1}}^{\text{OUT}} = Pr\left(|h_{\text{sd}}|^2 \le T/2 \times |h_{\text{sr}}|^2 > T, |h_{\text{sd}}|^2 + |h_{\text{rd}}|^2 < T\right) \approx \frac{3T^2}{8\delta_{\text{sd}}^2\delta_{\text{rd}}^2} \tag{25}$$

$$P_{\text{HISDF2}}^{\text{OUT}} = Pr\left(|h_{\text{sd}}|^2 \le T/2, |h_{\text{sr}}|^2 > T \times |h_{\text{sd}}|^2 + \min\left(|h_{\text{sr}}|^2, |h_{\text{rd}}|^2\right) < T\right) \approx \frac{3T^2}{8\delta_{\text{sd}}^2\delta_{\text{sr}}^2}. \tag{26}$$

At high SNRs, by adding (25) and (26), the approximate lower bound of the OP of the proposed ISDF is represented as

$$P_{\text{HISDF}}^{\text{OUT}} \ge \frac{3T^2}{8\delta_{\text{sd}}^2\delta_{\text{rd}}^2} + \frac{3T^2}{8\delta_{\text{sd}}^2\delta_{\text{sr}}^2} = \frac{3\left(\delta_{\text{sr}}^2 + \delta_{\text{rd}}^2\right)T^2}{8\delta_{\text{sd}}^2\delta_{\text{rd}}^2\delta_{\text{sr}}^2}. \tag{27}$$

In (27), the OP decreases with the increase in δ_{sd}^2 on the condition of the fixed T and the same SNR.

C. Computational Complexity Analysis

FSCL decoding is only derived from the SC and SCL decoding. The key is to increase special structures to stop SC decoding and estimate codewords simultaneously. In the binary tree of polar decoding with code length, the child node of each node is a subpolar code with a length halved. When the subcodes are the special structures, SC decoding is no longer used, and the codeword bits of the subpolar codes are estimated directly.

R0, Rep, SPC, and R1 are four special frame structures used by FSCL decoding. The decoder judges the four subpolar codes and then quickly decodes the special frame structures by the direct codeword bits estimation. The proposed FSCL decoding with the four special structures is then presented as follows.

1) R0 fast decoding. Only frozen bits are available, no information bit and information is carried.

2) Rep fast decoding. The sum of log-likelihood ratios (LLRs) [32] of received sequences is expressed as

$$\text{S} = \sum_{i=0}^{N} \ln \frac{\Pr(y_i|0)}{\Pr(y_i|1)} \tag{28}$$

where the decoding results are all 0 given $\text{S} \ge 0$. Otherwise, it is 1.

3) SPC fast decoding. If the sum of the hard decision $[\beta_1, \beta_2, \ldots, \beta_N]$ is 0, the decision is the result. Otherwise, the hard decision of the received bits with the smallest absolute value of the LLR is reversed as the result.

4) R1 fast decoding. The hard decision of the received sequence is the decoding result.

The measurement of the computational complexity of the proposed scheme is divided into addition, multiplication, and comparison times. The computation times of addition, multiplication, and comparison are expressed as $L_{\text{S}}N - \sum_{t=0}^{n}(N_t^l - 1)$, $L_{\text{S}}(2N+1) - 3\sum_{t=0}^{n}(N_t^l - 1)$, and $L_{\text{S}}N + (K - \log_2 L_{\text{S}})L_{\text{S}}(L_{\text{S}}-1) - \sum_{t=0}^{n} N_t^l((L_{\text{S}} - L_{\text{SC}})(L_{\text{S}} - L_{\text{SC}}-1)/2)$, respectively. L_{S} is the detection time, L_{SC} is the SC decoding time, N is the code length, N_t^l represents the number of subcodes under the node with the decision of the four special structures, and n is the detection times meeting four special polar subcodes.

Table I summarizes the complexity comparison between the proposed algorithm and the existing SCL decoding one. According to the above calculation, the FSCL algorithm performs fast decoding on the basis of SCL, reducing a large number of decoding steps during fast decoding. The specific values are shown in the Table I.

In summary, the proposed algorithm both reduces the complexity and improves the BER performance compared with those of the existing SCL algorithm.

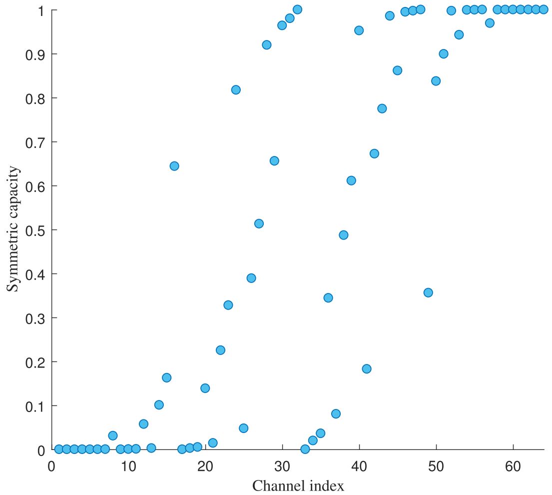

Fig. 4. Power of the PW codes in each subchannel.

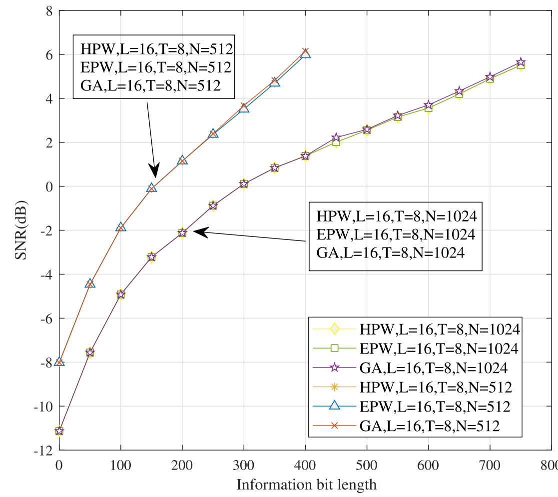

Fig. 5. Performance comparison of the HPW, EPW, and GA, when $L = 16$, $T = 8$, and decoding reaches a BLER of 10^{-3}.

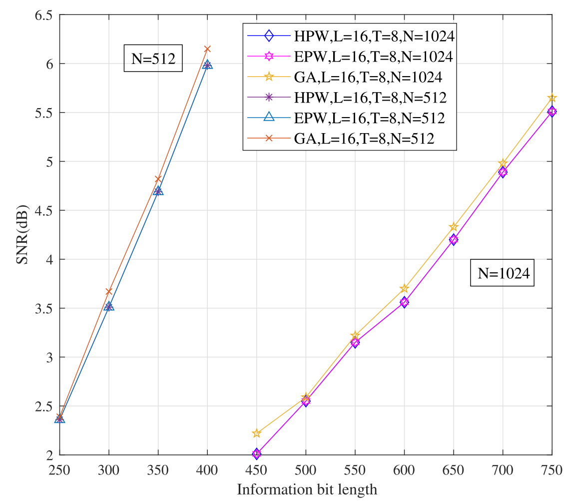

Fig. 6. Performance comparison of the HPW, EPW, and GA, when $L = 16$, $T = 8$, and decoding performance reaches a BLER of 10^{-3} after amplification.

VI. Numerical Simulations and Result Analyses

In simulations, the code length $N = 64$, the information length $K = 57$, and the weighted base $\beta = 2^{(1/4)}$ are set to perform channel polarization and test PW performance. In Fig. 4, the calculated power for each subchannel of a 64 codeword length polar code is given. The pulsewidth has a periodic characteristic with period $T = 4$. Subchannel 3 is at the peak of the first cycle, and subchannel 32 is at the valley of the ninth cycle. They are in different periods, but their PW values are close to each other. The reliability order of subchannels 3 and 32 is incorrectly reversed by the PW method. The single basis indicates that the PW cannot provide sufficiently accurate information to sort reliability orders for all subchannels. More information should be incorporated into the PW value to improve the reliability ranking and satisfy the decoders of various list sizes.

A. Performance Simulations and Analysis of HPW Coding

The number of blocks with cumulative error is set up to 2000 per SNR point to obtain stable results. The SNR step size is limited to 0.1 dB to achieve a BLER of 10^{-3} by linear interpolation. The performance of the HPW is evaluated under the SC decoder combined with the GA algorithm. The results are compared in Fig. 5. In the binary input, Gaussian channel of the SC decoder, the GA and DE algorithms have similar fluctuation. Thus, the GA gives the lower bound of the SNR for any sequence in the comparison. In Fig. 5, the HPW requires the GA to obtain a similar SNR to achieve a BLER of 10^{-3}, especially at the code length of less than or equal to 512. In the case of code length 1024, the SNR required by the HPW to implement a BLER of 10^{-3} is not completely lower than that of the GA algorithm when the information length is greater than 550. The performance comparison results under the decoder when the list is 16 are shown in Fig. 5. The HPW and EPW need a lower SNR than the GA algorithm to achieve a BLER of 10^{-3}, and the SNRs of the HPW and EPW are still consistent and similar. Finally, these differences are clearly illustrated in Fig. 6.

The HPW improves the coding efficiency while reducing the coding complexity. It makes the PW series methods robust to different decoder list sizes, information blocks, and codeword lengths. The new basis only introduces a small computational complexity in the summation, and it still keeps the mathematical simplicity of the PW equations. In general, this method greatly reduces the burden on the transmitter.

B. BER Analysis of the Proposed ISDF Scheme

The BER performance of the proposed scheme under different coding and decoding is simulated and compared with those of the existing ISDF cooperation schemes. The transmission power of the source and relay is 0.5 W. The information transmission rate $r = 1$ bit/s/Hz. Each channel experiences independent identity distribution ($i.i.d$) Rayleigh fading, the noise comprises AWGNs with zero mean and variance of 1, and the HPW channel and BPSK modulation are adopted.

The SC, SCL, CA-SCL, and FSCL algorithms are used as the counterparts to decode the HPW codes at the code rate and length of 0.5 and 1024, respectively, for verifying

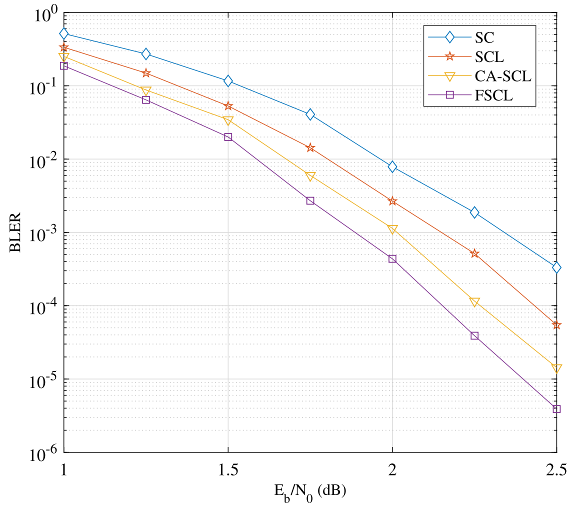

Fig. 7. BER performance of the proposed schemes with the FSCL, CA-SCL, SCL, and SC decoding algorithms.

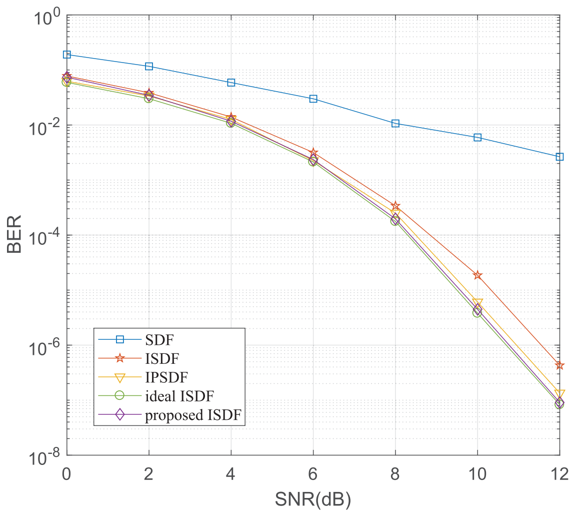

Fig. 8. BER performance comparison of the proposed ISDF, ideal ISDF, IPSDF, ISDF, and SDF schemes.

the effectiveness of the proposed FSCL decoding algorithm. In Fig. 7, the SNR performance of the proposed algorithm is improved by nearly 0.6, 0.3, and 0.1 dB compared with those of the SC, SCL, and CA-SCL, respectively, at BLER of 10^{-3}. This phenomenon can be explained as follows. FSCL is optimized by the SC and SCL criteria; moreover, it has four more special polar subcodes to be directly decoded under detection. Thus, it reduces a lot of complexity and BER for better decoding efficiency. In addition, FSCL has excellent error correction ability as same as the CA-SCL which outperforms the SCL in BER performance with the aid of the CRC. Therefore, the decoding performance of FSCL is better than others.

In Fig. 8, the BER curves of the proposed ISDF, ideal ISDF, ISDF, and SDF are simulated and determined with the noise variances of $\delta_{sd}^2 = \delta_{rd}^2 = \delta_{sr}^2 = 1$. At BER of 10^{-6}, the proposed ISDF has around 1 dB SNR gain compared with the ISDF. With the increase in SNR, the selection threshold T is decreasing and the probability of using DF in the cooperative transmission is increasing, too. The BER of the SDF is the

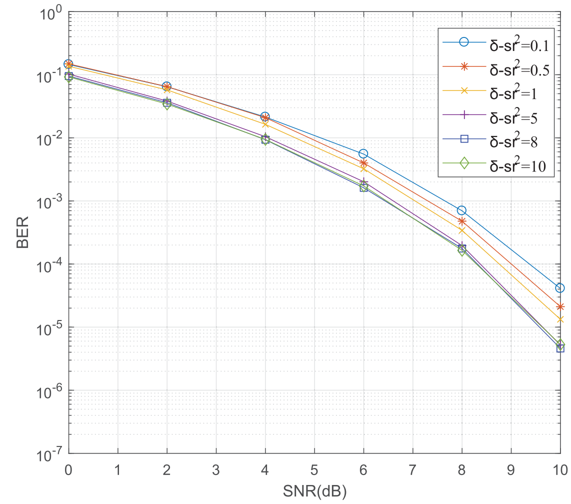

Fig. 9. BER comparison of the proposed ISDF protocol under different S-R channel qualities.

highest because it has no incremental retransmission under poor transmission quality. But in the destination, the error propagation easily occurs due to the incorrectly received signals. By (21), the traditional ISDF easily causes error transmission due to the decoding errors in the case of failed transmission. On the contrary, by (19), the proposed ISDF retransmits with a much lower BER than that of the original ISDF. Thus, the BER of the proposed ISDF is much lower than those of the ISDF and SDF. In conclusion, the BER performance of the proposed ISDF is improved significantly, which is much close to the ideal ISDF.

In Fig. 9, the BER curve of the proposed ISDF under $\delta_{sd}^2 = \delta_{rd}^2 = 0.1$ and $\delta_{sr}^2 = 0.1, 0.5, 1, 5, 8, 10$ are illustrated. At BER of 10^{-6}, the scheme of $\delta_{sr}^2 = 10$ has nearly 1.3 and 1 dB SNR performance gains compared with $\delta_{sr}^2 = 0.1$ and $\delta_{sr}^2 = 1$. With the improvement in the channel quality in link S-R, by (18), the BER of the DF scheme is lower than those of other schemes. Given the increased probability of $|h_{sr}|^2 > T$, and by (19), the relay adopts more DF schemes for cooperative transmission. Moreover, under the good quality of link S-R, using the best relays for transmissions, the BER performance is apparently improved at the cost of a little transmission rate. Therefore, the BER of the proposed ISDF decreases evidently with the increase in δ_{sr}^2.

C. Simulation Analysis of OP of the Proposed ISDF Scheme

After polar coding in the HPW channel, signals are passed through the polarization channel in the cooperative transmissions. The distance between nodes is normalized in the relay channel mode as a unit distance. In Fig. 10, the interrupt probability performance of the proposed ISDF, IPSDF, ISDF, and SDF is compared in Rayleigh fading channels. Given $\delta_{sd}^2 = \delta_{rd}^2 = \delta_{sr}^2 = 1$, the spectral efficiency of the transmission rate r is set as 1 bit/s/Hz for normalization. At OP of 10^{-2}, the performance of the proposed ISDF is 0.8 and 1.2 dB higher than those of the ISDF and SDF, respectively. Obviously, the SDF has the highest OP, that is,

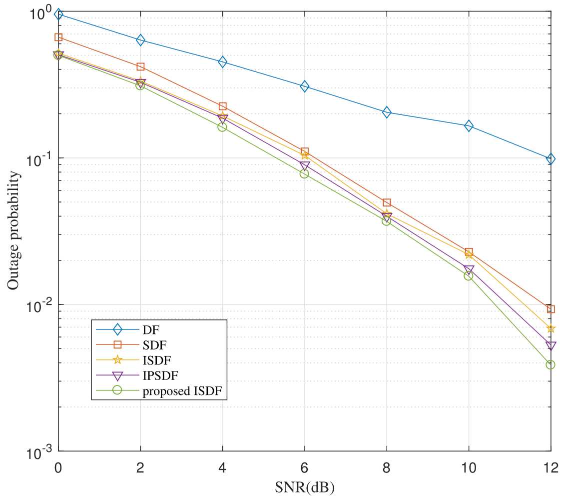

Fig. 10. OP comparison of the proposed ISDF, IPSDF, ISDF, SDF, and DF.

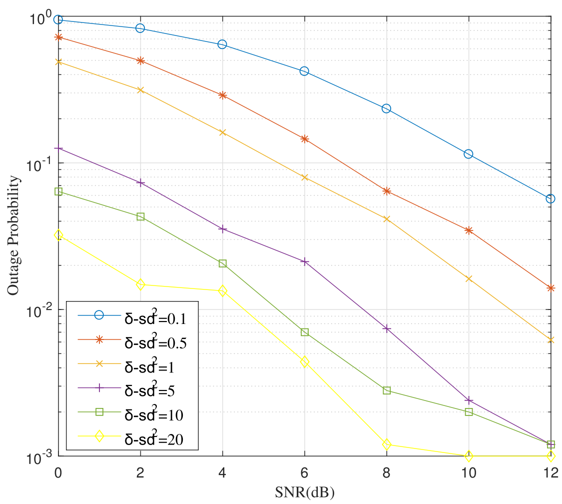

Fig. 11. OP comparison of the proposed ISDF with different S-D channel qualities of δ_{sd}^2.

the poorest performance. The proposed ISDF is incremental cooperation without transmission interruption, which usually occurs in cooperative transmission under low outages. By (24), because $C_{\text{DRT}} < r$ and $|h_{\text{sr}}|^2 > T$, when the error transmission occurs in the DF, the proposed ISDF has an incremental retransmission with a much lower OP than that of the ISDF.

In Fig. 11, the OP curve of the proposed ISDF shows that the OP performance under $\delta_{\text{rd}}^2 = \delta_{\text{sr}}^2 = 1$ and $\delta_{\text{sd}}^2 = 0.1$, 0.5, 1, 5, 10 and 20. In (24), with the improvement in the channel quality in link S-D, the probability of $|h_{\text{sd}}|^2 > T$ increases, the possibility of success in the direct transmission also becomes larger. Thus, the OP gradually turns out to be much lower than that of the traditional ISDF. By (25)–(27), under good channel quality in link S-D, the probability of direct transmission increases while the probability of DF decreases, and the utilization rate of direct transmission also improves considerably. Error transmission generally occurs under DF. Thus, the OP performance of $\delta_{\text{sd}}^2 = 10$ is much greater than those of $\delta_{\text{sd}}^2 = 1$ or 0.1. Furthermore, direct transmission significantly improves the transmission efficiency with channel quality enhancement in link S-D.

VII. Conclusion

In this article, an optimized HPW-coded ISDF is proposed to solve the high error rate of signal decoding and forwarding in cooperative SSNs. Combined with the classic three-node model, the specific model and equation are derived. First, the effects of the HPW-coded weight β are introduced to polarize channels. Second, an adaptive relay is proposed to determine the transmission mode according to CSI. Third, the FSCL decoding is used in the destination D, and four kinds of polar subcodes are used for fast decoding. Finally, the incremental retransmission by channel estimation reduces error propagation and improves OP performance. Simulation results show that the proposed scheme obtains approximately 1 dB gain at BER of 10^{-6} and 0.8 dB gain at an OP of 10^{-2}, respectively. Therefore, the proposed scheme possesses great potential in cooperative SSNs with low BER and OP in the future.

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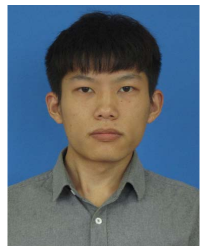
Bin Jiang received the B.S. and M.S. degrees in communication and electronic system from the School of Communication Engineering, Hangzhou Dianzi University, Hangzhou, China, in 1999 and 2004, respectively, and the Ph.D. degree in electronic science and technology from the School of Electronic and Information, Hangzhou Dianzi University, in 2021.

Currently, he is serving as a Senior Experimentalist with the School of Communication Engineering, Hangzhou Dianzi University. His main research interests include wireless communications, signal processing, information theory, and channel coding.



Xiaowei Wu received the B.S. degree from the China Jiliang University College of Modern Science and Technology, Hangzhou, China, in 2020. He is currently pursuing the master's degree in information and communication engineering with the School of Communication Engineering, Hangzhou Dianzi University, Hangzhou.

His research interests include wireless communications, cognitive radio, and compressive sensing.

Jianrong Bao (Senior Member, IEEE) received the B.S. degree in polymeric materials and engineering and the M.S. degree in communication and information systems from the Zhejiang University of Technology, Hangzhou, China, in 2000 and 2004, respectively, and the Ph.D. degree in information and communication engineering from the Department of Electronic Engineering, Tsinghua University, Beijing, China, in 2009.

He was a Postdoctoral Researcher with Zhejiang University, Hangzhou, from 2011 to 2013, and with Southeast University, Nanjing, China, from 2014 to 2017, and then a Visiting Scholar with Columbia University, New York City, NY, USA, in 2015, respectively. He is currently a Professor with the School of Communication Engineering, Hangzhou Dianzi University, Hangzhou. His main research interests include modern wireless communications, cognitive radio, information theory and coding, communication signal processing, and wireless sensor networks.

Chao Liu received the B.S. and Ph.D. degrees in information and communication engineering from the School of Electronic Information and Communications, Huazhong University of Science and Technology, Wuhan, China, in 2000 and 2005, respectively.

He is currently an Associate Professor with the School of Information Engineering, Hangzhou Dianzi University, Hangzhou, China. He is also a Visiting Scholar at the College of Information Science and Electronic Engineering, Zhejiang University, Hangzhou. His research interests include modern wireless communication and coding and MIMO multiuser detection.

Xianghong Tang received the B.S. and M.S. degrees in physics from Southwest Normal University, Chongqing, China, and Sichuan University, Chengdu, China, in 1985 and 1988, respectively, and the Ph.D. degree in EE from the University of Electronic Science and Technology, Chengdu, in 1997.

Currently, he is the Dean of the School of Communication Engineering, Hangzhou Dianzi University, Hangzhou, China. His research interests include multimedia signal processing, information theory, and source/channel coding.