Two-Path Successive Relaying With Hybrid Demodulate and Forward

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***Abstract*—This paper proposes a novel demodulation-and-forward (DMF) scheme for the two-path successive relay system. While the two-path relaying avoids the data rate loss that occurs in many one-relay cooperative systems, its performance is severely limited by interrelay interference. In this paper, we propose a hybrid DMF scheme for the two-path relay system so that the relays can switch between direct and differential demodulation modes according to channel conditions. The hybrid DMF scheme not only performs better than existing two-path approaches but is easy to achieve synchronization at the relays as well, which is particularly important as a relay receives signals from both the source and the other relay. The proposed hybrid DMF scheme provides an innovative way to implement the two-path relaying scheme.**

***Index Terms*—Cooperative communication, demodulate and forward (DMF), interference cancellation, two-path successive relay.**

I. Introduction

COOPERATIVE networks can significantly improve system performance with the assistance of relays [1]–[3]. In practical communication systems, antennas usually work in half-duplex mode so that signals are not transmitted and received at the same time. As a result, one transmission time slot is often divided into two or more subtime slots for the relays to receive and transmit data separately. This leads to 50% or more loss in data rate because now, more than one (sub)time slots are required to transmit one data symbol from the source to the destination. An attractive alternative to avoid the data rate loss is the two-path successive relay scheme proposed in [4] and [5].

The two-path relay scheme is illustrated in Fig. 1, where there is one source node S, one destination node D, and two relay nodes R_1 and R_2. At a transmission time slot, the source transmits data to one of the relays, and at the same time, the other relay node forwards the data received at the previous time slot to the destination. Because the source continually transmits data to the two relays alternatively, the loss in data rate is effectively avoided. Specifically, as the destination receives no data at the first time slot, $(N+1)$ time slots are required to transmit N data packets from the source to the destination, leading to a bandwidth efficiency of $N/(N+1)$ that is close to the full data transmission rate of 1 when N is sufficiently large.

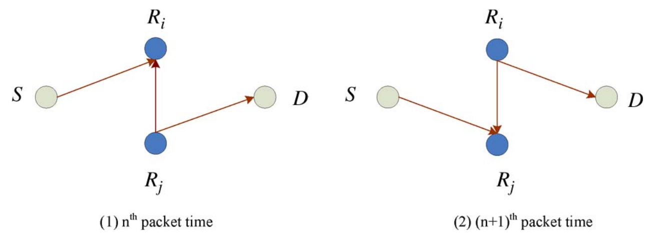

Fig. 1. Two-path successive relay scheme.

In the two-path relay scheme, due to the simultaneous transmission at the source and one of the relay nodes, the receiving relay node receives data not only from the source but also from the other relay. Such data from the other relay form the interrelay interference (IRI) that is the main issue in the two-path relay system. If it is not carefully handled, the IRI can significantly degrade, or even invalidate, the overall system. The effect of the IRI on the system performance depends on the relaying protocols. In general, the relay can apply the amplify-and-forward (AF) or decode-and-forward (DF) protocol (or its variants). In the AF protocol, the relays simply amplify the received signals and forward to the destination so that the IRI is also amplified and passed to the destination. Therefore, if the AF is applied at the relays, the IRI is usually cancelled at the destination [6]. On the other hand, if the DF protocol is applied where the data are decoded at the relays, there is no IRI passed to the destination, and the IRI mainly affects the decoding at the relays.

The AF is simpler to implement than the DF, and therefore, it is more suitable for mobile relays with limited computation capability. On the other hand, it is more difficult for the AF to be integrated with existing mobile protocols such as satisfying the instantaneous power constraint at the relays. In the latest "LTE release-10" (http://www.3gpp.org/lte-advanced), future cellular systems focus on fixed relays where the complexity becomes a less important issue, and the DF can be applied without much difficulty. The two-path relay system with DF was studied in

[3]. To successfully decode the data at the relays, the system must ensure that either the IRI is small enough or the IRI is strong enough so that the relay can detect the IRI first and subtract it from the received signal. Such requirement limits the performance and flexibility of the system. Particularly when the IRI and source data have similar powers at the relay, the decoding at the relay cannot be successful.

In this paper, we propose a novel hybrid demodulate-and-forward (DMF) scheme for the two-path relay system. In general, the DMF can be regarded as a special form of the DF, in which symbol level demodulation is applied at the relays, and the remodulated data are forwarded to the destination [7]. Since there is no decoding at the relays, the DMF has significantly less complexity and delay than the standard DF. Unlike the traditional DMF, in the hybrid DMF approach, the relay applies two kinds of demodulation schemes: When the IRI is small enough, the relay directly demodulates the source symbol; on the other hand, when the IRI is large, the relay demodulates the differential symbol between the source and IRI symbols.

The proposed hybrid DMF scheme has significantly better performance in suppressing the IRI than existing two-path relaying approaches. Simulation results show that the performance of the hybrid DMF scheme is close to the ideal case that the IRI can be perfectly removed. The hybrid DMF is also easy to achieve synchronization at the relays, which is particularly important in two-path relaying as the relay receives signals from both the source and the other relay. Furthermore, differential demodulation can also be used in the two-path relay system with the standard DF to improve the performance. The hybrid DMF scheme provides an innovative way to implement the two-path relay scheme. It suggests a new way for interference cancellation in relaying systems.

The rest of this paper is organized as follows. Section II describes the two-path succussive relay system. Section III proposes the hybrid DMF scheme for the two-path relay system. Section IV shows how the relays switch between direct and differential demodulation methods. Section V discusses implementation issues including the synchronization. Section VI verifies the proposed scheme with numerical simulations. Finally, Section VII summarizes this paper.

II. Two-Path Succussive Relay

The two-path succussive relay system is shown in Fig. 1, where we assume that the channels are slow flat fading that the channel coefficients remain unchanged during at least one packet time, each data packet contains M symbols, and there are N packets in total for transmission. We note that in practice that there may exist a direct transmission link between source S and D. While the $S \rightarrow D$ direct link may have significant effect on the performance at the destination, it has no effect at the relays. Therefore, to concentrate on the relaying protocols, which is the main issue in this paper, the $S \rightarrow D$ link is ignored, but the proposed relaying method can also be applied in the system with $S \rightarrow D$ direct link.

As shown in Fig. 1, at the nth packet time, S transmits data packet $\mathbf{x}_s(n)$ to R_i ($i = 1$ or 2), where $\mathbf{x}_s(n) = [x_s(n_1), \ldots, x_s(n_M)]^{\mathrm{T}}$, and $x_s(n_m)$ is the mth symbol in $\mathbf{x}_s(n)$. At the same time, R_j ($j \neq i$) forwards data packet $\mathbf{x}_j(n)$ to D, where $\mathbf{x}_j(n) = [x_j(n_1), \ldots, x_j(n_M)]^{\mathrm{T}}$, and $x_j(n_m)$ is the mth symbol in $\mathbf{x}_j(n)$.

Due to the simultaneous transmission at S and R_j, R_i receives signals from both S and R_j. Further noting that the channels are flat fading and remain constant within one packet, the received packet at R_i is given by

$$\mathbf{y}_i(n) = h_{si}(n)\mathbf{x}_s(n) + h_{ji}(n)\mathbf{x}_j(n) + \mathbf{w}_i(n) \quad (1)$$

where $\mathbf{y}_i(n) = [y_i(n_1), \ldots, y_i(n_M)]^{\mathrm{T}}$, $y_i(n_m)$ is the mth symbol in $\mathbf{y}_i(n)$, $h_{si}(n)$ is the channel coefficient between S and R_i at packet time n, $h_{ji}(n)$ is the interrelay channel coefficient between R_j and R_i at packet time n, and $\mathbf{w}_i(n)$ is the noise vector at R_i. Without losing generality, we assume that $h_{ji}(n) = h_{ij}(n)$. It is clear that the second term on the right-hand side of (1) forms the IRI.

For different relaying prototypes, $\mathbf{x}_j(n)$ can generally be expressed as

$$\mathbf{x}_j(n) = f\left(\mathbf{y}_j(n-1)\right) \quad (2)$$

where $\mathbf{y}_j(n-1)$ is the received packet at node R_j at packet time $(n-1)$, and $f(\cdot)$ is a function depending on relaying protocols. For the traditional DMF [7], $f(\cdot)$ gives the remodulation of the demodulated received data packet.

The received packet at the destination at the nth packet time is given by

$$\mathbf{y}_d(n) = h_{jd}(n)\mathbf{x}_j(n) + \mathbf{w}_d(n) \quad (3)$$

where $\mathbf{y}_d(n) = [y_d(n_1), \ldots, y_d(n_M)]^{\mathrm{T}}$, $y_d(n_m)$ is the mth symbol in $\mathbf{y}_d(n)$, $h_{jd}(n)$ is the channel coefficient between R_j and D at time n, and $\mathbf{w}_d(n)$ is the noise vector at D.

Similarly, at packet time $(n+1)$, S transmits packet $\mathbf{x}_s(n+1)$ to R_j, and R_i forwards $\mathbf{x}_i(n+1) = f(\mathbf{y}_i(n))$ to D. This process continues until all data packets are transmitted.

III. Hybrid Demodulation-and-Forward

In the classic DMF relay system, the relays directly demodulate the source data, remodulate it, and forward to the destination. As shown in (1), the performance of the direct demodulation can severely be limited by the IRI in the two-path relay system. In this section, a hybrid DMF scheme that applies both direct and differential demodulation at the relays is proposed to minimize the influence from the IRI.

For the Kth order modulation, each symbol $x_s(n_m)$ in the source packet $\mathbf{x}_s(n)$ corresponds to K bits as $\{b_{s,1}(n_m), \ldots, b_{s,K}(n_m)\}$, and each IRI symbol $x_j(n_m)$ corresponds to K bits as $\{b_{j,1}(n_m), \ldots, b_{j,K}(n_m)\}$. For better exposition, we consider the binary phase-shift keying (BPSK) below, but the results can easily be extended to higher modulations. For the BPSK, since there is only one bit per symbol, the bit index k is ignored without causing confusion. We further assume without losing generality that the bits 1 and 0 are modulated into symbols 1 and -1, respectively.

A. Direct Demodulation and Forward

As shown in (1), if the IRI is small, we can directly demodulate the source packet $\mathbf{x}_s(n)$ from the received signal $\mathbf{y}_i(n)$. The maximum likelihood (ML) approach to demodulate the mth symbol in $\mathbf{x}_s(n)$ is given by

$$\hat{b}_s(n_m) = \arg\max_{b_s(n_m)} \{P(y_i(n_m)|b_s(n_m) = 1), \\ P(y_i(n_m)|b_s(n_m) = 0)\} \quad (4)$$

where $P(y_i(n_m)|b_s(n_m) = 1)$ and $P(y_i(n_m)|b_s(n_m) = 0)$ are the probabilities of $y_i(n_m)$ when the transmission source bits are $b_s(n_m) = 1$ and $b_s(n_m) = 0$, respectively. From (1), we have

$$\begin{aligned} P(y_i(n_m)|b_s(n_m) = 1) &= P(y_i(n_m)|x_s(n_m) = 1) \\ &= P(x_j(n_m) = 1) \cdot P(y_i(n_m)|x_s(n_m) = 1, x_j(n_m) = 1) \\ &\quad + P(x_j(n_m) = -1) \\ &\quad \cdot P(y_i(n_m)|x_s(n_m) = 1, x_j(n_m) = -1). \end{aligned} \quad (5)$$

Without losing generality, we assume that $P(b_s(n_m) = 1) = P(b_s(n_m) = 0) = 1/2$ for all n and m, and the channel noise is circularly symmetric Gaussian with zero mean. We suppose initially (when $n = 1$) that the source transmits the first data packet $\mathbf{x}_s(1)$ to relay R_1. Since, at $n = 1$, R_1 only receives data from the source and we assume $P(b_s(n_m) = 1) = P(b_s(n_m) = 0)$, the demodulated bit at R_1 must also be equiprobable. Thus, at $n = 2$, when R_1 transmits the remodulated packet $\mathbf{x}_1(2)$, we have $P(x_1(2_m) = 1) = P(x_1(2_m) = -1) = 1/2$ for all m. At the same time, R_2 receives data packet from source and R_1, which both have equiprobable bits and are mutually independent. Thus, the demodulated bit at R_2 must also be equiprobable. Then, at $n = 3$, we have $P(x_2(3_m) = 1) = P(x_2(3_m) = -1) = 1/2$ for all m. Continuing this process for all data packet gives

$$P(x_j(n_m) = 1) = P(x_j(n_m) = -1) = \frac{1}{2} \quad (6)$$

for any n and m, and $j = 1, 2$. A similar observation in (6) is used in all demodulation methods in this paper.

Substituting (6) into (5) gives

$$\begin{aligned} P(y_i(n_m)|b_s(n_m) = 1) &= P(y_i(n_m)|x_s(n_m) = 1) \\ &= \frac{1}{2}\left[P(y_i(n_m)|x_s(n_m) = 1,\ x_j(n_m) = 1)\right. \\ &\quad \left.+ P(y_i(n_m)|x_s(n_m) = 1,\ x_j(n_m) = -1)\right]. \end{aligned} \quad (7)$$

Similarly, we have

$$\begin{aligned} P(y_i(n_m)|b_s(n_m) = 0) &= P(y_i(n_m)|x_s(n_m) = -1) \\ &= \frac{1}{2}\left[P(y_i(n_m)|x_s(n_m) = -1,\ x_j(n_m) = 1)\right. \\ &\quad \left.+ P(y_i(n_m)|x_s(n_m) = -1,\ x_j(n_m) = -1)\right]. \end{aligned} \quad (8)$$

We subsequently show that the ML demodulation of (4) can be simplified for the BPSK. We assume that the channel noise is Gaussian with mean zero and variance $N_0/2$. Then, from (1),

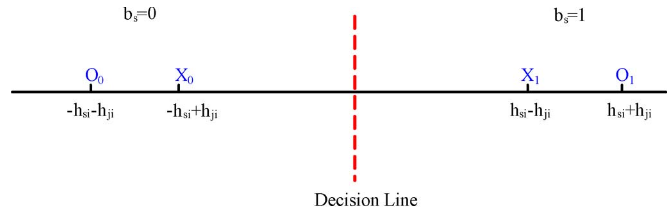

Fig. 2. Direct BPSK demodulation, where $h_{si}(n) > h_{ji}(n) > 0$.

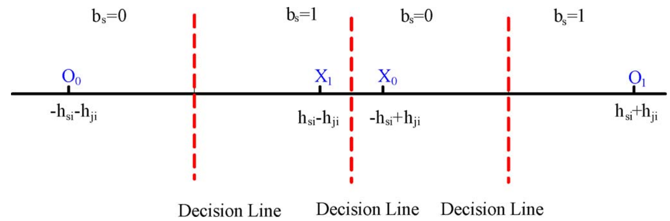

Fig. 3. Direct BPSK demodulation, where $h_{ji}(n) > h_{si}(n) > 0$.

for a given pair of $x_s(n_m)$ and $x_j(n_m)$, $y_i(n_m)$ is also Gaussian with mean $h_{si}(n)x_s(n_m) + h_{ji}(n)x_j(n_m)$ and variance $N_0/2$. For example, if $h_{si}(n) > h_{ji}(n) > 0$, the possible means of $y_i(n_m)$ are illustrated as points O_0, X_0, X_1, and O_1 in Fig. 2.

It is shown in Fig. 2 that the detection regions for $b_s(n_m) = 0$ and $b_s(n_m) = 1$ are symmetric, which implies that the decision line is $y_i(n_m) = 0$ so that $\hat{b}_s(n_m) = 1$ if $y_i(n_m) \geq 0$ and $\hat{b}_s(n_m) = 0$ if $y_i(n_m) < 0$. It is clear that the demodulation performance is determined by the distance between points X_0 and X_1.

If the signs of $h_{si}(n)$ and $h_{ji}(n)$ are considered, we can obtain that, when $|h_{si}(n)| > |h_{ji}(n)|$, the ML BPSK demodulation in (4) is equivalent to

$$\hat{b}_s(n_m) = \begin{cases} \frac{1+\text{sign}(h_{si}(n))}{2}, & y_i(n_m) \geq 0 \\ \frac{1-\text{sign}(h_{si}(n))}{2}, & y_i(n_m) < 0. \end{cases} \quad (9)$$

On the other hand, when $|h_{si}(n)| < |h_{ji}(n)|$, the BPSK demodulation is illustrated in Fig. 3, where it is clearly shown that the demodulation performance is determined by the minimum distance of (O_0, X_1), (X_1, X_0), and (X_0, O_1).

After all of the M symbols ($\hat{b}_s(n_m)$ for $m = 1, \ldots, M$) in the packet are demodulated and remodulated as ± 1, they are forwarded to the destination in the $(n+1)$th packet time.

B. Differential DMF

While the direct demodulation of source data packet works well when the IRI is small, the performance varies significantly with the level of IRI (or the value of $|h_{ji}(n)|$). It is clearly shown in Figs. 2 and 3 that the worst scenario occurs when $|h_{si}(n)| = |h_{ji}(n)|$ so that the distance between points X_0 and X_1 is 0.

We subsequently describe the differential DMF scheme. We first illustrate the fundamental of the scheme through a simple example and then describe the ML differential demodulation at the relays.

1) Differential Demodulation at the Relay: To show the fundamental of the differential DMF, we first consider a particular case in which there is no noise and $h_{si}(n) = h_{ji}(n) = 1$ in (1) such that the source and IRI symbols have the same powers in the received signal at relay R_i. It is clear that $y_i(n_m)$ can take three possible values: -2, 0, and 2. When $y_i(n_m) = 0$, it is impossible to directly demodulate $b_s(n_m)$ because both pairs of $\{x_s(n_m) = 1, x_j(n_m) = -1\}$ and $\{x_s(n_m) = -1, x_j(n_m) = 1\}$ lead to $y_i(n_m) = 0$.

On the other hand, if $x_s(n_m) = x_j(n_m)$, we have $y_i(n_m) = \pm 2$, and if $x_s(n_m) \neq x_j(n_m)$, we have $y_i(n_m) = 0$. But $x_s(n_m) = x_j(n_m)$ and $x_s(n_m) \neq x_j(n_m)$ correspond to $b_{s\oplus j}(n_m) = 0$ and 1, respectively, where we define

$$b_{s\oplus j}(n_m) = b_s(n_m) \oplus b_j(n_m) \tag{10}$$

and $\oplus$ is the XOR operation. This implies that, although we cannot directly demodulate $b_s(n_m)$, we can demodulate the differential of $b_s(n_m)$ and $b_j(n_m)$ as

$$b_{s\oplus j}(n_m) = \begin{cases} 0, & y_i(n_m) = \pm 2 \\ 1, & y_i(n_m) = 0. \end{cases} \tag{11}$$

At the next packet time $(n+1)$, the transmission bit for the mth symbol in the packet at relay R_i is $b_i((n+1)_m) = b_{s\oplus j}(n_m)$. Every $b_i((n+1)_m)$ for $m = 1, \ldots, M$ in the packet is then remodulated as $x_i((n+1)_m) = \pm 1$ and forwarded to the destination.

2) Differential Detection at the Destination: As in (3), at packet time $(n+1)$, the received signal at the destination is given by $\mathbf{y}_d(n+1) = h_{id}(n)\mathbf{x}_i(n+1) + \mathbf{w}_d(n+1)$, which is used to demodulate $b_i((n+1)_m)$ for $m = 1, \ldots, M$. If it is successful, the demodulation gives

$$\text{demod}\left(y_d(n+1)_m)\right) = b_i\left((n+1)_m\right). \tag{12}$$

Since differential demodulation is applied at relay R_i at packet time n, we have $b_i((n+1)_m) = b_{s\oplus j}(n_m)$. Further, from (10), we have

$$\text{demod}\left(y_d\left((n+1)_m\right)\right) = b_s(n_m) \oplus b_j(n_m). \tag{13}$$

On the other hand, at packet time n, the destination receives data packet $\mathbf{x}_j(n)$ from relay R_j. Similar to (12), if the demodulation is successful, we have

$$\text{demod}\left(y_d(n_m)\right) = b_j(n_m). \tag{14}$$

We particularly note that $b_j(n_m)$ can be either direct or differential bit, i.e., either $b_j(n_m) = b_s((n-1)_m)$ or $b_j(n_m) = b_s((n-1)_m) \oplus b_i((n-1)_m)$ is possible.

Finally, if the previous demodulated bit demod$(y_d(n_m))$ is correct and stored, the source bit for the mth symbol in the nth packet can be recovered at the destination by the differential detection as

$$\begin{aligned} &\text{demod}\left(y_d\left((n+1)_m\right)\right) \oplus \text{demod}\left(y_d(n_m)\right) \\ &\quad = \left(b_s(n_m) \oplus b_j(n_m)\right) \oplus b_j(n_m) = b_s(n_m) \end{aligned} \tag{15}$$

for $m = 1, \ldots, M$.

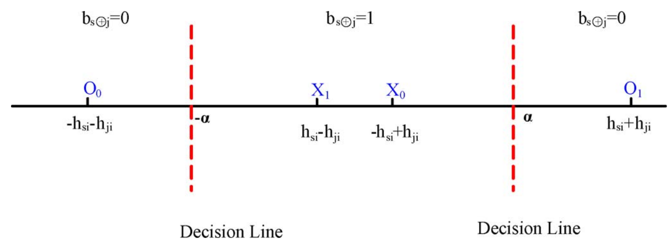

Fig. 4. Differential demodulation, where $h_{ji}(n) > h_{si}(n) > 0$.

3) ML Differential Demodulation: The preceding illustration clearly shows that when IRI and source data have comparable powers at the relays, the source packet can still be reliably forwarded to the destination with differential demodulation at the relay and differential detection at the destination.

The ML differential demodulation for the mth symbol in the nth packet at relay R_i is given by

$$\begin{aligned} \hat{b}_{s\oplus j}(n_m) = \arg \max_{b_{s\oplus j}(n_m)} &\left\{P\left(y_i(n_m)|b_{s\oplus j}(n_m) = 0\right),\right. \\ &\left. P\left(y_i(n_m)|b_{s\oplus j}(n_m) = 1\right)\right\} \end{aligned} \tag{16}$$

where $P(y_i(n_m)|b_{s\oplus j}(n_m) = 1)$ and $P(y_i(n_m)|b_{s\oplus j}(n_m) = 0)$ are the probabilities of $y_i(n_m)$ when the differential bits are $b_{s\oplus j}(n_m) = 1$ and $b_{s\oplus j}(n_m) = 0$, respectively. From (1), we have

$$\begin{aligned} &P\left(y_i(n_m)|b_{s\oplus j}(n_m) = 1\right) \\ &\quad = P\left(y_i(n_m)|x_s(n_m) \neq x_j(n_m)\right) \\ &\quad = \frac{1}{2}\left[P\left(y_i|x_s(n_m) = 1,\ x_j(n_m) = -1\right)\right. \\ &\qquad \left. + P\left(y_i(n_m)|x_s(n_m) = -1,\ x_j = 1\right)\right] \end{aligned} \tag{17}$$

$$\begin{aligned} &P\left(y_i(n_m)|b_{s\oplus j}(n_m) = 0\right) \\ &\quad = P\left(y_i(n_m)|x_s(n_m) = x_j(n_m)\right) \\ &\quad = \frac{1}{2}\left[P\left(y_i(n_m)|x_s(n_m) = 1,\ x_j(n_m) = 1\right)\right. \\ &\qquad \left. + P\left(y_i(n_m)|x_s(n_m) = -1,\ x_j = -1\right)\right]. \end{aligned} \tag{18}$$

Similar to the direct demodulation, the ML differential demodulation of (16) can be simplified to determine the decision ranges of $y_i(n_m)$ for the BPSK. For illustration, if $h_{ji}(n) > h_{si}(n) > 0$, the demodulation rule for differential demodulation is shown in Fig. 4. There are two decision regions of $b_{s\oplus j}(n_m) = 0$ and $b_{s\oplus j}(n_m) = 1$, respectively, separated by decision lines $y_i(n_m) = \alpha$ and $y_i(n_m) = -\alpha$, where α is a positive number that will be discussed later. It is clear that the demodulation performance depends on the distance of (O_0, X_1) or (O_1, X_0). If $h_{si}(n) > h_{ji}(n) > 0$, the decision rule is the same as in Fig. 4, except that the points X_1 and X_0 are swapped.

If the signs of $h_{si}(n)$ and $h_{ji}(n)$ are considered, the ML differential demodulation for BPSK can be equivalent to

$$\hat{b}_{s\oplus j}(n_m) = \begin{cases} \frac{1+\text{sign}(h_{si}(n)h_{ji}(n))}{2}, & -\alpha \leq y_i(n_m) \leq \alpha \\ \frac{1-\text{sign}(h_{si}(n)h_{ji}(n))}{2}, & y_i(n_m) > \alpha \\ & \text{or} \quad y_i(n_m) < -\alpha. \end{cases} \tag{19}$$

The demodulation rule given by (19) is valid for both $|h_{si}(n)| > |h_{ji}(n)|$ and $|h_{si}(n)| \leq |h_{ji}(n)|$.

At packet time $(n+1)$, after all $\hat{b}_s(n_m)$ for $m = 1, \ldots, M$ are demodulated and remodulated as ± 1, they are forwarded to the destination. At the destination, the received packet is demodulated and the source bits $b_s(n_m)$ $(m = 1, \ldots, M)$ are recovered by differential detection, as shown in (15).

We particularly highlight that, as shown in [8], the optimum receiver at the destination also depends on the bit error rate (BER) information at the relays. This is left for future research as the main purpose of this paper is to describe the optimum DMF scheme at the relay nodes.

The direct/differential DMF scheme based on BPSK can easily be extended to higher order modulations with bitwise XOR operation for every bit in a symbol, although the simplified ML detection rules as in (9) and (19) may not be available.

IV. Switching Between Direct and Differential Demodulation

We show above that a relay can apply either direct or differential demodulation, and accordingly, the destination needs to apply direct or differential detection, respectively. To be specific, when a relay receives a data packet, depending on channel conditions, it decides which demodulation method should be applied for the best performance and then notifies the destination of the demodulation method. We particularly highlight that the two relays R_1 and R_2 may or may not apply the same demodulation methods.

A key issue is how the relays switch between direct and differential demodulation methods, which is discussed below.

A. BER-Based Switch

In the BER-based switching rule, the relays choose the demodulation mode with smaller BER, or

$$\begin{cases} \text{Differential demodulation}, & \text{if } P_{\mathrm{DFD}}(n) < P_{\mathrm{DD}}(n) \\ \text{Direct demodulation}, & \text{if } P_{\mathrm{DFD}}(n) \geq P_{\mathrm{DD}}(n) \end{cases} \tag{20}$$

where $P_{\mathrm{DD}}(n)$ and $P_{\mathrm{DFD}}(n)$ are the BERs for the direct and differential demodulations in the nth packet time, respectively.

Since we assume that the channel coefficients keep unchanged during one packet time, both $P_{\mathrm{DD}}(n)$ and $P_{\mathrm{DFD}}(n)$ remain unchanged within one packet as well. Therefore, only one extra bit per packet is required for the relays to notify the destination of the demodulation method. As a result, $1/(MK)$ times more bits are forwarded to the destination. It is obvious that this has little effect on the overall data rate since M (the number of symbols per one packet) is often large enough.

We hereafter show that a simplified BER-based switching rule can be derived for BPSK/quadrature PSK (QPSK). For simplicity, the derivation is based on BPSK, but the results can be straightforwardly extended to QPSK, which can be regarded as two parallel BPSKs in the I and Q channels, respectively. For BPSK, as illustrated in Figs. 3 and 4, when $|h_{si}(n)| \leq |h_{ji}(n)|$, the differential demodulation should be used as it has better BER performance than the direct demodulation. When $|h_{si}(n)| > |h_{ji}(n)|$, the BER performance is calculated as follows.

1) BER of the Direct BPSK Demodulation: When $|h_{si}(n)| > |h_{ji}(n)|$, the ML direct BPSK demodulation rule is given by (9). As illustrated in Fig. 2, the detection regions for $b_s(n_m) = 0$ and $b_s(n_m) = 1$ are symmetric. If we further assume that $P(b_s(n_m) = 0) = P(b_s(n_m) = 1)$, we have $P(e|b_s(n_m) = 1) = P(e|b_s(n_m) = 0)$, which are the probabilities of error for $b_s(n_m) = 1$ and $b_s(n_m) = 0$, respectively. Thus, the BER for direct BPSK demodulation is given by

$$\begin{aligned} P_{\mathrm{DD}}(n) &= P\left(e|b_s(n_m) = 1\right) = \int_{-\infty}^{0} P\left(y|x_s(n_m) = 1\right) dy \\ &= \frac{1}{2} \int_{-\infty}^{0} \left(P\left(y|x_s(n_m) = 1, x_j(n_m) = 1\right)\right. \\ &\qquad \left. + P\left(y|x_s(n_m) = 1, x_j(n_m) = -1\right)\right) dy \\ &= \frac{1}{2} Q\left(\sqrt{\frac{2\varepsilon}{N_0}} \left(|h_{si}(n)| + |h_{ji}(n)|\right)\right) \\ &\quad + \frac{1}{2} Q\left(\sqrt{\frac{2\varepsilon}{N_0}} \left(||h_{si}(n)| - |h_{ji}(n)||\right)\right) \end{aligned} \tag{21}$$

where ε is the symbol power, $N_0/2$ is the noise variance, and $Q(.)$ is the Q-function [9].

2) BER of the Differential BPSK Demodulation: The ML differential demodulation rule for BPSK is given by (19). The probability of error for $b_{s\oplus j}(n_m) = 0$, or when the source and the other relay transmit the same symbols [(i.e., $x_s(n_m) = x_j(n_m)$)], is given by

$$\begin{aligned} &P\left(e|b_{s\oplus j}(n_m) = 0\right) \\ &\quad = \frac{1}{2} \int_{-\alpha}^{\alpha} \left(p\left(y|x_s(n_m) = 1, x_j(n_m) = 1\right)\right. \\ &\qquad \left. + p\left(y|x_s(n_m) = -1, x_j(n_m) = -1\right)\right) dy \\ &\quad = \frac{1}{2}\left[1 - Q\left(\left(\alpha + \sqrt{\varepsilon}\left(|h_{si}(n)| + |h_{ji}(n)|\right)\right)\sqrt{\frac{2}{N_0}}\right)\right. \\ &\qquad \left. - Q\left(\left(\alpha - \sqrt{\varepsilon}\left(|h_{si}(n)| + |h_{ji}(n)|\right)\right)\sqrt{\frac{2}{N_0}}\right)\right]. \end{aligned} \tag{22}$$

The probability of error for $b_{s\oplus j}(n_m) = 1$, or $x_s(n_m) \neq x_j(n_m)$, is given by

$$\begin{aligned} &P\left(e|b_{s\oplus j}(n_m) = 1\right) \\ &\quad = \frac{1}{2} \int_{-\infty}^{-\alpha} p\left(y|x_s(n_m) = 1, x_j(n_m) = -1\right) dy \\ &\qquad + \frac{1}{2} \int_{\alpha}^{\infty} p\left(y|x_s(n_m) = -1, x_j(n_m) = 1\right) dy \\ &\quad = \frac{1}{2} Q\left(\left(\alpha - \left(|h_{si}(n)| - |h_{ji}(n)|\right)\sqrt{\varepsilon}\right)\sqrt{\frac{2}{N_0}}\right). \end{aligned} \tag{23}$$

Because $b_{s\oplus j}=1$ and $b_{s\oplus j}=0$ are equally likely to happen, the BER of the differential demodulation is given by

$$P_{\mathrm{DFD}}(n)=\frac{1}{2}P\left(e|b_{s\oplus j}(n_m)=0\right)+\frac{1}{2}P\left(e|b_{s\oplus j}(n_m)=1\right). \tag{24}$$

The optimum value of α, or the optimum decision lines, can be obtained by letting $P(e|b_{s\oplus j}(n_m)=1)=P(e|b_{s\oplus j}(n_m)=0)$. It is clear from (22) and (23) that the optimum α can only be obtained via numerical methods. A suboptimum α is derived as follows. First, from (22), it is obvious that $P(e|b_{s\oplus j}(n_m)=0)$ is dominated by the second Q function so that we have

$$P\left(e|b_{s\oplus j}(n_m)=0\right) \approx\frac{1}{2}\left[1-Q\left(\left(\alpha-\sqrt{\varepsilon}\left(|h_{si}(n)|+|h_{ji}(n)|\right)\right)\sqrt{\frac{2}{N_0}}\right)\right]. \tag{25}$$

Letting (25) equal (23) gives

$$\left(\alpha-\sqrt{\varepsilon}\left(|h_{si}(n)|+|h_{ji}(n)|\right)\right)\sqrt{\frac{2}{N_0}} =-\left(\alpha-\left(|h_{si}(n)|-|h_{ji}(n)|\right)\sqrt{\varepsilon}\right)\sqrt{\frac{2}{N_0}}. \tag{26}$$

Simplifying (26) gives

$$\alpha=|h_{si}(n)|\sqrt{\varepsilon}. \tag{27}$$

This implies that the optimum decision lines in Fig. 4 are in the middle of (O_0,X_0) and (X_1,O_1), respectively.

3) Simplified Switching Rules for BPSK: From (21), $P_{\mathrm{DD}}(n)$ is dominated by the second term so that for $|h_{si}(n)|>|h_{ji}(n)|$, we have

$$P_{\mathrm{DD}}(n)\approx\frac{1}{2}Q\left(\sqrt{\frac{2\varepsilon}{N_0}}\left(|h_{si}(n)|-|h_{ji}(n)|\right)\right). \tag{28}$$

Similarly, for $|h_{si}(n)|>|h_{ji}(n)|$, and with (27), we have

$$P_{\mathrm{DFD}}(n)\approx\frac{1}{2}Q\left(|h_{ji}(n)|\sqrt{\frac{2\varepsilon}{N_0}}\right). \tag{29}$$

Applying (28) and (29) in (20), and further noting that the differential demodulation should be used if $|h_{si}(n)|\le|h_{ji}(n)|$, we obtain the simplified BER-based switching rule for the BPSK as

$$\begin{cases}\text{Differential demodulation,} & \text{if } |h_{si}(n)|<2\,|h_{ji}(n)|\\ \text{Direct demodulation,} & \text{if } |h_{si}(n)|\ge 2\,|h_{ji}(n)|.\end{cases} \tag{30}$$

Accordingly, the final BER at the relays is given by

$$P_F(n)=P\left(|h_{si}(n)|<2\,|h_{ji}(n)|\right)\cdot P_{\mathrm{DFD}}(n) +P\left(|h_{si}(n)|\ge 2\,|h_{ji}(n)|\right)\cdot P_{\mathrm{DD}}(n). \tag{31}$$

The switching rule given by (30) describes a very simple way for the relays to choose the demodulation methods. For other higher order modulations, BER closed forms may not exist, and it is not always possible to find the simplified rules as in (30).

B. Symbol Log Likelihood Ratio (LLR)-Based Switch

While the BER calculation can be too complicated for higher order modulations, alternatively, the relays can choose the demodulation method based on the LLR, which reflects the reliability of the ML detection/demodulation [10].

For a Kth-order modulation, $b_{k,s}(n_m)$ and $b_{k,j}(n_m)$ are the kth bit for the mth source and IRI symbols at packet time n, respectively, where $k=1,\ldots,K$, and $m=1,\ldots,M$. After the relay R_i receives the nth packet, it calculated the LLR for every symbol in the packet. If direct demodulation is applied, the overall LLR to demodulate the mth symbol in the packet is given by

$$\mathcal{L}_{\mathrm{DD}}(n_m)=\sum_{k=1}^{K}|\mathcal{L}_{\mathrm{DD}}(n_m,k)| \tag{32}$$

where $\mathcal{L}_{\mathrm{DD}}(n_m,k)$ is the LLR of the kth bit for $x_s(n_m)$, which is given by

$$\mathcal{L}_{\mathrm{DD}}(n_m,k)=\log\frac{P\left(y_i(n_m)|b_{k,s}(n_m)=1\right)}{P\left(y_i(n_m)|b_{k,s}(n_m)=0\right)}. \tag{33}$$

Similarly, the overall LLR for the differential demodulation of the mth symbol is given by

$$\mathcal{L}_{\mathrm{DFD}}(n_m)=\sum_{k=1}^{K}|\mathcal{L}_{\mathrm{DFD}}(n_m,k)| \tag{34}$$

where $\mathcal{L}_{\mathrm{DFD}}(n_m,k)$ is the LLR to differentially demodulate the kth bit as

$$\mathcal{L}_{\mathrm{DFD}}(n_m,k)=\log\frac{P\left(y_i(n_m)|b_{k,s\oplus j}(n_m)=1\right)}{P\left(y_i(n_m)|b_{k,s\oplus j}(n_m)=0\right)} =\log\frac{P\left(y_i(n_m)|b_{k,s}(n_m)\neq b_{k,j}(n_m)\right)}{P\left(y_i(n_m)|b_{k,s}(n_m)=b_{k,j}(n_m)\right)}. \tag{35}$$

Then, the symbol LLR-based switching rule is obtained as

$$\begin{cases}\text{Direct demodulation,} & \text{if } |\mathcal{L}_{\mathrm{DD}}(n_m)|\ge|\mathcal{L}_{\mathrm{DFD}}(n_m)|\\ \text{Differential demodulation,} & \text{if } |\mathcal{L}_{\mathrm{DD}}(n_m)|<|\mathcal{L}_{\mathrm{DFD}}(n_m)|.\end{cases} \tag{36}$$

Due to the noise effect, even if the channel coefficients remain unchanged within one packet, different symbols may have different LLRs and thus apply different demodulation methods. Therefore, the symbol LLR-based switching rule in (36) needs to be checked for every symbol in the packet. As a result, M bits per packet are required to notify the destination of the demodulation method applied at the relay. This leads to $1/K$ times extra bits forwarded to the destination, which is a large overhead for many systems. On the other hand, since the symbol LLR-based switching rule in (36) is checked for every single symbol, it is more "individually" optimized and performs better than the BER-based switching rule. Therefore, it is regarded as an "ideal" switching rule in this paper.

Alternatively, blind approaches at the destination may be developed to determine whether the direct or differential bits are forwarded from the relays, which is left as an interesting topic for future research.

C. Packet LLR-Based Switch

In a packet-based system, the packet error rate is often used as a performance index, where even if there is only one symbol with detection error, the whole packet is deemed as error. Therefore, we can apply a switching rule to avoid the worst symbol demodulation in a packet. Since the LLR reflects the reliability for different demodulations, the "packet LLR-based" switching rule is described as follows.

1) For every symbol in the nth packet, the relay calculates the LLR for both demodulation methods, which are given by (32) and (34), respectively.
2) For the nth packet, find out the minimum LLR among all symbols with different demodulation methods as

$$\mathcal{L}_{\min}(n) = \min\left\{\mathcal{L}_{\rm DD}(n_m), \mathcal{L}_{\rm DFD}(n_m) | m = 1, \ldots, M\right\}. \quad (37)$$

3) The relay chooses the demodulation method that does not include $\mathcal{L}_{\min}(n)$.

Like the BER-based rule, the packet LLR-based switching rule chooses the same demodulation for all symbols in a packet and so only 1 bit is required to notify the destination. Simulation results show that the packet LLR- and BER-based switching rules have similar performances.

D. Discussion

We have shown three switching rules for the relays to choose the demodulation methods. Both BER- and packet LLR-based switching rules only require one extra bit per packet to notify the destination of the demodulation used at the relays. While the BER-based rule is very easy to implement for simple modulations like BPSK or QPSK, it can be hard to apply with higher order modulations. The packet LLR-based rule, on the other hand, can be applied in any modulation method with similar performance to the BER-based rule.

The symbol LLR-based rule checks the LLR for every symbol in a packet and has the best performance among all switching rules. It however requires M bits per packet to notify the destination of the demodulation method at the relays. This prevents it from implementing in practice unless blind approaches can be developed. The symbol LLR-based rule can be used as a benchmark to compare different switching rules.

We highlight that for all of the three switching rules, no channel state information (CSI) feedback is required. To be specific, the receiving relay only requires the CSI from the source to the relay and that from the other relay to the receiving relay. The destination node requires the CSI from the relays to the destination but not those from the source to the relays.

Finally, it is interesting to point out that the proposed switching strategy between the two demodulation methods is closely related to the planar binning concept introduced in the coarse network coding strategy [11].[1] In the planar binning approach, the received signal at the relay is "encoded" by a scaling lattice code, and the coding structure is optimized by finding the best scaling factor depending on the channel realization. This is actually similar to the idea of choosing the best demodulation method for different channels. The coarse network coding strategy in [11] implies an interesting possible way to generalize the proposed approach in this paper by, for example, considering all possible "binning" patterns, including (but not just) the scaling factor. This further implies that the proposed approach suggests a new way to handle the interference in general network coding scenarios. This will be left as an interesting topic for future investigation.

V. Implementation

A. Synchronization

In the two-path succussive relay system, the synchronization at the relays is important because a relay receives data from both the source and the other relay. At the receiving relay, because the signals from the transmitting relay is treated as interference (i.e., IRI), it is not necessary to require the source and the transmitting relay to be synchronized in transmission. The receiving relay only needs to be synchronized with the signals from the source, i.e., the sampling instants at the relay are tuned to achieve the highest signal-to-noise ratio (SNR) for the source signals. To be specific, in the direct demodulation mode, the symbols from the transmitting relay are not demodulated so they do not need to be synchronized. If the differential demodulation mode is applied at the relay, on the other hand, differential detection is applied at the destination to detect only the source symbols. This implies that the relay needs not to be synchronized with the IRI symbols because it does not affect the SNR to detect the source symbols at the destination at all.

Correspondingly, the channel coefficients $h_{si}(n)$ and $h_{ji}(n)$ in the system model of (1) are actually the combining effects from both the channels[2] and synchronization. The receiving relay needs to know the timing reference of the receiving symbols from the source to estimate $h_{si}(n)$ and $h_{ji}(n)$ and to demodulate receiving symbols.

Therefore, the relays in the two-path relay system with the proposed hybrid DMF scheme have the same requirement in synchronization as the relay in the traditional three-node relay system [12], making it very attractive in practice. This contrasts sharply with the physical layer network coding (PLNC) [13]. In the PLNC approach, the relay receives informative data from two sources, where similar differential demodulation and detection approaches are applied at the relay and destination, respectively. At the relay, because the data from both sources are informative, they must be synchronized, as otherwise, the performance can be greatly degraded.

Finally, we highlight that, since the receiving relay node only needs to be synchronized with the signals from the source, it can tolerate any value of the delay from the transmitting relay (which is regarded as the interference). On the other hand, if we consider the destination node in the overall system, some

[1]We would like to thank a reviewer of this manuscript for pointing out this interesting reference.

[2]The channel effect includes the transmitting filter, channel, and receiving filter.

level of synchronization at packet level should be obtained. Because the destination receives data packets from the two relays alternatively, particular methods such as adding prefix symbols to each packet are necessary to avoid the interpacket interference at the destination. The detail of this issue is beyond the scope of this paper.

B. Hybrid DF-DMF Scheme

In the proposed hybrid DMF scheme for the two-path relaying, the relays switch between direct and differential modes according to channel conditions. Alternatively, differential demodulation can also be applied with the traditional DF scheme. To be specific, as shown in [3], the traditional DF scheme requires the IRI to be either small or large enough to ensure successful decoding. A straightforward way to improve the traditional DF scheme is to switch the relays from the DF mode to the differential DMF mode when none of the decoding for the source and IRI data is successful. It is obvious that the hybrid DF-DMF scheme has better performance than the traditional DF scheme because it can deal with the case that the source and IRI data have similar powers at the relays. The details are left for future research.

VI. Simulation

In this section, we show the BER performance of the hybrid DMF scheme with different switching rules through numerical simulations. For comparison, the performance of the classic DMF scheme that the relays directly demodulate the source data is also shown. To single out the effect from the DMF, no channel coding is used in the simulation.

In the simulations below, the QPSK is used, and all the BER curves are obtained through averaging over 10 000 independent runs, where in each run the number of total packets for transmission is $N = 30$, and each packet contains $M = 128$ QPSK symbols. For fair comparison, the signal powers per information bit are set the same for different approaches. Therefore, for all of the "BER versus SNR" curves in this section, the SNR refers to the ratio of the signal power per information bit to the noise power. Because the BER-based and packet LLR-based switching rules require one more bit per packet to notify the destination, to have the same signal power per information bit, we let

$$\text{SNR (hybrid DMF)} = \frac{MK-1}{MK} \cdot \text{SNR (classic DMF)} \qquad (38)$$

where K is the modulation order, which is 2 for QPSK, and SNR (hybrid DMF) and SNR (classic DMF) are the signal power per bit to noise power ratio for hybrid and classic DMF relaying, respectively. But for the symbol LLR-based switching rule, we ideally assume that a blind approach can be developed where no extra bit is needed to notify the destination, and hence, no rate penalty on the SNR similar to (38) is applied. We particularly note that this is solely for comparison purposes here to show the best potential performance that the hybrid DMF can achieve, where the symbol LLR-based switching rule is used as an ideal performance benchmark for other more "practical" switching rules.

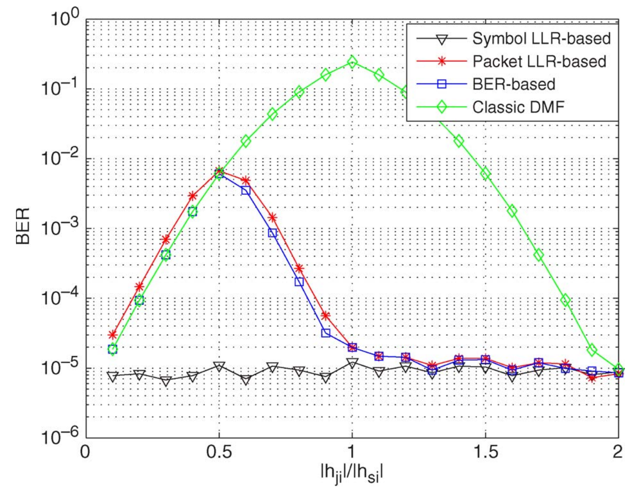

Fig. 5. Static Gaussian channels, where SNR = 10 dB, and $|h_{si}| = 1$.

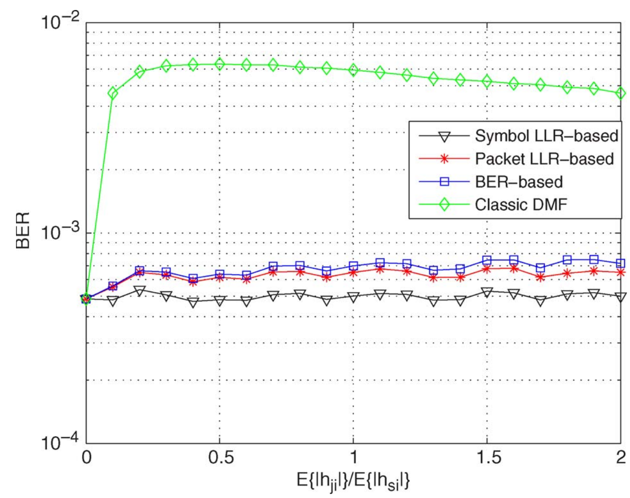

Fig. 6. Fading channels, SNR = 30 dB, and $E[|h_{si}(n)| = 1]$.

First, we consider static channels where all channel coefficients are fixed and where the SNR is also fixed at 10 dB. In particular, we set $|h_{s1}| = |h_{s2}| = |h_{1d}| = |h_{2d}| = 1$, $|h_{12}| = |h_{21}|$, which varies between [0, 2] for different tests. Clearly, the ratio of $|h_{ji}|/|h_{si}|$ reflects the level of the IRI. Fig. 5 shows the BER versus $|h_{ji}|/|h_{si}|$. It is clearly shown that the BER performance for the classic DMF approach is severely limited by the IRI, where, as expected, the worst case occurs when $|h_{ji}|/|h_{si}| = 1$. On the contrary, the hybrid DMF scheme with the "BER-based" switching rule has significantly better performance than the classic DMF. The worst case occurs when $|h_{ji}|/|h_{si}| = 0.5$, which is in fact the "switching" point in the BER-based switching rule. The hybrid DMF with "packet LLR-based" rule performs similarly to the BER-based approach. It is also clear that the hybrid DMF with the "symbol LLR-based" rule has the best performance among all approaches.

Fig. 6 shows the BER versus IRI for flat fading channels. Specifically, all channels are flat Rayleigh fading but remain constant within one packet time, where $E[|h_{s1}(n)|] = E[|h_{s2}(n)|] = E[|h_{1d}(n)|] = E[|h_{2d}(n)|] = 1$ and $E[|h_{12}(n)|] =$

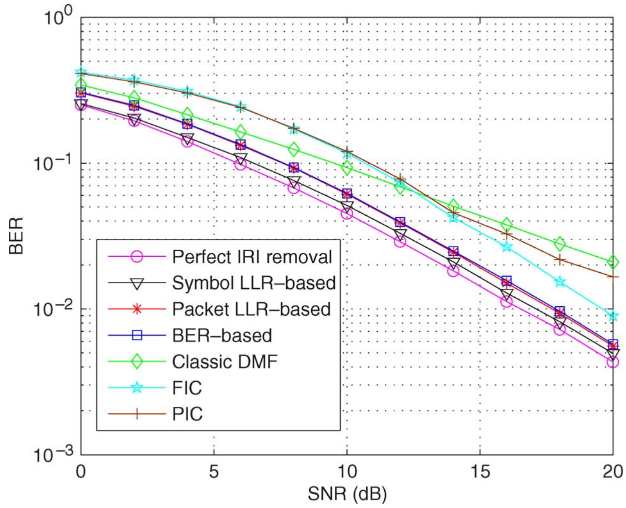

Fig. 7. BER performance: $\mathrm{E}\{|h_{12}(n)|^2\} = 1$.

$\mathrm{E}[|h_{21}(n)|]$, which varies between [0, 2] for different tests, and the SNR is fixed at 30 dB. It is clear that the ratio of $\mathrm{E}[|h_{ji}(n)|]/\mathrm{E}[|h_{si}(n)|]$ reflects the average IRI level. Fig. 6 shows that the hybrid DMF schemes with different switching rules not only have much better performance than the classic DMF scheme but are more robust to IRI variation as well.

It is interesting to observe in Fig. 6 that the worst BER performance of the classic DMF does not occur when $E[|h_{ji}|] = E[|h_{si}|]$. This is because, for different data packets, h_{ji} and h_{si} are different realizations of random Rayleigh processes, while the BER curves are obtained by averaging over 10 000 independent runs with different realizations of channel coefficients.

Fig. 7 shows the BER versus SNR for flat Rayleigh fading channels, where $\mathrm{E}[|h_{12}(n)|] = \mathrm{E}[|h_{21}(n)|] = 1$, and all the other channels have an average gain of 1. For comparison, the results for the AF two-path relay with partial interference cancelation (PIC) [14] and full interference cancelation (FIC) [6] are both shown. It is clearly shown that the hybrid DMF has significantly better performance than the classic DMF, PIC, and FIC approaches. It is interesting to observe that the "BER-based" and "packet LLR-based" approaches have similar BER performances, while the "symbol LLR-based" approach has close performance to the ideal approach, where the IRI is perfectly removed.

For further verification, Figs. 8 and 9 show the BER versus SNR performance for $\mathrm{E}[|h_{ij}|] = 0.1$ and 2, respectively, corresponding to very weak and strong IRIs, respectively, where all the other parameters are the same as those in Fig. 7. It is clear that, even for the very low IRI case with $\mathrm{E}[|h_{ij}|] = 0.1$, the hybrid DMF still performs significantly better than the classic DMF approach. Other results are similar to those in Fig. 7.

VII. Conclusion

This paper has proposed a hybrid DMF scheme for the two-path succussive relay system. Switching between direct and differential demodulations according to different channel conditions, the relays can well handle the IRI, which is the main factor in the two-path relaying. The differential DMF can also be applied with the classic DF approach to improve the performance. The hybrid DMF scheme not only has significant better performance than existing approaches but also is easy to achieve synchronization at the relays, making it an attractive approach in practice.

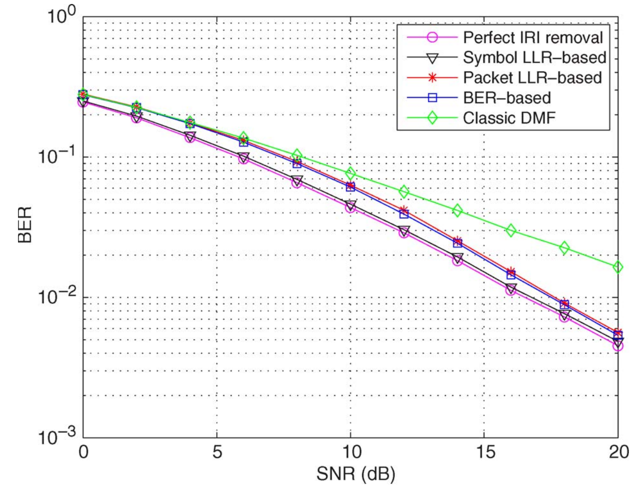

Fig. 8. BER performance: $\mathrm{E}\{|h_{12}(n)|^2\} = 0.1$.

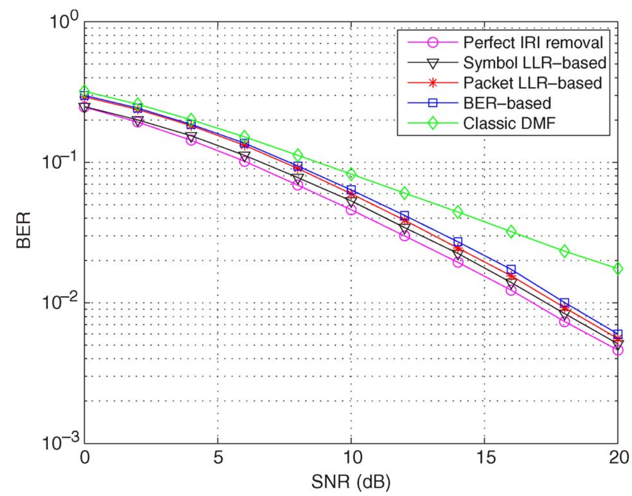

Fig. 9. BER performance: $\mathrm{E}\{|h_{12}(n)|^2\} = 2$.

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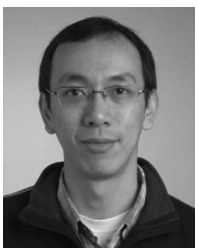

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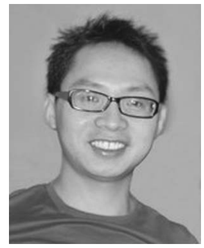

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