Virtual Full-Duplex for Two-Way Relaying in SOQPSK Modulation in Small-Scale Satellite Network Application

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Abstract. In this paper, to achieve high network throughput (NT) in the half-duplex mode, a virtual full-duplex multi-hop two-way relay network is developed (VFD-MH-TWRN) using physical network coding (PNC) and SOQPSK modulation for space exploration application in which do not need instantaneous channel state information. In the proposed VFD-MH-TWRN scheme, two full-duplex source nodes exchange their information with the help of multi half-duplex relay nodes. As the main contribution, at first we define a novel data transmission strategy and then analytically derive the end-to-end bit error rate (BER) and, which are validated by the simulation results. It is shown that network throughput is higher than all of the previously defined networks and the simulation results show that the proposed scheme with SOQPSK modulation is close to DF-TWRN the bit error rate and they have similar performance.

Keywords: Multi-hop two-way relay network · Virtual full-duplex · Physical network coding

1 Introduction

Cooperative communication indicates the elements of a communication system that relay signals from one source to another via relays. Recently, relay-based communication networks have utilized small-scale satellites (SSS) known as pico and femto-satellites [1]. The use of SSS as relay nodes can potentially extend radio coverage, enhance link reliability and channel capacity, facilitate deep space and galaxy exploring and perform scientific measurements. SSS has been researched in the Kicksat project [2], in the Edison Demonstration of Small-sat Networks (EDSN) mission [3] and in Femto-satellites at zeroG (an experimental project in ISS). In addition, SSS can be a starting point for next-generation satellite communication and have provided extraordinary access for data collection [4, 5]. So easily can be defined an idea about cooperative communication application in satellite communications especially SSS considering that communication links have used some relay-based cooperative communication. The performance

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enhancement of the multi-hop network is so critical in this kind of network and also the two-way relay network (TWRN) can improve the data rate of a cooperative system. Half-duplex (HD) TWR via physical-layer network coding (PNC) transmits only two packets in two-time slots bi-directionally, in contrast with conventional HD TWR, which requires four-time slots [6–9]. Therefore, it improves network throughput and spectral efficiency. Additionally, PNC uses De-Noise and Forward (DNF) protocol to double the throughput of TWR related to Decode and Forward (DF) protocol [7, 9]. Therefore, in a relay-based communication network, SSS can be utilized as a relay and can offer a higher degree of freedom, so the relay-based SSS network is suitable for a lower latency communication in deep space. To realize it, a modulation that can provide power efficiency by offering a more significant improvement in bandwidth efficiency should be selected. Meanwhile, shaped offset quadrature PSK (SOQPSK) [10, 11] is a continuous phase and constant amplitude modulation that is compatible with the existing efficient non-linear class C power amplifier. [5]

In this paper, a Virtual Full Duplex Multi-Hop Two-Way Relay Network (VFD-MH-TWRN) with SOQPSK modulation, which does not need instantaneous channel state information is developed to improve network throughput. In Sect. 2 TWRN and MH-TWRN schemes are presented and in Sect. 3, the system model of L-node M-message VFD-MH-TWRN and transmission schemes are described and then analytically derives its throughput. Section 4 formulates Virtual Full-Duplex Denoise-And-Forward TWR (VFD-DNF-TWR) Scheme, and in Sect. 5, the Bit Error Rate (BER) performance of modulation is analyzed. Then, Sect. 6 presents the simulation results of the proposed scheme. Finally our summary is given in Sect. 7.

2 Two-Way Relay Network Concept

A two-way relay network (TWRN) system is shown in Fig. 1.a, in which source nodes A and B (N_A, N_B) are not directly linked together and instead transmit messages through relay node R using the PNC. All nodes are half-duplex (HD) and are equipped with a single antenna and relay utilize in DeNoise–And–Forward protocol. Therefore, they cannot send and receive simultaneously, so then their mode is alternated in each time slot. Data transmission generally consists of two stages: first one is multiple access (MAC) in which A and B data transmit to the relay simultaneously, and the relay detects

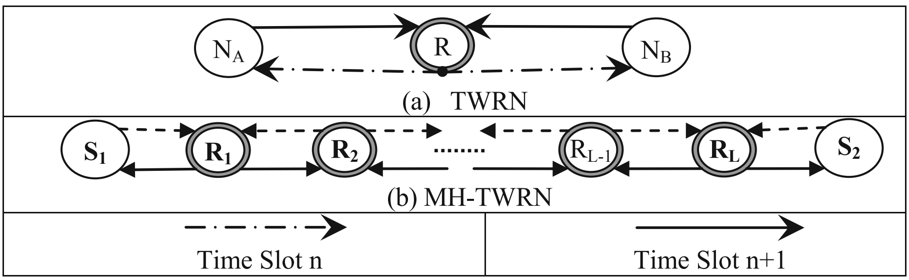

Fig. 1. TWR under PNC and half duplex system.

combined data from superimposed received signal and second one is broadcasting (BC) in which the relay forwards combined data to sources and sources decode new data. The term combined data means when two packet data are XORed with standard PNC. Also MH-TWRN with PNC is shown the in Fig. 1.b in which sources S_i; $i = \{1, 2\}$ are not directly linked together and instead transmit messages through L relay nodes (R_l, $l = 1, \ldots, L$). Indeed it is extended version of TWRN.

3 System Model

3.1 VFD-MH-TWRN Data Transmission Strategy

We assume the VFD-MH-TWRN shown in Fig. 2.a in which sources S_i; $i = \{1, 2\}$ are not directly linked together and instead transmit messages through L relay nodes (R_l, $l = 1, \ldots, L$) using the PNC protocol symmetrically. All relays have HD systems that are equipped with a single antenna, and therefore, they cannot send and receive simultaneously so then their mode is alternated in each time slot. Another side, sources have the FD system that are equipped with a two independent antenna, and therefore, they can send and receive simultaneously because of these properties we can name it to virtual full-duplex multi-hop two-way relay network.

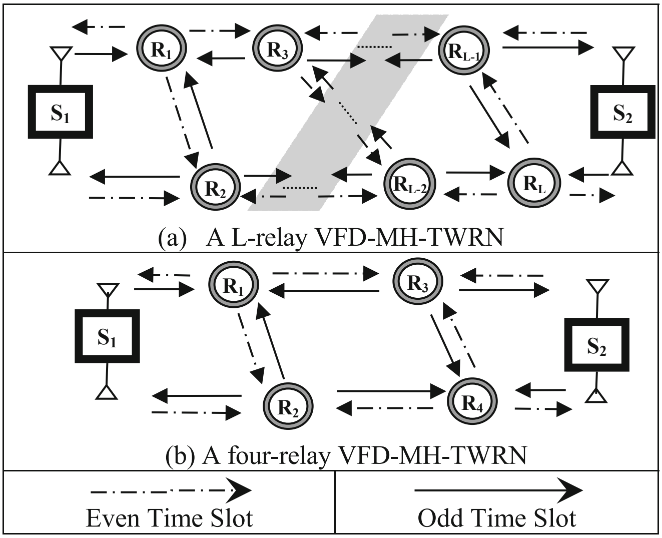

Fig. 2. The schematic of proposed virtual full duplex multi-hop two-way relay network.

Each relay has a limited buffer size that its capacity is equal with only one packet data. Each one of sources can send a packet data in one time slot that transmitted packet by sources S_1 and S_2 in t^{th} time slot, are noted as $P^t_{s_1}$ and $P^t_{s_2}(t = 1, \ldots, N)$, respectively and all of the packets have the same length. Each relay can only receive signals from its adjacent nodes and signals received from the non-neighboring are negligible due to the long distance. It is assumed each relay has a neighbor relay that they are pair as $\{(R_1, R_2), (R_3, R_4) \ldots (R_{L-1}, R_L)\}$ in network so in receive mode, each relay received from its pair and two adjacent nodes from two sides. Each pair relay work as complementary, when one of them is in broadcasting (sender) mode, another one is in receiving mode and vice versa. (Number of relays is an odd number). Sources can only receive signals from one of the relays in adjacent pair (source 1 can receive from R_1 or R_2 also, source 2 can receive from R_{L-1} or R_L) in each time slot, and also it receives self-interference (SI) signal from its antenna transmitter simultaneously. The channel properties stay constant state for a frame or packet duration and vary independently from one frame to another as static fading channel (block fading channel).

As illustrated in Fig. 3, data transmission strategy in relays consists of two modes. In Receiver Mode, relay R_l receive combined data from adjacent relays (R_{l-2} and R_{l+2}) and own pair relay R_{l+1} *if l is odd or* R_{l-1} *if l is* even sor from source and adjacent relay and own pair relay $\{[S_2, R_{l-2}, (R_{L-1}\ or\ R_L)], [S_1, R_{l+2}, (R_2\ or\ R_1)]\}$. In transmitter Mode, relay R_l send its combined data ($P^t_{R_l}$) to source and adjacent relay and own pair relay. But data transmission strategy in sources is just one mode. Sources broadcast $P^t_{S_i}$ to pair adjacent relays and receive combined data from one of pair adjacent relays and its self-interference (SI) data ($P^t_{S_i}$)simultaneously in each time slot.

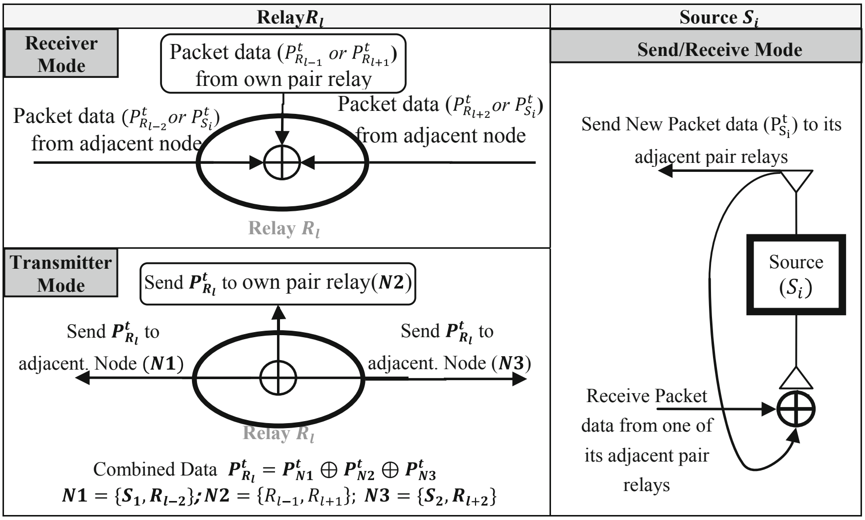

Fig. 3. Illustration of relay and source operations in proposed VFD-MH-TWRN.

In order to simplify and explain all the possible transmission states of VFD-MH-TWRN, a four-relay model is depicted in Fig. 2.b and also a 4-relay 4-message VFD-MH-TWRN is Illustrated in Fig. 4 (where ⊕ is the modulo-2 addition operator). It is obvious, the transmission events at each node are independent of the total number of packets and each relays do not need to extract received data and just need to receive combined data and broadcast it, but sources can decode other source new data by previous received and sent data. (The term combined packet data means when two packet data are XORed with standard PNC) So in case of L-node M-message (packet data) can be easily extended from the same procedure presented in Fig. 4. In generalized VFD-MH-TWRN scheme with L-node M-message that L (the number of relays) is even and the total number of message sequences for exchanging by two sources is symbolized to $2M$, at all, $L/2+1$ time slots are required to transmit the one frame so $L/2+M$ time slots are needed to transmit 2 M frames mutually.

TS	I/O	Source 1	Relay 1	Relay 2	Relay 3	Relay 4	Source2	I/O
1	I:$P_{S_1}^1$	T: $P_{S_1}^1$	R: $P_{S_1}^1$			R: $P_{S_2}^1$	T: $P_{S_2}^1$	I:$P_{S_2}^1$
	-	R: $P_{S_1}^1$					R: $P_{S_2}^1$	-
2	I:$P_{S_1}^2$	T: $P_{S_1}^2$	T: $P_{S_1}^1$	R: $P_{S_1}^1 \oplus P_{S_1}^2 \oplus P_{S_2}^1$	R: $P_{S_2}^1 \oplus P_{S_2}^2 \oplus P_{S_1}^1$	T: $P_{S_2}^1$	T: $P_{S_2}^2$	I:$P_{S_2}^2$
	-	R: $P_{S_1}^2 \oplus P_{S_1}^1$					R: $P_{S_2}^2 \oplus P_{S_2}^2$	-
3	I:$P_{S_1}^3$	T: $P_{S_1}^3$	R: $P_{S_1}^3 \oplus P_{S_1}^2 \oplus P_{S_2}^2$	T: $P_{S_1}^1 \oplus P_{S_1}^2 \oplus P_{S_2}^1$	T: $P_{S_2}^1 \oplus P_{S_2}^2 \oplus P_{S_1}^1$	R: $P_{S_2}^3 \oplus P_{S_1}^2 \oplus P_{S_2}^2$	T: $P_{S_2}^3$	I:$P_{S_2}^3$
	O:$P_{S_2}^1$	R: $P_{S_1}^3 \oplus P_{S_1}^1 \oplus P_{S_1}^2 \oplus P_{S_2}^1$					R: $P_{S_2}^3 \oplus P_{S_2}^1 \oplus P_{S_2}^2 \oplus P_{S_1}^1$	O:$P_{S_1}^1$
4	I:$P_{S_1}^4$	T: $P_{S_1}^4$	T: $P_{S_1}^3 \oplus P_{S_1}^2 \oplus P_{S_2}^2$	R: $P_{S_1}^3 \oplus P_{S_2}^3 \oplus P_{S_1}^4$	R: $P_{S_1}^3 \oplus P_{S_2}^3 \oplus P_{S_2}^4$	T: $P_{S_2}^3 \oplus P_{S_1}^2 \oplus P_{S_2}^2$	T: $P_{S_2}^4$	I:$P_{S_2}^4$
	O:$P_{S_2}^2$	R: $P_{S_1}^4 \oplus P_{S_1}^3 \oplus P_{S_1}^2 \oplus P_{S_2}^2$					R: $P_{S_2}^4 \oplus P_{S_2}^3 \oplus P_{S_1}^2 \oplus P_{S_2}^2$	O:$P_{S_1}^2$
5	-	T:∅	R: $P_{S_1}^4 \oplus P_{S_2}^4$	T: $P_{S_1}^3 \oplus P_{S_2}^3 \oplus P_{S_1}^4$	T: $P_{S_1}^3 \oplus P_{S_2}^3 \oplus P_{S_2}^4$	R: $P_{S_1}^4 \oplus P_{S_2}^4$	T:∅	-
	O:$P_{S_2}^3$	R: $P_{S_1}^3 \oplus P_{S_2}^3 \oplus P_{S_1}^4$					R: $P_{S_1}^3 \oplus P_{S_2}^3 \oplus P_{S_2}^4$	O:$P_{S_1}^3$
6	-	T:∅	T: $P_{S_1}^4 \oplus P_{S_2}^4$	R:∅	R: ∅	T: $P_{S_1}^4 \oplus P_{S_2}^4$	T:∅	-
	O:$P_{S_2}^4$	R: $P_{S_1}^4 \oplus P_{S_2}^4$					R: $P_{S_1}^4 \oplus P_{S_2}^4$	O:$P_{S_1}^4$

Fig. 4. A transmission states illustration of 4-Relay 4-message VFD-MH-TWRN.

Then Network Throughput is equal with $\frac{2M}{L/2+M}$ and when the number of messages (M) is much larger than the number of relays (L), it can be achieved an upper limit of the network throughput which is:

$$\lim_{M \gg L} \frac{2M}{L/2+M} \cong 2; \quad if\ L = 2k,\ k \in \mathbb{N} \tag{1}$$

3.2 SOQPSK Signal Model

It is known that the complex envelope of SOQPSK is defined as follows:

$$s(t;\alpha) = \sqrt{\frac{E_s}{T_s}} exp\left\{ j \sum_i \alpha_i q(t - iT_s) \right\} \tag{2}$$

Where the energy and time duration of symbol are denoted by E_s, T_s respectively and $i \in \mathbb{Z}$ is the discrete-time index and $\boldsymbol{\alpha} = \{\boldsymbol{\alpha}_i\}$ is the transmitted ternary symbol sequence where each symbol has duration T_s where α_i consist of alphabet i.e. (−1, 0, +1) that α_i is come from the true input binary data sequence (b) the b_i take on $\{1, -1\}$ values as follows [11]:

$$\boldsymbol{\alpha}_i = (-1)^{i+1}\frac{b_{i-1}(b_i - b_{i-2})}{2}; \quad (b_i)_{i\in\mathbb{Z}} \in \{1, -1\} \tag{3}$$

And also the phase modulation $\phi(t, \alpha)$ can be expressed as

$$\phi(t,\alpha) = 2\pi h \sum_i \boldsymbol{\alpha}_i q(t - iT_s) \tag{4}$$

That $h = 1/2$ is the modulation index. It is assumed that the signal $s(t;\alpha)$ is full-response [12]. In the appendix 1 is depicted role of previous bits in phase variation in SOQPSK modulation and also is shown phase variation range for the new symbol $\left(\Delta\theta_i \in \left\{\frac{m\pi}{2}, m = 0, 1, -1\right\}\right)$. So we can infer the following the mapping and approximation for phase variation.

$$\begin{gathered}\theta_{i+1} = \Delta\theta_i(t) + \theta_i \\ \theta_i \in \left\{\tfrac{m\pi}{4}, m = 1,3,5,7\right\};\ iT_b \le t \le (i+1)T_b\end{gathered} \tag{5}$$

4 A Virtual Full-Duplex Denoise-and-Forward TWR Scheme

As shown in Fig. 2.a, this network consists of two sources and four relays so be defined channels as $S_1 \leftrightharpoons R_1, S_1 \leftrightharpoons R_2, R_1 \leftrightharpoons R_2, R_1 \leftrightharpoons R_3, R_2 \leftrightharpoons R_4, R_3 \leftrightharpoons R_4, S_2 \leftrightharpoons R_3$, $S_2 \leftrightharpoons R_4$, and the RSI channels $S_1 \leftrightharpoons S_1$ and $S_2 \leftrightharpoons S_2$ that their corresponding channels coefficients denoted by

$$h_{S_1R_1},\ h_{R_1S_1},\ h_{S_1R_2},\ h_{R_2S_1},\ h_{R_1R_2},\ h_{R_2R_1},\ h_{R_1R_3},\ h_{R_3R_1},\ h_{R_2R_4},\ h_{R_4R_2},\ h_{R_3R_4}$$
$$h_{R_4R_3},\ h_{S_2R_3},\ h_{R_3S_2},\ h_{S_2R_4},\ h_{R_4S_2}$$

All the channel properties and coefficients stay static during one time slot (t), but change from one time slot to another one independently. We suppose the channels between two nodes and the RSI channels are under Rayleigh fading and suppose instantaneous CSI is unknown at any node but long-term (statistics) CSI is known i.e. as $h^t_{S_iR_j} \sim \mathcal{CN}\left(0, \sigma^2_{S_iR_j}\right)$, $i = 1, 2$ and $j = 1, 2, 3, 4$ where $\sigma^2_{S_iR_j}$ denotes the variance as corresponding channel gain in time slot t. The additive white Gaussian noise (AWGN) at each node is indicated by $Z^t_{Si}(n) \sim \mathcal{CN}\left(0, \sigma^2_{S_i}\right) Z^t_{Ri}(n) \sim \mathcal{CN}\left(0, \sigma^2_{R_i}\right)$.

In the odd time slot (t = *2 k-1, k* $\in \mathbb{N}$), sources S_1, S_2 transmit their n^{th} packet symbols to R_1, R_4 respectively and R_2 forwards to R_1, S_1 and R_3 forwards to R_4, S_2 the received symbols in the last time slot. So the received signals at S_1, S_2, R_1, R_4 in t^{th} timeslot can be expressed as

$$y^t_{S1}(n) = \sqrt{E_{R2}}h^t_{R_2S_1}R^t_2(n) + \sqrt{E_{S1}}h^t_{S_1S_1}S^t_1(n) + Z^t_{S1}(n) \tag{6}$$

$$y_{S2}^{t}(n) = \sqrt{E_{R3}} h_{R_3S_2}^{t} R_3^t(n) + \sqrt{E_{S2}} h_{S_2S_2}^{t} S_2^t(n) + Z_{S2}^t(n) \quad (7)$$

$$y_{R1}^{t}(n) = \sqrt{E_{S1}} h_{S_1R_1}^{t} S_1^t(n) + \sqrt{E_{R2}} h_{R_2R_1}^{t} R_2^t(n) + \sqrt{E_{R3}} h_{R_3R_1}^{t} R_3^t(n) + Z_{R1}^t(n) \quad (8)$$

$$y_{R4}^{t}(n) = \sqrt{E_{S2}} h_{S_2R_4}^{t} S_2^t(n) + \sqrt{E_{R3}} h_{R_3R_4}^{t} R_3^t(n) + \sqrt{E_{R2}} h_{R_2R_4}^{t} R_2^t(n) + Z_{R4}^t(n) \quad (9)$$

In the even time slot, sources S_1, S_2 transmits their n^{th} packet symbols to R_2, R_3 respectively and R_1 forwards to R_2, S_1 and R_4 forwards to R_3, S_2 the received signal in the last time slot. So the received signals at S_1, S_2, R_2, R_3 can be written as

$$y_{S1}^{t+1}(n) = \sqrt{E_{R1}} h_{R_1S_1}^{t+1} R_1^t(n) + \sqrt{E_{S1}} h_{S_1S_1}^{t+1} S_1^t(n) + Z_{S1}^{t+1}(n) \quad (10)$$

$$y_{S2}^{t+1}(n) = \sqrt{E_{R4}} h_{R_4S_2}^{t+1} R_3^{t+1}(n) + \sqrt{E_{S2}} h_{S_2S_2}^{t+1} S_2^{t+1}(n) + Z_{S2}^{t+1}(n) \quad (11)$$

$$y_{R2}^{t+1}(n) = \sqrt{E_{S1}} h_{S_1R_2}^{t+1} S_1^{t+1}(n) + \sqrt{E_{R1}} h_{R_1R_2}^{t+1} R_1^{t+1}(n) + \sqrt{E_{R4}} h_{R_4R_2}^{t+1} R_4^{t+1}(n) + Z_{R2}^{t+1}(n) \quad (12)$$

$$y_{R4}^{t+1}(n) = \sqrt{E_{S2}} h_{S_2R_3}^{t} S_2^t(n) + \sqrt{E_{R4}} h_{R_4R_3}^{t} R_4^t(n) + \sqrt{E_{R2}} h_{R_2R_3}^{t} R_2^t(n) + Z_{R4}^t(n) \quad (13)$$

It should mention here, in the t^{th} time slot, source S_i transmit K-bit symbol $b_{si}^t(n) = \left\{b_{si,K}^t(n)\right\}$ where K index denotes bit index in one symbol and n denote the symbol index in one frame. There are M frames to be transmitted at each source node, so L/2 + M time slots are needed to transmit 2M frames mutually. Sources generate SOQPSK signals $S_i^t(n)$ base on $e^{j\theta_i(n)}$ where $\theta_i(n) \in \{\frac{m\pi}{4}, m = 1, 3, 5, 7\}$. As mentioned in the previous section, it can be changed to $\pm\frac{\pi}{2}$ *or* 0 related to the previous one so $\Delta\theta_i$ can be shown as $\Delta\theta_i(n) \in \left\{\frac{m\pi}{2}, m = 0, 1, -1\right\}$ so $\theta_i^t(n+1) = \Delta\theta_i(n) + \theta_i^t(n)$. Now we want to define two vectors, at first a vector of two successive received signals at the node *as* $Y = \left[y(n+1)\ y(n)\right]^T$ is defined [13, 14] and the second one is a vector of combined received data at node as $b(n) = b_\alpha(n) \oplus b_\beta(n)$ that α, β denote adjust transmitter nodes. And the mapping from $b_i(n)$ to $\theta_i(n)$ is described by appendix. For simplicity, it is defined these conditions for decoding relay R_1, which these results can be extended to other nodes easily.

$$\mathbb{Y}_{R1}^t(n) = \left[y_{R1}^t(n+1)\ y_{R1}^t(n)\right]^T \quad (14)$$

$$b_{R1}^t(n) = b_{S1}^t(n) \oplus b_{R2}^t(n) \oplus b_{R3}^t(n) \quad (15)$$

So we can rewrite (14) for R_1 as

$$\mathbb{Y}_{R1}^t(n) = \sqrt{E_{S1}} h_{S_1R_1}^{t} \mathbb{S}_1^t(n) + \sqrt{E_{R2}} h_{R_2R_1}^{t} \mathbb{R}_2^t(n) + \sqrt{E_{R3}} h_{R_3R_1}^{t} \mathbb{R}_3^t(n) + \mathbb{Z}_{R1}^t(n) \quad (16)$$

According to the above definition, the related vectors are expressed as $\mathbb{S}_i^t(n) = \left[S_i^t(n+1)\ S_i^t(n)\right]^T$ (i = 1,2) and $\mathbb{R}_2^t(n) = \left[R_j^t(n+1)\ R_j^t(n)\right]^T$ (j = 1,2,3,4) and

$\mathbb{Z}^t_{Xi}(n) = \left[Z^{t+1}_{Xi}(n+1)\ Z^{t+1}_{Xi}(n)\right]^T$ ($\mathrm{X_i = S_i, R_j}$) so the covariance matrix (COV(.) is covariance operator) at receiver base on $\mathbb{Y}$ can be calculated as (17) For given $\Delta\theta_{s1}$, $\Delta\theta_{R2}$, $\Delta\theta_{R3}$ that $\mathbb{E}(.)$ is expected value operator.

$$\begin{aligned} COV\left(\mathbb{Y}^t_{R1}(n)\right) &= \mathbb{E}\left(\mathbb{Y}^t_{R1}(n).\mathbb{Y}^t_{R1}(n)^T\right) \\ &= \mathbb{E}\begin{pmatrix} y^t_{R1}(n+1)^2 & y^t_{R1}(n+1).y^t_{R1}(n)^T \\ y^t_{R1}(n).y^t_{R1}(n+1)^T & y^t_{R1}(n)^2 \end{pmatrix} \\ &= \begin{pmatrix} \mathbb{E}(\mathrm{y^t_{R1}(n+1)^2}) & \mathbb{E}(\mathrm{y^t_{R1}(n+1).y^t_{R1}(n)^T}) \\ \mathbb{E}(\mathrm{y^t_{R1}(n).y^t_{R1}(n+1)^T}) & \mathbb{E}(\mathrm{y^t_{R1}(n)^2}) \end{pmatrix} \end{aligned} \tag{17}$$

$$\begin{aligned} \mathbb{E}(y^t_{R1}(n)^2) &= \mathbb{E}(y^t_{R1}(n+1)^2 \\ &= E_{S1}\sigma^2_{S_1R_1} + E_{R2}\sigma^2_{R_2R_1} + E_{R3}\sigma^2_{R_3R_1} + \sigma^2_{R_1} \end{aligned} \tag{18}$$

$$\begin{aligned} \mathbb{E}\left(y^t_{R1}(n+1).y^t_{R1}(n)^T\right) &= E_{S1}\sigma^2_{S_1R_1}e^{j\Delta\theta_{s1}(n)} \\ &+ E_{R2}\sigma^2_{R_2R_1}e^{j\Delta\theta_{R2}(n)} + E_{R3}\sigma^2_{R_3R_1}e^{j\Delta\theta_{R3}(n)} \end{aligned} \tag{19}$$

$$\begin{aligned} \mathbb{E}(y^t_{R1}(n).y^t_{R1}(n+1)^T) &= E_{S1}\sigma^2_{S_1R_1}e^{-j\Delta\theta_{s1}(n)} \\ &+ E_{R2}\sigma^2_{R_2R_1}e^{-j\Delta\theta_{R2}(n)} + E_{R3}\sigma^2_{R_3R_1}e^{-j\Delta\theta_{R3}(n)} \end{aligned} \tag{20}$$

If it is assumed $b^t_{R1temp}(n) = b^t_{S1}(n) \oplus b^t_{R2}(n) \oplus b^t_{R3}(n) \approx \Delta\theta(n)$ where $\Delta\theta(n) \in \left\{\frac{m\pi}{4}, m = 1, 3, 5, 7\right\}$, so at relay R1, result of $b^t_{R1}(n)$ decoding is presented as $\widehat{b^t_{R1}(n)} \approx \Delta\theta_{R1}(n)$ then according to the above equation, base on the de-noising (mapping) function using ML principle which it was mentioned in [15], that relay 1 can use of $\widehat{b^t_{R1}(n)}$ to decode superimposed symbols as is shown in Fig. 4.

$$\widehat{b^t_{R1}(n)} = arg \max_{b^t_{R1}(n)=b^t_{S1}(n)\oplus b^t_{R2}(n)\oplus b^t_{R3}(n)} f(\mathbb{Y}^t_{R1}(n)|b^t_{R1temp}(n)) \tag{21}$$

Where $f(\mathbb{Y}|b)$ denotes the conditional probability density function (PDF) of $\mathbb{Y}$ when b is given. Then the conditional probability density function (PDF) of $\mathbb{Y}^t_{R1}(n)$ can be calculated as (22) and (23) when $\theta_{s1}(n)$, $\theta_{R2}(n)$ and $\theta_{R3}(n)$, are given according to total probability theorem.

$$f\left(\mathbb{Y}^t_{R1}(n)|b^t_{R1}(n)\right) = \frac{1}{4}\sum_{b^t_{R1}(n)=b^t_{S1}(n)\oplus b^t_{R2}(n)\oplus b^t_{R3}} f\left(\mathbb{Y}^t_{R1}(n)|b^t_{S1}(n), b^t_{R3}(n), b^t_{R2}(n)\right) \tag{22}$$

$$f\left(\mathbb{Y}^t_{R1}(n)|b^t_{S1}(n), b^t_{R3}(n), b^t_{R2}(n)\right) = \frac{1}{\pi^2\left|COV\left(\mathbb{Y}^t_{R1}(n)\right)\right|}e^{-\mathbb{Y}^t_{R1}(n)^T COV\left(\mathbb{Y}^t_{R1}(n)\right)^{-1}\mathbb{Y}^t_{R1}(n)} \tag{23}$$

5 Performance Analysis

In this section, we use symbol error rate (SER) to performance analysis under the DNF-TWR scheme. Then base on total probability theorem, and mapping signal to its phase (it is mentioned above) so the PDF of $\mathbb{Y}^t_{R1}(n)$ conditioned on $\Delta\theta_{R1}(n)$ is presented with (24).

$$\begin{aligned}
&f(\mathbb{Y}^t_{R1}(n)|\Delta\theta_{R1}(n)=\pi/4)=\\
&1/4\{f\left[\mathbb{Y}^t_{R1}(n), COV_{\pi/4,\pi/4,7\pi/4}\left(\mathbb{Y}^t_{R1}\right)\right]+\\
&f\left[\mathbb{Y}^t_{R1}(n), COV_{\pi/4,7\pi/4,\pi/4}\left(\mathbb{Y}^t_{R1}\right)\right]f\left[\mathbb{Y}^t_{R1}(n), COV_{7\pi/4,\pi/4,\pi/4}\left(\mathbb{Y}^t_{R1}\right)\right]\\
&f\left[\mathbb{Y}^t_{R1}(n), COV_{3\pi/4,7\pi/4,7\pi/4}\left(\mathbb{Y}^t_{R1}\right)\right]+f\left[\mathbb{Y}^t_{R1}(n), COV_{7\pi/4,7\pi/4,3\pi/4}\left(\mathbb{Y}^t_{R1}\right)\right]+\\
&f\left[\mathbb{Y}^t_{R1}(n), COV_{7\pi/4,3\pi/4,7\pi/4}\left(\mathbb{Y}^t_{R1}\right)\right]+\left[\mathbb{Y}^t_{R1}(n), COV_{5\pi/4,5\pi/4,7\pi/4}\left(\mathbb{Y}^t_{R1}\right)\right]+\\
&f\left[\mathbb{Y}^t_{R1}(n), COV_{5\pi/4,7\pi/4,5\pi/4}\left(\mathbb{Y}^t_{R1}\right)\right]+f\left[\mathbb{Y}^t_{R1}(n), COV_{7\pi/4,5\pi/4,5\pi/4}\left(\mathbb{Y}^t_{R1}\right)\right]+\\
&\left[\mathbb{Y}^t_{R1}(n), COV_{5\pi/4,3\pi/4,\pi/4}\left(\mathbb{Y}^t_{R1}\right)\right]+f\left[\mathbb{Y}^t_{R1}(n), COV_{5\pi/4,\pi/4,3\pi/4}\left(\mathbb{Y}^t_{R1}\right)\right]+\\
&f\left[\mathbb{Y}^t_{R1}(n), COV_{3\pi/4,5\pi/4,\pi/4}\left(\mathbb{Y}^t_{R1}\right)\right]+\left[\mathbb{Y}^t_{R1}(n), COV_{3\pi/4,\pi/4,5\pi/4}\left(\mathbb{Y}^t_{R1}\right)\right]+\\
&f\left[\mathbb{Y}^t_{R1}(n), COV_{\pi/4,5\pi/4,3\pi/4}\left(\mathbb{Y}^t_{R1}\right)\right]+f\left[\mathbb{Y}^t_{R1}(n), COV_{\pi/4,3\pi/4,5\pi/4}\left(\mathbb{Y}^t_{R1}\right)\right]+\\
&f\left[\mathbb{Y}^t_{R1}(n), COV_{3\pi/4,3\pi/4,3\pi/4}\left(\mathbb{Y}^t_{R1}\right)\right]\}
\end{aligned} \tag{24}$$

That $COV_{\theta_{S1},\theta_{R2},\theta_{R3}}\left(\mathbb{Y}^t_{R1}(n)\right)$ is covariance matrix of $\mathbb{Y}^t_{R1}(n)$ conditioned by $b^t_{S1}(n), b^t_{R2}(n)$ and $b^t_{R3}(n)$ when they are mapped to $\theta_{S1}(n), \theta_{R2}(n)$ and $\theta_{R3}(n)$, and it can be rewritten for another state of $\Delta\theta_{R1}(n)$: $f(\mathbb{Y}^t_{R1}(n)|\Delta\theta_{R1}(n) = 3\pi/4)$, $f(\mathbb{Y}^t_{R1}(n)|\Delta\theta_{R1}(n) = 5\pi/4)$ and $f(\mathbb{Y}^t_{R1}(n)|\Delta\theta_{R1}(n) = 7\pi/4)$. Now we can define SER base on phase as

$$\begin{aligned}
P_{SER\pi/4,R1} &= P(\Delta\theta_{R1}(n) \neq \pi/4|\Delta\theta(n) = \pi/4)\\
P_{SER3\pi/4,R1} &= P(\Delta\theta_{R1}(n) \neq 3\pi/4|\Delta\theta(n) = 3\pi/4)\\
P_{SER5\pi/4,R1} &= P(\Delta\theta_{R1}(n) \neq 5\pi/4|\Delta\theta(n) = 5\pi/4)\\
P_{SER7\pi/4,R1} &= P(\Delta\theta_{R1}(n) \neq 7\pi/4|\Delta\theta(n) = 7\pi/4)
\end{aligned} \tag{25}$$

So finally SER in the relay 1 is presented in (26).

$$\begin{aligned}
&P\left(\widehat{b^t_{R1}(n)} \neq b^t_{R1temp}(n)\right)\\
&\qquad = 1/4\left\{P_{SER\pi/4,R1} + P_{SER3\pi/4,R1} + P_{SER5\pi/4,R1} + P_{SER7\pi/4,R1}\right\}
\end{aligned} \tag{26}$$

Considering that this structure embraces all of structured named virtual full duplex two-way relay network Fig. 2.a so it easily can develop this method to use for all nodes in the network (including relays and sources) in this structure.

6 Simulation and Results

Finally, we simulate the proposed scheme and show simulation results. In the simulation, it is assumed $E_{S1} = E_{S2} = E_{R1} = E_{R2} = E_{R3} = E_{R4} = E$ and all of the channel variances are equal with σ^2. It is assumed Rayleigh fading channel, AWGN and always relay node located on the middle of line connecting two sender node or center of three sender node. BER means the error probability of decoding at sources and system SNR refers to $\gamma = \frac{E}{2\sigma^2}$.

In Fig. 5, we compare the simulated BER of DF-TWRN with DQPSK and DNF-TWRN with SOQPSK modulation. It can be observed that the BER performance of with DNF-TWR is closed to that of DF, and BER becomes smaller with the increase of SNR. The simulation results show that the BER performance of DF-TWRN scheme and DNF-TWRN scheme are similar while Network Throughput has increased.

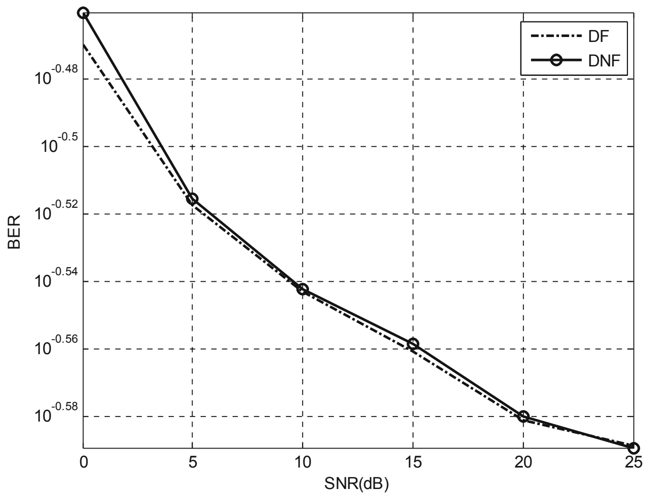

Fig. 5. BER of DF-TWR and DNF-TWR with SOQPSK modulation.

7 Summary

In this paper has proposed a virtual full-duplex de-noise and forward two-way relaying (VFD-DNF-TWRN) scheme with SOQPSK modulation, which does not need instantaneous channel state information (CSI). In the proposed scheme, two full-duplex source nodes exchange their information with the help of multi half-duplex relay node. It has shown that network throughput is higher than all of the previously defined networks and the simulation results show that the proposed scheme with SOQPSK modulation can is close to DF-TWRN the bit error rate and they have similar performance.

Appendix

See Table 1.

Table 1. Relation previous bits and symbol phase variation for SOQPSK

a_i	i	$(-1)^{i+1}$	*I* a_{i-2}	*Q* a_{i-1}	*I* a_{i-1}	*Q* a_{i-2}	*i-1th phase state.*	a_i	*I Q New*	*ith phase state*	α	*Ph.diff (i,i-1)*
I	even	−1	00				π/4	0	00	π/4	0	0
I	even	−1	00				π/4	1	10	3π/4	1	π/2
Q	odd	1			00		π/4	0	00	π/4	0	0
Q	odd	1			00		π/4	1	01	7π/4	−1	−π/2
I	even	−1	01				7π/4	0	01	7π/4	0	0
I	even	−1	01				7π/4	1	11	5π/4	−1	−π/2
Q	odd	1			01		7π/4	1	01	7π/4	0	0
Q	odd	1			01		7π/4	0	00	π/4	1	π/2
I	even	−1	10				3π/4	1	10	3π/4	0	0
I	even	−1	10				3π/4	0	00	π/4	−1	−π/2
Aa	odd	1			10		3π/4	0	10	3π/4	0	0
Q	odd	1			10		3π/4	1	11	5π/4	1	π/2
I	even	−1	11				5π/4	1	11	5π/4	0	0
I	even	−1	11				5π/4	0	01	7π/4	1	π/2
Q	odd	1			11		5π/4	1	11	5π/4	0	0
Q	odd	1			11		5π/4	0	10	3π/4	−1	−π/2

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