Physical Layer Network Coding with Channel and Delay Estimation

Yixin Li and Fu-Chun Zheng
School of Systems Engineering
The University of Reading, Reading, RG6 6AY, UK
E-mail: {yixin.li@pgr.reading.ac.uk}

***Abstract*—Decode-and-forward physical layer network coding (PLNC) is one of the promising high-performance techniques for wireless relay networks, but little has been reported on the case of asynchronous scenarios. This paper presents a channel and delay estimation algorithm along with a detection scheme for Two-Way-Relay-Network (TWRN) in Rayleigh block fading channels. Prefix and suffix training sequences are added for frame-based synchronization and channel estimation. The Cramer-Rao Bound (CRB) is given, and simulations show that the mean square error(MSE) of channel estimation of the proposed scheme could reach the CRB. The end-to-end BER performance is also shown in simulation.**

Key words: TWRN, PNC, delay, channel estimation, Rayleigh block-flat-fading channel, decode-and-forward.

I. Introduction

Two way relay networks (TWRNs) have recently attracted much attention. In these networks, relay nodes collaborate with each other to establish a communication link between two terminals. Two way channels were first studied by Shannon in his early work [1], which did not assume any use of relays. When the direct communication link between two nodes is poor, a two way relaying scheme could be applied for reliable transmission. Different relaying schemes have been presented in the literature where the relays perform different operations on the received signal before retransmitting it. It was pointed out that by applying physical layer network coding (PLNC) [2], where decode-and-forward (DF) scheme is used, or analog network coding (ANC) [3], where amplify-and-forward (AF) scheme is used, the traditional collision at the relay caused by the simultaneous transmission from source terminals can be utilized via a network coding manner to enhance the capacity and throughput.

In ANC, each relay simply amplifies and retransmits the received superimposed signals. Thus the complexity at relay is low but the performance is affected by the amplification of noise. In PLNC, the relay first decodes or denoises the received signal and transmits the network coded data to the users. Most previous works [2]–[7] assume perfect synchronization (i.e. simultaneous arrival of signals) and channel state information (CSI) at the relay and user terminals. However in practice, perfect synchronization is not always the case, and CSI estimation in TWRN is a significant issue. In AF-based TWRN, only user terminals need to estimate the CSI for two links [8], [9]. In DF-based TWRN, it is important for both relay and user terminals to estimate the delay and channel responses. Unfortunately, little has been reported on this issue.

The delay and channel estimation at the relay node for DF-based TWRNs is similar to the estimation at the destination node of asynchronous one-way cooperative relay networks, but existing methods could not be directly applied. When OFDM is employed to combat asynchronous errors, the symbol offset in time domain is transformed to a phase shift as long as it is within the cyclic prefix [10]. But, OFDM-PLNC TWRNs is very sensitive to carrier frequency offset (CFO). Unlike the point-to-point system, CFO in OFDM-PLNC system cannot be fully compensated at relay, which can lead to significant performance degradation [11]. For the non-OFDM systems, when the symbol offset is more than one symbol, PLNC operation will have to be divided into two parts: the non-overlapping parts and the overlapping part. Normal PLNC scheme could be applied for the data-overlapping part and two non-data overlapping parts. However the XOR result is no longer the perfect aligned data from two users. User terminals could not directly recover the data without the information of the relative delay at the relay. Thus it is necessary to study this scenario.

In this paper, we address the above issue and study the delay and channel estimation for DF-based TWRNs. Inspired by [12] (which was for asynchronous one-way cooperative networks), training sequences are added as prefix and suffix for the purpose of estimation. At relay nodes, delay and CSI are first estimated, followed by the PLNC. We improved the delay estimation with the help of a coefficient corresponding to the window size. The mapped misaligned signal is broadcast to the user terminals in the second time slot. At user terminals, delay and CSI are estimated, followed by self data removal and decoding. The mean square error(MSE) of the channel estimations is compared with the corresponding Cramer-Rao bound (CRB). We show that the proposed scheme could reach the CRB at high SNR. The end-to-end BER performance for the proposed scheme is also presented.

Notations: Superscripts $(.)^T$,$(.)^*$,$(.)^H$ represent matrix transpose, complex conjugate, and Hermitian, respectively. **E(.)** is the mathematical expectation. $tr(\mathbf{A})$ is the trace of matrix $(\mathbf{A})$. $|x|$ is the absolute value of scalar x, and $||\mathbf{x}||$ is the norm of the vector **x**. Ω denotes the modulation constellations.

This work is supported by the UK Engineering and Physical Science Research Council (EPSRC) under Grant EP/H016945/1.

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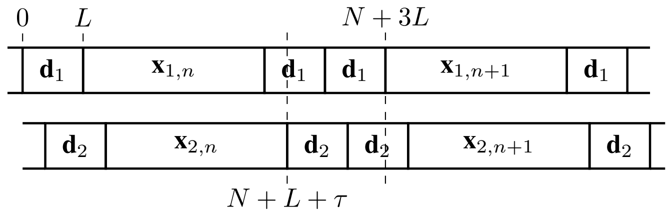

Fig. 1. Data Structure: two consecutive data blocks

II. SYSTEM MODEL

The system considered has two user terminals exchanging their data with the help of a relay node. Each node is equipped with a single antenna which works in half-duplex mode. Each link of the system is considered as a point-to-point link, and the channels are assumed to be Rayleigh block-flat-fading channels. BPSK modulation is applied.

Let $\mathbf{x}_{i,n} = [x_{i,n}(1), ..., x_{i,n}(N)]$, with length N, denote the n-th data block transmitted by user i. In order to estimate the CSI, two Zadoff-Chu sequences† [13], $\mathbf{d}_1 = \mathbf{z}_{\mu 1}$ and $\mathbf{d}_2 = \mathbf{z}_{\mu 2}$, each with length L are added as the prefix and suffix of data block, where $z_\mu(k) = \exp(-j\frac{\pi\mu k(k-1)}{L})$ for $k = 1, .., L$. Then we obtain two vectors $\mathbf{s}_{1,n}$ and $\mathbf{s}_{2,n}$ with the length of $(N + 2L)$, where

$$\mathbf{s}_{1,n} = \begin{bmatrix}\mathbf{d}_1 & \mathbf{x}_{1,n} & \mathbf{d}_1\end{bmatrix} \quad \text{, and} \tag{1}$$

$$\mathbf{s}_{2,n} = \begin{bmatrix}\mathbf{d}_2 & \mathbf{x}_{2,n} & \mathbf{d}_2\end{bmatrix} \quad . \tag{2}$$

Consider two consecutive data blocks, $\boldsymbol{\alpha}_1$ and $\boldsymbol{\alpha}_2$, shown in Fig 1, where

$$\boldsymbol{\alpha}_1 = \begin{bmatrix}\mathbf{s}_{1,n} & \mathbf{s}_{1,n+1}\end{bmatrix} \quad \text{, and} \tag{3}$$

$$\boldsymbol{\alpha}_2 = \begin{bmatrix}\mathbf{s}_{2,n} & \mathbf{s}_{2,n+1}\end{bmatrix} \quad . \tag{4}$$

At the first time slot of PLNC, User 1 and 2 simultaneously transmit data to relay node. Let $\mathbf{r}$ denote the received signal in vector form. Define τ_1 as the arrival time of the signal from the first user and τ_2 as that for the second user. Without loss of generality, we assume $\tau_1 \leq \tau_2$. At time m, the received signal at relay node can be expressed as,

$$r(m) = h_{1,R}\alpha_1(m) + h_{2,R}\alpha_2(m - L_\tau) + v(m) \quad , \tag{5}$$

where $L_\tau = \tau_2 - \tau_1$ is the relative delay which is bounded by L, and $v(n)$ is the Additive white Gaussian noise (AWGN) vector with variance $N_0/2 = \sigma^2$. $h_{i,R}$ denotes the Rayleigh fading channel gain from i-th user to the relay node, which is the circular complex Gaussian with $CN(0, \phi_{i,R})$. We assume that the relative delay τ is an integer multiple of the symbol duration, thus no fraction delay is considered in this paper.

†Any training sequences would work, but Zadoff-Chu sequences are used here to reduce the computational complexity, which will be discussed in Section IV.

The relay node then estimates the timing offset L_τ and channel gains $h_{i,R}$, and maps the received signal according to certain PLNC rules. Let $\mathbf{C} = f(\boldsymbol{\alpha}_1, \boldsymbol{\alpha}_2)$ with length N denote the mapped signal at relay. Another training sequence $\mathbf{d}_r = \mathbf{z}_{\mu_r}$ is attached to $\mathbf{C}$ as prefix.

At the second time slot, the relay node broadcasts $\mathbf{C}$ to user 1 and 2. The received signal at user i can be expressed as,

$$\mathbf{y}_i = \mathbf{C}h_{R,i} + \mathbf{n} \quad , \tag{6}$$

where $\mathbf{n}$ is the AWGN, and $h_{R,i}$ is the Rayleigh fading channel gain from relay node to user i, which is the circular complex Gaussian with $CN(0, \phi_{R,i})$.

Each user then estimates channel gain $h_{R,i}$, and the relative delay L_τ. After self data removal, the desired signal can be decoded.

III. ESTIMATION AND DETECTION AT RELAY NODE

Due to the timing offset, the received signals are divided into two parts: the non-data overlapping part and the data overlapping parts, as was shown in Fig.1. Note that the received signals $r(m)$ from $m = N + L + \tau + 1$ to $N + 3L$ is the superimposed signal of the two transmitted training sequences. We now exploit this structure to detect the delay and estimate the channels.

A. Delay and Channel Estimation

Let $\mathbf{h} = [h_{1,R}, h_{2,R}]^T$ denote the channel gains in vector form. In order to estimate the delay L_τ and channel gains $\mathbf{h}$, we first define two vectors $\mathbf{d}_{1s,\tau} = [d_1(\tau + 1), ..., d_1(L), d_1(1), ..., d_1(L)]^T$ and $\mathbf{d}_{2s,\tau} = [d_2(1), ..., d_2(L), d_2(1), ..., d_2(L - \tau)]^T$, represent the shifted overlapped training sequences.

Then we define matrix $\mathbf{S}_\tau$ and vector $\mathbf{z}_\tau$ as follows,

$$\mathbf{S}_\tau = \begin{bmatrix}\mathbf{d}_{1s,\tau} & \mathbf{d}_{2s,\tau}\end{bmatrix} \quad , \tag{7}$$

and,

$$\mathbf{z}_\tau = [r(N + L + \tau + 1), ..., r(N + 3L)]^T \quad . \tag{8}$$

Matrix $\mathbf{S}_\tau$ consists of the shifted overlapping training sequences $\mathbf{d}_1$ and $\mathbf{d}_2$, and vector $\mathbf{z}_\tau$ is part of the received superimposed signal. Thus they are all known signals at the relay.

From (5), the received training sequences is given by,

$$\mathbf{z}_{L_\tau} = \mathbf{S}_{L_\tau}\mathbf{h} + \mathbf{v} \quad . \tag{9}$$

Thus the least square estimation of $\mathbf{h}$ can be written as

$$\widetilde{\mathbf{h}}_\tau = (\mathbf{S}_\tau{}^H\mathbf{S}_\tau)^{-1}\mathbf{S}_\tau{}^H\mathbf{z}_\tau \quad . \tag{10}$$

Among all possible delays, $||\mathbf{z}_\tau - \mathbf{S}_\tau\widetilde{\mathbf{h}}_\tau||^2/(2L - \tau)$ will be minimized at the exact correct delay. Different from the algorithm in [12], a normalization coefficient $1/(2L - \tau)$ is added for fair comparison, due to the different window size for different τ. We will show in the simulation that the coefficient significantly improve the delay estimation accuracy.

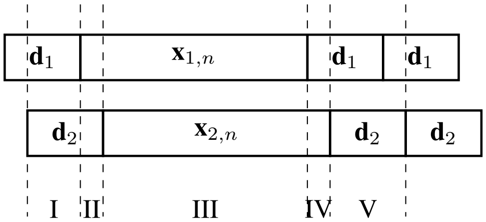

Fig. 2. Received Data Structure.

Therefore the estimation algorithm can be described as follows,

Step 1: For each $\tau = 0, 1, .., L-1$, the relay computes $\widetilde{\mathbf{h}}_\tau$ according to (10).

Step 2: The estimated timing offset $\hat{\tau}$ and estimated channel gain $\hat{\mathbf{h}}$ are given by

$$\hat{\tau} = \arg\min_{\tau<L} \frac{||\mathbf{z}_\tau - \mathbf{S}_\tau \widetilde{\mathbf{h}}_\tau||^2}{2L-\tau} \quad , \tag{11}$$

and,

$$\hat{\mathbf{h}} = (\mathbf{S}_{\hat{\tau}}{}^H \mathbf{S}_{\hat{\tau}})^{-1} \mathbf{S}_{\hat{\tau}}{}^H \mathbf{z}_{\hat{\tau}} \quad . \tag{12}$$

The Mean Square Error(MSE) of the channel estimation is defined by

$$MSE(\mathbf{h}) = \mathbf{E}[||\mathbf{h} - \hat{\mathbf{h}}||^2] \quad . \tag{13}$$

The Cramer-Rao Bound (CRB) for the channel estimation at the relay is studied to examine the estimation accuracy. The complex Fisher Information Matrix is given in [12],

$$\begin{aligned} \mathbf{I}(\mathbf{h}) &= \frac{1}{N_0} \left(\frac{\partial \mathbf{h}^H \mathbf{S}_\tau^H}{\partial \mathbf{h}^*}\right) \left(\frac{\partial \mathbf{h}^H \mathbf{S}_\tau^H}{\partial \mathbf{h}^*}\right)^H \\ &= \frac{1}{N_0} \mathbf{S}_\tau^H \mathbf{S}_\tau \quad . \end{aligned} \tag{14}$$

Thus the CRB is given by

$$CRB = tr(\mathbf{I}(\mathbf{h})^{-1}) = tr(N_0 (\mathbf{S}_\tau^H \mathbf{S}_\tau)^{-1}) \quad . \tag{15}$$

B. Mapping at the relay

After channel estimation, PLNC is then performed at relay. Due to the received misaligned signal structure, the superimposed signal is divided into five parts as shown in Fig 2. Part I and V are the overlapping parts for training sequences, which we used for delay and channel estimation. Part II and IV are the overlapping parts for training sequence and data, where desired data could be recovered. Part III is the overlapping part for two sets of data. Therefore the PLNC process is divided into two parts: the non-data-overlapping part, i.e. part II and IV, and the data-overlapping part, i.e. part III.

For the descriptions below, k is the index of the mapped signal $\mathbf{C}$ and l is the index of the received signal $\mathbf{r}$. For simplicity of notation, we omit the subscript n from $\mathbf{x}_{i,n}$.

1) Non-data-overlapping part:

The received signal in part II can be expressed as,

$$\begin{aligned} & r(l) = h_{1,R} x_1(l-L) + h_{2,R} d_2(l-\hat{\tau}) + v(l) \\ & for \quad l = L+1, ..., L+\hat{\tau} \quad . \end{aligned} \tag{16}$$

Also, the received signal in part IV can be expressed as,

$$\begin{aligned} & r(l) = h_{1,R} d_1(l-L-N) + h_{2,R} x_2(l-L-\hat{\tau}) + v(l) \\ & for \quad l = N+L+1, ..., N+L+\hat{\tau} \quad . \end{aligned} \tag{17}$$

As the relay knows what are the $\mathbf{d}_1$, $\mathbf{d}_2$, $h_{1,R}$, and $h_{2,R}$, the desired data $\hat{\mathbf{x}_1}$ and $\hat{\mathbf{x}_2}$ can be decoded by,

$$\begin{aligned} & \hat{x_1}(l-L) = \\ & \arg\min_{x_1 \in \Omega} ||r(l) - h_{1,R} x_1(l-L) + h_{2,R} d_2(l-\hat{\tau})||^2 \\ & for \quad l = L+1, ..., L+\hat{\tau} \quad , \end{aligned} \tag{18}$$

$$\begin{aligned} & \hat{x_2}(l-L-\hat{\tau}) = \\ & \arg\min_{x_2 \in \Omega} ||r(l) - h_{1,R} d_1(l-L-N) + h_{2,R} x_2(l-L-\hat{\tau})||^2 \\ & for \quad l = N+L+1, ..., N+L+\hat{\tau} \quad , \end{aligned} \tag{19}$$

where Ω is the BPSK modulation constellations. We then map the two non-data-overlapping parts $\hat{\mathbf{x}_1} \oplus \hat{\mathbf{x}_2}$ to $\mathbf{C}$, where

$$\begin{aligned} & C(k) = \begin{cases} -1, & if \quad \hat{x_1}(k) \oplus \hat{x_2}(k+L-\hat{\tau}) = 1 \\ +1, & if \quad \hat{x_1}(k) \oplus \hat{x_2}(k+L-\hat{\tau}) = 0 \end{cases} \\ & \quad for \quad k = 1, ..., \hat{\tau} \quad . \end{aligned} \tag{20}$$

2) Data overlapping part:

The data-overlapping part, corresponding to part III in Fig 2, is the same as in a normal PLNC system.

The received signal can be expressed as,

$$\begin{aligned} & r(l) = h_{1,R} x_1(l-L) + h_{2,R} x_2(l-\hat{\tau}) + v(l) \\ & for \quad l = L+\hat{\tau}+1, ..., N+L \quad , \end{aligned} \tag{21}$$

We consider a particular time index. A posteriori probability of the combination of source symbols (x_1, x_2) is given by

$$\begin{aligned} & Pr(x_1, x_2 | r) = \frac{Pr(r|x_1, x_2) Pr(x_1, x_2)}{Pr(r)} \\ & = \frac{1}{4Pr(r)\sqrt{2\pi\sigma^2}} \exp\left(-\frac{|R - h_{1,R}x_1 - h_{2,R}x_2|^2}{2\sigma^2}\right) \quad , \end{aligned} \tag{22}$$

where the factor of 4 in the denominator is due to the fact that for BPSK (x_1, x_2) has four combinations.

$$\begin{aligned} & P_0 = Pr(x_1 = 1, x_2 = 1 | r) \\ & P_1 = Pr(x_1 = -1, x_2 = 1 | r) \\ & P_2 = Pr(x_1 = 1, x_2 = -1 | r) \\ & P_3 = Pr(x_1 = -1, x_2 = -1 | r) \quad . \end{aligned} \tag{23}$$

Obviously, $\sum_{i=0,...,3} P_i = 1$. And,

$$\begin{aligned} & Pr(x_1 \oplus x_2 = 0 | R) = P_0 + P_3 \\ & Pr(x_1 \oplus x_2 = 1 | R) = P_1 + P_2 \quad . \end{aligned} \tag{24}$$

We therefore can map the XOR of the two data to $\mathbf{C}$,

$$C(k) = \begin{cases} -1, & Pr(x_1 \oplus x_2 = 0|R) < Pr(x_1 \oplus x_2 = 1|R) \\ +1, & Pr(x_1 \oplus x_2 = 0|R) > Pr(x_1 \oplus x_2 = 1|R) \end{cases}$$
$$for \quad k = \hat{\tau}+1, ..., L \quad . \tag{25}$$

From the above non-data overlapping(Eq(20)) and data overlapping(Eq(25)) parts, we have obtained $\mathbf{C}$, i.e, the XOR of $\mathbf{x}_1$ and cyclic shifted $\mathbf{x}_2$, where $\mathbf{C}$ is a vector with length N.

C. Estimation and Decoding at Users

One issue for asynchronous PLNC is that data from user 2 is delayed by L_τ, therefore both user terminals could not recover the data without the information of relative delay τ. To estimate the relative delay L_τ and the channel gain $h_{R,i}$ at user terminals, another Zadoff-Chu sequence $\mathbf{d}_r = \mathbf{z}_{\mu_r,\hat{\tau}}$ is attached to $\mathbf{C}$ at the relay, where $z_{\mu_r,\hat{\tau}}(k) = \exp(\frac{-j\mu_r(k-\hat{\tau})(k-\hat{\tau}-1)}{L})$ for $k = 1, ..., L$. It's well known that Zadoff-Chu sequence exhibits the useful cyclic shift properties that the shifted versions of itself remains orthogonal to one another. The relative delay $\hat{\tau}$ at relay could be obtained at user terminal by exploiting the structure of the shifted training sequence $\mathbf{z}_{\mu_r,\hat{\tau}}$, as well as the channel estimation. The mapped signal $\mathbf{C}$ with length $N+L$ is broadcast to user 1 and 2 in the second time slot. Considering the received training sequence part, the estimated relative delay $\hat{\tau}_i$ at user i is given by

$$\begin{aligned} \hat{\tau}_i &= \arg\max_{\tau<L} |\mathbf{y}_i \mathbf{z}^H_{\mu_r,\tau}| \\ &= \arg\max_{\tau<L} |(h_{R,i}\mathbf{z}_{\mu_r,\hat{\tau}} + \mathbf{n})\mathbf{z}^H_{\mu_r,\tau}| \quad . \end{aligned} \tag{26}$$

The above equation should have a maximum value of $L|h_{R,i}|$ at the correct delay and 0 at all other incorrect delays when noise is not taken into the consideration. When relative delay and channel gain are known at the user terminal, self data removal is performed, and the desired data can be recovered. Apart from the delay information is required at the user terminals, this step is similar as common point-to-point system, thus is not be discussed explicitly in this paper.

IV. Analysis

Computational complexity is an important issue for relay networks. At the relay node, the complexity is mainly from two parts:1)delay detection and channel estimation; 2)the decoding of data-overlapped part, where posteriori probabilities are calculated. However, the DF scheme always requires decoding at the relay, and our decoding approach is similar to the normal PLNC system. Thus only the estimation complexity is examined below.

For Zadoff-Chu sequences $\mathbf{d}_1 = \mathbf{z}_{\mu_1}$ and $\mathbf{d}_2 = \mathbf{z}_{\mu_2}$, when $\mu_1 + \mu_2 = L$, $\mathbf{d}_1 = \mathbf{d}_2{}^*$. This property could reduce half of the matrix multiplication complexity in (10). For a particular τ, the computational complexity is $O(2L-\tau)$. Thus through all possible τ, the complexity for delay detection and channel estimation is given by $O(3L^2+L)$.

The proposed delay and channel estimation algorithm with detection scheme only works in Rayleigh block flat fading channels. It requires the channels to remain the same for the whole data block. Also, in order to combat a maximum delay with length L, $2L$ extra symbols are used. Thus the throughput is reduced, and the effective data rate is modified by $N/(N+2L)$.

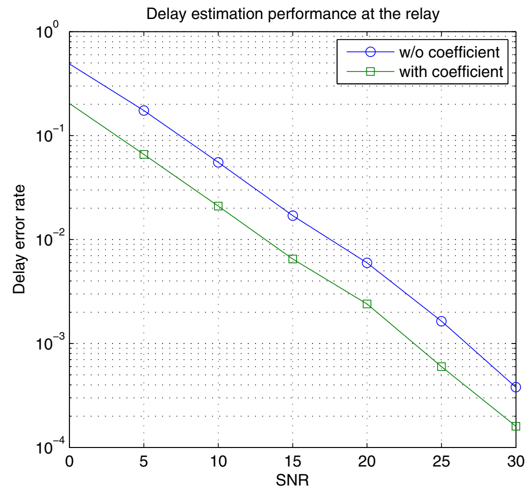

Fig. 3. Delay estimation performance at the relay, with burst transmission.

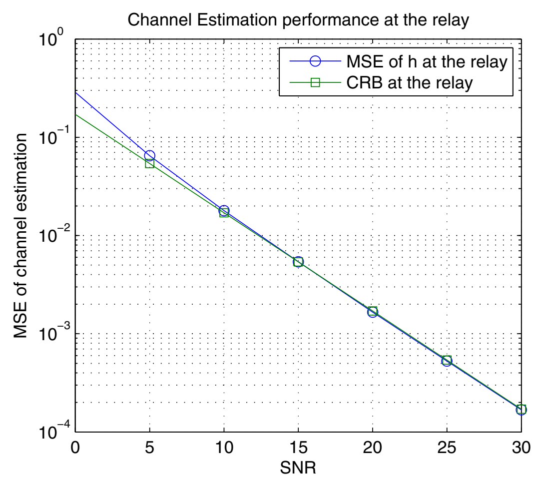

Fig. 4. Channel Estimation performance at the relay, with burst transmission

V. Simulation Result

Monte Carlo simulations are carried out to evaluate the performance. $N = 112$, $L = 17$. $\mathbf{d}_1$ and $\mathbf{d}_2$ are two Zadoff-Chu sequences with length L, and roots $u = 4, 13$. $\mathbf{z}_{\mu_r,0}$ is the Zadoff-Chu sequence with length L, and root $\mu_r = 15$. BPSK modulation is applied. Burst transmission mode is used here, where each frame has a random delay.

Fig.3 shows the performance of the delay estimation at relay node for burst transmission mode. We define the delay error rate as the number of estimated errors divided by the total number of simulations. An error happens when the estimated delay is not equal to the actual delay, $\hat{\tau} \neq L_\tau$. The results show that the delay estimation is much more accurate with the coefficient $1/(2L-\tau)$. This is due to different window size

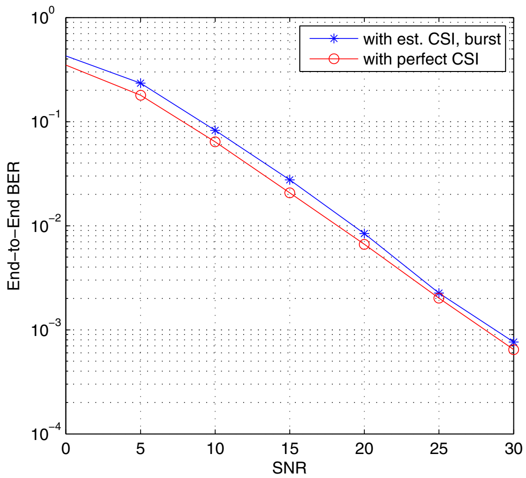

Fig. 5. End-to-End BER performance for the proposed TWRN system, with burst transmission.

in (10) for each possible τ. When the relative delay $L_\tau = 0$, a delay estimation error will happen when $||\mathbf{z}_0 - \mathbf{S}_0\widetilde{\mathbf{h}}_0||^2$ is larger than $||\mathbf{z}_{L-1} - \mathbf{S}_{L-1}\widetilde{\mathbf{h}}_{L-1}||^2$, which has greater possibilities since the former summation has $2L$ elements and the latter has only $L+1$ elements.

The MSE of the channel estimation is compared with Cramer Rao Bound (CRB), shown in Fig 4. It shows that the proposed scheme could reach the CRB at high signal to noise ratio (SNR) range when the delay estimation is much more accurate. Fig.5 illustrates the end-to-end BER performance for the proposed asynchronous system. The channel estimation error will cause about 0.5-1dB loss in terms of end-to-end BER.

VI. Conclusion

In this paper, we studied the delay and channel estimation algorithm for DF-based TWRNs along with PLNC and detection scheme under Rayleigh block flat fading channels. We extended the algorithm for asynchronous one-way cooperative networks in [12] to the TWRNs. Training sequences are added as prefix and suffix for the purpose of estimation. The relay node could estimate CSI by exploiting the structure of proposed scheme. In addition we improved the delay detection method by applying a coefficient corresponding to the window size. Relative delay estimation at the user terminals is also addressed. Simulation results show the effectiveness of delay and channel estimation algorithm. The MSE of channel estimation could reach the Cramer-Rao Bound at high SNR when delay estimation is accurate. Compared with the PLNC scheme under perfect CSI, the proposed PLNC scheme under delay and channel estimation algorithm has a 0.5 to 1dB loss in end-to-end BER performance.

In future work, we plan to focus on delay and channel estimation algorithm with feedback scheme from user terminals to further reduce the complexity. In addition, we will study the system performance under fractional delay.

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