CAPACITY EVALUATION WITH CHANNEL ESTIMATION ERROR FOR THE DECODE-AND-FORWARD RELAY PLC NETWORKS

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ABSTRACT

In this paper, the achievable information rates of three Decode-and-Forward (DF) relay protocols are investigated with linear minimum mean square error (LMMSE) channel estimation in powerline communications (PLC) networks. Analysis of how the channel estimation errors impact the performance of unidirectional and bidirectional relay protocols is given. Realistic simulations are performed to evaluate the performance for varying the number of pilot Orthogonal Frequency-Division Multiplexing (OFDM) symbols and the robustness of different protocols is discussed. Solutions for how to mitigate the impact of channel and noise on the protocol to maximise performance are also discussed.

1. INTRODUCTION

Powerline Communications (PLC) which uses the existing power grid as the data transmission medium draws increasing attention with the spread of the Smart Grid concept. In [1], it has been proved that to use power cables as a broadband communications channel is feasible. A variety of potential applications, such as High-Definition Television (HDTV), Voice over IP (VoIP) and Smart Energy have been proposed in the Homeplug AV and AV2 standards. However, research to optimise the data transmission capacity of PLC is still on going. Relays, or repeaters, are one technique that will help increase network capacity and coverage in PLC environments.

Among the current discussions on relays in PLC networks, Decode-and-forward (DF) schemes and corresponding sub-carrier and power allocation schemes are investigated in [2]. Space-time coding schemes are proposed for the multi-hop PLC networks in [3], where the impact of repeater location is also studied. A series of relay protocols which involve beamforming and bidirectional techniques in PLC relay transmission have been studied in [4], where DF has been shown to have significant advantages in PLC environments. Previous research on relays is usually based on the assumption that relay nodes know the channel state information (CSI) perfectly. This paper investigates the achievable information rates for multi-relay unidirectional, 3-step bidirectional and 2-step bidirectional DF schemes. We consider the impact of channel estimation error in frequency selective fading PLC channel and coloured background noise environment. The contributions of this paper are: First, a multi-pilot based linear minimum mean square error (LMMSE) channel estimation method is proposed for the above relay schemes. Second, in Section 3 a realistic analysis for the achievable information rate for the above relay schemes in PLC is given. Finally, the best choice of the number of pilot for DF PLC relay schemes is obtained.

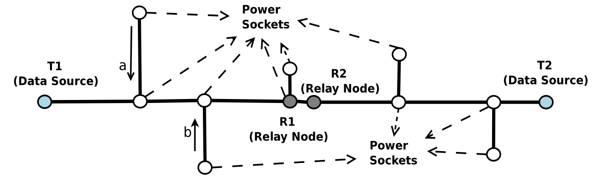

Figure 1: Typical In-door PLC Network Topology.

The remaining parts of this paper are organised as follows. In Section 2, channel, noise characteristics and modelling in PLC are introduced. Also, the notation used in this paper are defined. The basic LMMSE estimation method and the channel estimation method used in this paper are described in Section 2.2. Analysis of achievable information rates for 3 DF relay protocols is given in Section 3. In section 4, the simulation results are plotted and the reasons for the results are discussed. Finally, Section 5 concludes the paper and gives future research direction.

2. SYSTEM MODEL AND CHANNEL ESTIMATION

2.1 System Model

Fig. 1 shows a typical in-door PLC network including a group of power sockets where PLC modems can be plugged in as data transmitters/receivers or relay nodes. Because of the existence of reflections such as *a* and *b* which are shown in Fig. 1, the power cable presents as a typical frequency selective fading channel in the frequency domain, and a multipath channel in the time domain. Here, a method based on the Transmission Line Theory which is proposed in [5] and [15] is employed to model the PLC channel. The transfer functions for the Data Terminal 1 to Data Terminal 2 ($T_1 \rightarrow T_2$), Data Terminal 1 to Relay Node 1 ($T_1 \rightarrow R_1$) and Relay Node 1 to Data Terminal 2 ($R_1 \rightarrow T_2$) links in Fig. 1 are shown in Fig. 2. In this paper, the house connection cable of type NAYY35 which is also used in [13] is employed to model the channel. As can be seen from Fig. 2 the channels suffer deep fading at some frequencies which will cause low information rate.

The noise in PLC appears as coloured background noise blended with impulse noise. The source of the noise has been studied and classified into 5 categories in [6]. Noise types 1 and 2 in [6] that are the sum of several low power noise sources and narrowband interference induced by medium and short wave broadcasts often have a stable power spectral density over seconds, minutes and even hours, thus, they are considered as background noise. The others three sources may change rapidly within microseconds and milliseconds, therefore, are considered to be as impulse noise. In this pa-

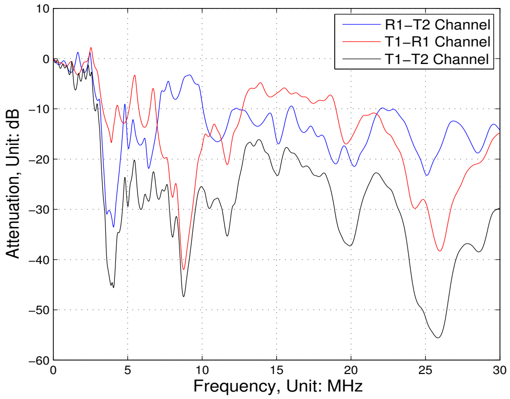

Figure 2: Transfer Functions for the Data Source to Relay nodes link, Data Source to Data Destination link and Relay node to Data Destination link, here, Distance of $T_1 \longleftrightarrow T_2$ is 100 m, and Relay node is at the middle point between T_1 and T_2

per, we only consider the impact of the background noise. A synthesis process in [7] that passes White Gaussian Noise (WGN) through a coloured filter is used to model the background noise.

Based on the frequency selective fading property of the PLC channel and the harsh noise conditions in the frequency domain, Orthogonal Frequency-Division Multiplexing (OFDM) is used to combat these issues. Assume that the bandwidth is divided into K orthogonal subcarriers in the frequency domain. Here, we use the vector $H_{t_1t_2}{=}\left[h^1_{t_1t_2}, h^2_{t_1t_2}, \cdots, h^K_{t_1t_2}\right]$ to denote the frequency domain channel transfer function for the $T_1 \longrightarrow T_2$ link, where, $h^k_{t_1t_2}$ ($k \in [1, 2, \cdots, K]$) denotes the channel gain on the k_{th} sub-carrier. The vectors H_{t_1r} and H_{rt_2} for the $T_1 \longrightarrow R$ and $R \longrightarrow T_2$ links are defined in the same way. In addition, $N_{t_2}{=}\left[n^1_{t_2}, n^2_{t_2}, \cdots, n^K_{t_2}\right]$ stands for the noise samples at T_2, where $n^k_{t_2}$ denotes noise on the k_{th} sub-carrier with power $\left(\sigma^k_{t_2}\right)^2$. Similarly, N_{t_1}, N_r denote the noise samples on T_1 and R with power $\left(\sigma^k_{t_1}\right)^2$ and $\left(\sigma^k_r\right)^2$ on the k_{th} subcarrier, respectively. Furthermore P is defined as the data transmit power on each sub-carrier. Thus, data transmission on the $T_1 \longrightarrow T_2$ link with sequence $X{=}\left[x^1, x^2, \cdots, x^K\right]$ can be modelled as (1):

$$Y_{t_2} = \sqrt{P} \cdot H_{t_1t_2} \cdot X + N_{t_2} \tag{1}$$

Where, $Y_{t_2}{=}\left[y^1_{t_2}, y^2_{t_2}, \cdots, y^K_{t_2}\right]$ is the received signal sequence on the receive side. The data communication processes through other links can also be modelled in the same way as (1).

2.2 Channel Estimation

Generally, in DF protocols, the terminal at the receive side should estimate the CSI based on the pilot OFDM symbols sent by the adjacent terminal which sends the signal. We use the frame structure in [8] where each frame contains 256 OFDM symbols and 64 frames form a superframe. Thus, there are a total of $N = 16384$ symbols in a superframe. Assume that there are M OFDM symbols used as pilot symbols per superframe. For each pilot symbol, the LMMSE method proposed in [9] is employed to estimate frequency domain transfer function. The estimated channel transfer function based on the m_{th} pilot is:

$$\widehat{H}_m {=} R_{HH}\left(R_{HH}{+}\Theta_m\left(X_m X_m^H\right)^{-1}\right)^{-1} H_m^{ls} {=} H{+}E_m \tag{2}$$

where, $\widehat{H}_m^{ls}{=}X_m^{-1}Y_m{=}[\widehat{h}_m^1, \widehat{h}_m^2, \cdots, \widehat{h}_m^K]$ is the least-square (LS) estimate of H and $\widehat{h}_m^k$ is the estimated channel gain on k_{th} sub-carrier. The matrix $\Theta_m{=}\mathrm{d}iag[(\sigma_m^1)^2, (\sigma_m^2)^2, \cdots, (\sigma_m^K)^2]$ is the variance matrix of the noise for the m_{th} pilot on the receive terminal, and $(\sigma_m^k)^2$ is the noise power on k_{th} sub-carrier, $R_{HH}{=}E\left\{HH^H\right\}$ is covariance matrix of H, $E_m{=}[\varepsilon_m^1, \varepsilon_m^2, \cdots, \varepsilon_m^K]$ is the channel estimation error vector and ε_m^k is the channel estimation error for the m_{th} pilot in the k_{th} sub-carrier.

According to [9], a statistical time domain channel model is needed to evaluate R_{HH} in (2). To keep the complexity low but use a realistic channel approximation, in this paper, L randomly generated channels in the frequency domain are employed to calculate R_{HH}. The channel correlation matrix used in (2) is then obtained:

$$R_{HH} = [r_{m,n}] = \left[E\left[\left(h_l^m - \mu^m\right)\left(h_l^n - \mu^n\right)\right]\right] \tag{3}$$

where, h_l^k is the channel gain of l_{th} randomly generated channel at the k_{th} sub-carrier, and μ^k is the average channel gain at the k_{th} sub-carrier over all the L generated channels.

On the basis of the LMMSE estimation result above, the average value of all the M estimated channel transfer functions is used as the final channel estimation result.

$$\widehat{H} = \frac{1}{M}\sum_{m=1}^{M}\widehat{H}_m = H + \frac{1}{M}\sum_{m=1}^{M}E_m \tag{4}$$

here, we define the second phase of (4) as the channel estimation error $E = [\varepsilon^1, \varepsilon^2, \cdots, \varepsilon^K]$ for the multi-pilot scenario, where $\varepsilon^k = \frac{1}{M}\sum_{m=1}^{M}\varepsilon_m^k$. Assume the variance of ε_m^k is a_m^k which is also can be considered as the noise power induced by the inaccuracy of channel estimation. The estimation noise on each pilot symbol, E_m, is mutually independent and identically distributed. Thus, the variance of ε^k is $\frac{1}{M}a_m^k$ which means that using more pilot symbols will lead to a more precise estimation result.

In the following part of this paper, we use $\widehat{H}_{xy} = [\widehat{h}_{xy}^1, \widehat{h}_{xy}^2, \cdots, \widehat{h}_{xy}^k]$ and $E_{xy} = [\varepsilon_{xy}^1, \varepsilon_{xy}^2, \cdots, \varepsilon_{xy}^K]$ to denote the estimated channel and channel estimation error for the $x \longrightarrow y$ link, where $\widehat{h}_{xy}^k$ and ε_{xy}^k denote the estimated channel and channel estimation error on the k_{th} sub-carrier for this link. One further point should be noted. In the perfect channel estimation scenario, the channel transfer function for $x \longrightarrow y$ and $y \longrightarrow x$ link can be assumed the same, but if the channel estimation error is considered, $\widehat{H}_{xy}$ will not equal to $\widehat{H}_{yx}$ for the reason that the different disturbance situations on x and y will cause different channel estimation results.

3. ACHIEVABLE INFORMATION RATE OF DIFFERENT RELAY PROTOCOLS

The conclusion in [4] shows that in PLC environments the DF protocols often provide more robustness and higher capacity performance than AF protocols. Therefore, in this paper, 3 DF protocols are investigated with the existence of channel estimation error.

3.1 Protocol 1: 2Relay-1Way DF with Beamforming

Theoretically, all the available sockets between data source and destination, for example R_1 and R_2 in Fig. 1., can be considered as potential relay nodes. Thus, multi-relay operation is possible in a PLC network. Due to the physical distribution of power sockets we made the assumption that sockets often appear in pairs, which means we can often find two sockets which are closely located. Though applying the transmit beamforming technique in the 2nd hop in a DF relay scheme with perfect channel estimation has been discussed in [16] for wireless communications, here the focus is the achievable information rate with channel estimation error in PLC channel environment.

As described in [4], in this protocol, T_1 transmits messages to T_2 with the help of R_1 and R_2. R_1 and R_2 decode the message independently in the 1st phase, then the relays forward the re-encoded message to T_2. Further define the first M OFDM symbols in a super frame as the pilot symbols. During the channel estimation period, R_1 and R_2 estimate the channel transfer functions for $T_1 \longrightarrow R_1$ and $T_1 \longrightarrow R_2$ links respectively, then apply beamforming to forward the signal to T_2 Thus, the information rate for the 1st phase can be written as:

$$R_{t_1 r_1 r_2} = \sum_{k=1}^{K} \log_2 \left(1 + \min \left\{ SNR^k_{t_1 \to r_1}, SNR^k_{t_1 \to r_2} \right\}\right) \qquad (5)$$

where, $SNR^k_{t_1 \to r_1} = \frac{P|\widehat{h}^k_{t_1 r_1}|^2}{\left(\left(\sigma^k_{r_1}\right)^2 + P|\varepsilon^k_{t_1 r_1}|^2\right)\Gamma}$ and $SNR^k_{t_1 \to r_2} = \frac{P|\widehat{h}^k_{t_1 r_2}|^2}{\left(\left(\sigma^k_{r_1}\right)^2 + P|\varepsilon^k_{t_1 r_2}|^2\right)\Gamma}$ are the SNRs for $T_1 \to R_1$ and $T_1 \to R_2$ links at k_{th} sub-carrier.

Considering the existence of the difference on the channel phases and local oscillators, there always phase differences between $R_1 \longrightarrow T_2$ and $R_2 \longrightarrow T_2$ channel. Here, the complex channels are written as $\mid h^k_{r_1 t_2} \mid e^{j\theta_1}$ and $\mid h^k_{r_2 t_2} \mid e^{j\theta_2}$. If $\theta = \mid \theta_1 - \theta_2 \mid$ falls in $[\frac{-\pi}{2}, \frac{\pi}{2}]$, the amplitude of simple superposed signal as $\mid \sqrt{P} h^k_{r_1 t_2} + \sqrt{P} h^k_{r_2 t_2} \mid$ will be increased at receive side. If θ falls in $[\frac{\pi}{2}, \frac{3\pi}{2}]$, the received amplitude will reduce rather than increase. Taking account the fact that channel status keeps stationary and the Time Division Duplex (TDD) work mode in PLC, wen can assume that transmitter fully knows channel status. Thus, transmit beamforming can be employed to compensate the phase difference, thus θ always equals 0, which means the superposed signal is always enhanced. Then information rate for the 2nd phase thus is given by:

$$R_{r_1 r_2 t_2} = \sum_{k=1}^{K} \log_2 \left(1 + \frac{P\left(\mid \widehat{h}^k_{r_1 t_2} \mid + \mid \widehat{h}^k_{r_1 t_2} \mid\right)^2}{\left(\left(\sigma^k_{t_2}\right)^2 + P \mid \varepsilon^k_{r_1 t_2} \mid^2 + P \mid \varepsilon^k_{r_2 t_2} \mid^2\right)\Gamma}\right) \qquad (6)$$

where, Γ denotes SNR gap which is used to indicate the information rate loss caused by link protection techniques such as channel coding, synchronising overhead. From the statement in [11], for the uncoded modulation system, the achievable information rate is often 10 dB less than the Shannon capacity. If convolutional coding is applied, the performance will be improved by 7 to 8 dB. Thus, here we make the assumption that $\Gamma = 3$ dB is reasonable. Then the overall achievable information rate for this protocol is given by:

$$R^{DF}_{2R1W\_BF} = \frac{1}{2}\left(1 - \frac{M}{N}\right) \min \{R_{t_1 r_1 r_2}, R_{r_1 r_2 t_2}\} \qquad (7)$$

where, the factor $\frac{1}{2}$ denotes the half-duplex operation of the relay, and the factor $\frac{M}{N}$ denotes the overhead loss caused by pilot symbols.

3.2 Protocol 2: 1Relay-2Way-3Step DF

Due to the half-duplex mode on relay nodes, all the unidirectional relay protocols suffer information rate loss. We consider bidirectional schemes which will help the system increase its spectral efficiency. Assume that T_1 and T_2 have messages to send to each other. In bidirectional protocols, relay nodes collect the messages from both directions and forward the superposed signal in a broadcast manner. Then T_1 and T_2 extract their expected message from the superposed signal by removing their own message first. As discussed in [12] and [14], bidirectional relay operation can be implemented in both AF and DF scenarios. In this paper the performance of bidirectional relay protocols in PLC channel environment with channel estimation error is investigated.

First a 3-Step protocol is discussed. In this protocol, the whole data transmission is accomplished in 3 steps. First, T_1 sends X_1 to R_1, which is decoded and stored at R_1. Second, T_2 sends X_2 to R_1, which is also decoded and stored. At R_1, the two decoded messages are superposed into $X_3 = [x^1_3, x^2_3, \cdots, x^K_3]$, where, $x^k_3 = \sqrt{\frac{1}{2}P} x^k_1 + \sqrt{\frac{1}{2}P} x^k_2$. In the third phase, R_1 broadcasts X_3, T_1 and T_2 then receive X_3 and extract their expected messages. For the pilot symbols, T_1 and T_2 send their pilot sequences on the first M symbols. Then, R_1 fills the pilot symbols with its own sequence. This sequence is broadcasted to T_1 and T_2.

In this protocol, the achievable information rate consists of 2 data streams: $T_1 \longrightarrow R_1 \longrightarrow T_2$ and $T_2 \longrightarrow R_1 \longrightarrow T_1$. The sum-rate of this protocol is given by:

$$R^{DF}_{1R2W\_3S} = \frac{1}{3}\left(1 - \frac{M}{N}\right)\left(R_{t_1 r_1 t_2} + R_{t_2 r_1 t_1}\right) \qquad (8)$$

where, the factor $1/3$ denotes the fact that the transmission process should be completed in 3 time-slots due to the half-duplex operation of the relay node, and:

$$R_{t_1 r_1 t_2} = \min \left\{ \sum_{k=1}^{K} \log_2 \left(1 + \frac{P \mid \widehat{h}^k_{t_1 r_1} \mid^2}{\left(\left(P \mid \varepsilon^k_{t_1 r_1} \mid^2 + \sigma^k_{r_1}\right)^2\right)\Gamma}\right), \right.$$
$$\left. \sum_{k=1}^{K} \log_2 \left(1 + \frac{1}{2} \frac{P \mid \widehat{h}^k_{r_1 t_2} \mid^2}{\left(P \mid \varepsilon^k_{r_1 t_2} \mid^2 + \left(\sigma^k_{t_2}\right)^2\right)\Gamma}\right) \right\} \qquad (9)$$

$$R_{t_2 r_1 t_1} = \min \left\{ \sum_{k=1}^{K} \log_2 \left(1 + \frac{P \mid \widehat{h}^k_{t_2 r_1} \mid^2}{\left(P \mid \varepsilon^k_{t_2 r_1} \mid^2 + \left(\sigma^k_{r_1}\right)^2\right)\Gamma}\right), \right.$$
$$\left. \sum_{k=1}^{K} \log_2 \left(1 + \frac{1}{2} \frac{P \mid \widehat{h}^k_{r_1 t_1} \mid^2}{\left(P \mid \varepsilon^k_{r_1 t_1} \mid^2 + \left(\sigma^k_{t_1}\right)^2\right)\Gamma}\right) \right\} \qquad (10)$$

stand for information rates of the $T_1 \longrightarrow R_1 \longrightarrow T_2$ link and the reverse link, respectively.

3.3 Protocol 3: 1Relay-2Way-2Step DF

Merging the first and second phases in Protocol 3 into one phase and using V-BLAST detection at R_1, a 2-step directional DF relay protocol is constructed. The step in which T_1 and T_2 transmit concurrently to R_1 is called the $Multi-Access$ (MA) phase. Here, we assume R_1 detects the data stream from T_1 first, by considering the signal from T_2 as interference. Then R_1 subtracts out the detected signal and decodes T_2. For the channel estimation process in this protocol, at the first phase, T_1 and T_2 send the mutual orthogonal pilot sequences on pilot symbols to ensure that the estimation processes for $T_1 \rightarrow R_1$ and $T_2 \rightarrow R_1$. links do not impact each other. Then R_1 fills the pilot symbols into superframe and forwards the signal to T_1 and T_2. Thus the information rate for $T_1 \rightarrow R_1 \rightarrow T_2$ link is:

$$R^{2S}_{t_1 r_1 t_2} = \min\left\{ \sum_{k=1}^{K} \log_2\left(1+\frac{P \mid \widehat{h}^k_{t_1 r_1} \mid^2}{\left(P \mid \varepsilon^k_{t_1 r_1} \mid^2 + \left(\sigma^k_{r_1}\right)^2\right)\Gamma}\right), \right.$$
$$\left. \sum_{k=1}^{K} \log_2\left(1+\frac{\frac{1}{2}P \mid \widehat{h}^k_{r_1 t_2} \mid^2}{\left(P \mid \varepsilon^k_{r_1 t_2} \mid^2 + \left(\sigma^k_{t_2}\right)^2\right)\Gamma}\right)\right\} \quad (11)$$

In (11), $P \mid h^k_{t_2 r_1} \mid^2$ denotes the received power from T_2 at R_1 which is considered as interference for R_1 decoding T_1. Before decoding the message from T_2, X_1 should be subtracted out. Thus, the information rate for the reverse link is:

$$R^{2S}_{t_2 r_1 t_1} = \min\left\{ \sum_{k=1}^{K} \log_2\left(1+\frac{P \mid \widehat{h}^k_{t_2 r_1} \mid^2}{\left(P \mid \varepsilon^k_{t_2 r_1} \mid^2 + \left(\sigma^k_{r_1}\right)^2\right)\Gamma}\right), \right.$$
$$\left. \sum_{k=1}^{K} \log_2\left(1+\frac{\frac{1}{2}P \mid \widehat{h}^k_{r_1 t_1} \mid^2}{\left(P \mid \varepsilon^k_{r_1 t_1} \mid^2 + \left(\sigma^k_{t_1}\right)^2\right)\Gamma}\right)\right\} \quad (12)$$

Thus, the total information rate for the case of detecting the data for T_1 first is:

$$R^{DF'}_{1R2W\_2S} = \frac{1}{2}\left(R_{t_1 r_1 t_2\_2S} + R_{t_2 r_1 t_1\_2S}\right) \quad (13)$$

In the same way, the information rate $R^{DF''}_{1R2W\_2S}$ which denotes the information rate for detecting the T_2 data stream first can be obtained. Therefore, the achievable information rate for 2-step bidirectional DF protocol is given by:

$$R^{DF}_{1R2W\_2S} = \left(1-\frac{M}{N}\right) \cdot \max\left\{R^{DF'}_{1R2W\_2S}, R^{DF''}_{1R2W\_2S}\right\} \quad (14)$$

4. SIMULATION AND NUMERICAL RESULTS

The PVC-insulated cables that are widely used in low-voltage power distribution grid are used in [13] to simulate the network shown in Fig 1. One generated channel can be used during a superframe since the PLC channel is considered stationary for seconds or tens of seconds. According to the background noise characteristics described in [6], the noise power spectral density (PSD) on a node can be assumed to be unchanged during a superframe. In order to make the simulation realistic, channel transfer functions are re-generated by using a group of randomly located branches with random branch length and a new group of background noise PSDs for T_1, T_2, R_1 and R_2 are re-generated according to [7] for each new superframe. It is assumed that each terminal in the system transmits a signal at the same power level with equal power allocation on each sub-carrier. Pilot symbols are transmitted with the same power level as the data symbols. A transmit power spectral density (PSD) of -60 dBm/Hz which is used for many actual PLC products [1] is used in this paper.

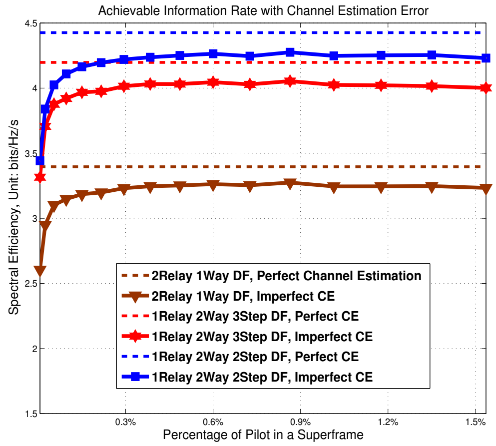

Figure 3: Data rate trends with increasing numbers of pilot symbols, when the $T_1 \leftrightarrow T_2$ distance is 10m.

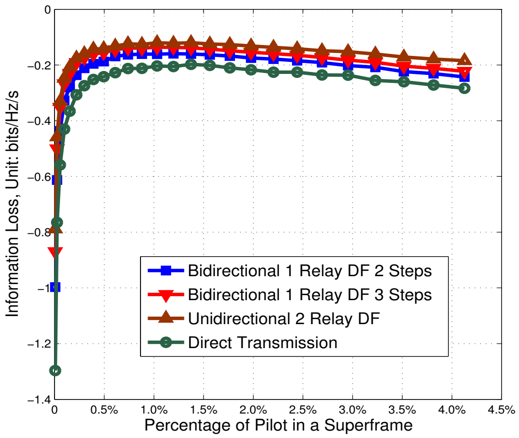

Figure 4: Information gaps between perfect channel estimation scenario and scenario with channel estimation error when the $D_{T_1 \leftrightarrow T_2}$ distance is 10m.

Fig. 3 shows the trend of achievable information rates by increasing the number of pilot symbols. When there is only 1 pilot symbol, the information rate for bidirectional 3-step DF and 2-step is almost the same. But with increasing numbers of pilot symbols, the 2-step protocol improves throughput faster than 3-step protocol. This phenomenon means that 2-step protocol is more sensitive to CSI errors than the 3-step protocol. To utilise the benefit of bidirectional 2-step scheme, precise channel estimation procedures should be guaranteed.

The information gap, which is difference of rate between the estimated CSI data rate and the rate with prefect CSI, is defined here to measure the performance of protocols. From Fig. 4, we can see that direct transmission has an obviously larger gap than the relay schemes. The reason is that without the help of the relay the received signal at T_2 is weaker due to the larger channel attenuation. Thus, a less accurate channel estimation is obtained which leads to higher information loss. By using a relay node to decode and forward the transmission, the signal can be detected more reliably at the receiver. Thus, the information gap of unidirectional single relay DF protocol is smaller than the direct transmission. For the bidirectional protocols, they can benefit from the DF signal reconstruction operation but are limited by the power split operation in the broadcasting phase. In particular, for the 2-step bidirectional DF protocol, the performance of V-BLAST detection degraded when channel estimation errors are present. For example, due to the inaccuracy of channel estimation of $T_1 \rightarrow R$ link, after decoding the signal X_1 from T_1, the impact of X_1 can not be totally subtracted, and the residual interference will limit the capability to detect X_2 from T_2. Therefore, the 2-step bidirectional protocol has a larger information gap than the 3-step bidirectional protocol.

In Fig. 3 and Fig. 4, we can see that performance does not always increase with number of the pilots because the pilots reduce the available data payload in a superframe. From the simulation results, when the number of pilot occupies 0.5% of the total the symbols in a superframe, the protocols have the best performance. From the simulation of [4], the average channel attenuation incerase with the increasing of $T_1 \leftrightarrow T_2$ distance. Thus, more pilot symbols are required for accurate channel estimation. In practical system, the length of pilot symbols is a trade-off design. In addition, considering the slow channel varying of PLC, an adaptive pilot control mechanism can be developed for keeping relay PLC system always in optimal status without frequently update.

5. CONCLUSION AND FUTURE WORK

From the analysis and simulation above, the achievable information rates for unidirectional single direction DF, bidirectional 3-step DF and 2-step DF are given with consideration of channel estimation error in the PLC environment. The results of the simulation proved that DF technique can help PLC transmission system to combat the hostile noise and channel conditions to improve throughput. The bidirectional 2-step DF protocol shows superiority in transmission capacity, but is vulnerable to noise disturbance which will impact the channel estimation accuracy. With accurate channel estimation using multiple pilot symbols, the 2-step protocol will minimise such deterioration. The 3-step protocol show more robustness then the 2-step protocol when channel estimation errors are present. This paper showed that bidirectional relay techniques can be a good choice for PLC transmission. In future work, the impact of impulse noise and methods to mitigate it will be studied, and the a relation between the average channel gain and optimal pilot length will be investigated in detail.

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