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Fundamental Properties of Wireless Relays and Their Channel Estimation

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Synonyms

One-way relay; Two-way relay; Wireless relay channel; Wireless relay system

Definition

A wireless relay system involves at least three nodes: a source node, a relay node, and a destination node. The relay node assists the transmission of information from the source to the destination. The relay channels include all channels between these nodes.

Historical Background

Due to the complicated transmission media, fading has been considered as a key characteristic feature of the wireless communications. As the wireless fading greatly shortens the delivery distance, the main task in wireless communication systems is to combat the fading to achieve reliable communication. To address this issue, a number of transmission techniques have been proposed. Among them, wireless (radio frequency) relays are widely known to be useful for combating radio channel fading over long distances. Relay technique is a promising technique since it allows a highly flexible equipment deployment to solve the fading problem (Soldani and Dixit 2008). This advantage further enables a cost-effective enhancement of coverage, throughput and network capacity. The relay technique is very helpful in some harsh environments, for example, in rural areas where the population is sparsely distributed and traffic density is low that makes building traditional cellular access networks not economical. There has been a long history in the development of both theory and practice of wireless relays. The earliest concept of wireless relay can be traced back to year 1997 when Scott Guthery used it to construct the relay star network where the relay helps to connect fixed wireless nodes to central server (Guthery 1997). Many of the recent developments and their roots can be traced from Hua et al. (Hua et al. 2012, 2013). Another new angle of understanding the relay assisted communications is from the cooperative communication perspective (Nosratinia et al. 2004; Hong et al. 2007; Sheng et al. 2011). As shown in Fig. 1 where a source node S intends to transmit messages to the destination node D, the source node S sends the signal in the first time slot and the signal is received by both the destination node D and the relay node R; then in the second time slot, the relay node forwards the

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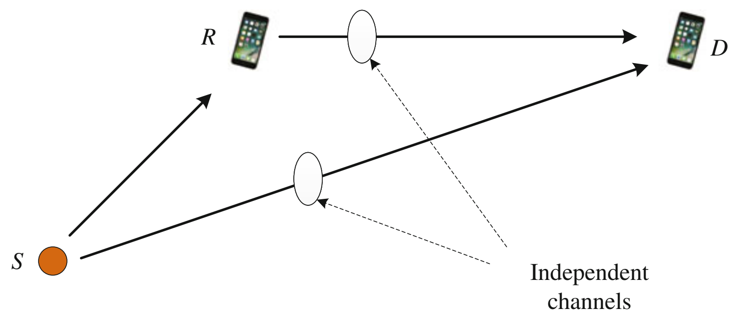


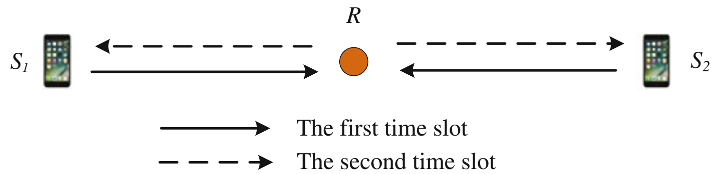
Fundamental Properties of Wireless Relays and Their Channel Estimation, Fig. 1 Wireless one-way relay channel.

received signal to the destination node D. With an assistance of the relay node R, two copies of signal transmitted from the source S are received at the destination node D where one from S to D and another from S to R then to D. As the channels in those two links are generally independent, two copies of signals can be combined at the destination node D to achieve a more reliable detection. From the communication theory point of view, the performance gain comes from an inherent spatial diversity. As here the wireless relay helps to forward one-way message delivery, i.e., from source to destination, we refer to this channel model as one-way relay channel.

As illustrated in Fig. 1, although one-way relay channel can achieve a more reliable transmission, it requires one more time slot to complete message delivery compared to point-to-point transmission, which sacrifices spectrum efficiency. Later on, to compensate the spectral efficiency loss, in a scenario of two-way transmission where two nodes intend to exchange the messages with each other via a middle-placed relay node, the technique of physical-layer network coding (PLNC) is utilized to improve the spectrum efficiency (Wang and Tao 2012). The relay assisted two-way transmission is referred to as two-way relay channel. As shown in Fig. 2 where source node S_1 desires to transmit signal x_1 to source node S_2 and source node S_2 intends to transmit signal x_2 to source node S_1, the whole transmission is completed in two time slots. In the first time slot, both source nodes transmit their signals to the relay node simultaneously. In this case, the relay node receives the combination of signals x_1 and x_2. After performing certain processing, the combination is forwarded to nodes S_1 and S_2 in the second time slot. As two source nodes know their transmitted signals, the self-interference can be canceled from the received combination before decoding the desired signals. It is easy to observe that in two-way relay channel, two messages are delivered within two time slots. In contrast to the one-way relay channel, where two time slots are required to complete one message delivery, two-way relay channel significantly improves the spectrum efficiency.

Several relay processing strategies have been proposed in wireless relay channel. Basically, different strategies usually require different complexity and possess different performance. Two main strategies are amplify-and-forward (AF) strategy and decode-and-forward (DF) strategy. In AF strategy, the relay node simply amplifies the received signal and forwards it directly without decoding the messages. In DF strategy, the relay node decodes the messages from the received signals and regenerates new signals which are sent to the destination subsequently.

As the transmission protocol of the relay channel is quite different from the traditional point-to-point transmission, the corresponding physical layer techniques are greatly modified, especially the channel estimation which is used to obtain the channel state information required for physical layer designs including power allocation (Chen et al. 2017; Ma et al. 2014), precoding design (Cirik et al. 2014; Xu and Hua 2011; Yu and Hua 2010; Rong and Hua 2009; Rong et al. 2009), etc. In wireless relay channel, we generally need to estimate the channels of two-hop transmissions, i.e., from the source to the relay and from the relay



Fundamental Properties of Wireless Relays and Their Channel Estimation, Fig. 2 Wireless two-way relay channel

to the destination. Lots of new and challenging problems are introduced. In this article, we aim to provide a brief review of the channel estimation in wireless relay channel.

Foundations

According to transmission protocol, the two-hop channel estimation of wireless relay channel can be performed using the training signals received at the relay and the destination. If the relay node can perform the channel estimation and can transmit the training sequences, the two-hop channel estimation can be decoupled. For example, in the one-way relay channel, the first hop channel, i.e., the channel from the source S to the relay R, can be estimated at the relay node and the second hop channel, i.e., the channel from the relay R to the destination D, can be estimated at the destination node D separately. In this case, the overall channel estimation problem simply reduces to the two point-to-point channel estimations. In the two-way relay channel, we cannot directly decouple the two-hop channel estimation into two point-to-point channel estimation problems as it involves four independent channels. In this case, in the first hop, the channel can be considered as a multiple access channel (MAC) where received training signal at the relay node is used to estimate the channels from the source S_1 to the relay node R and from the source S_2 to the relay node R. While in the second hop, the channel can be treated as a broadcasting (BC) channel where the single training sequence sending from the relay node is received at the destination nodes and is then utilized to estimate the channels from the relay node R to two destination nodes S_1 and S_2.

In another scenario, if the relay node cannot perform channel estimation or send training sequence, the channel estimation must be conducted at the destination nodes and corresponding channel estimation problem becomes relatively more complicated. Under this setup, besides estimating the individual channels of two-hop transmission, estimating the combined channels, i.e., the cascade of two-hop channels, is an efficient way to simplify the channel estimation problems. The following brief review of the channel estimation in wireless relay channel is given from four classifications: single-antenna single-carrier case, single-antenna multi-carrier case, multi-antenna single-carrier case, and multi-antenna multi-carrier case.

Single-Antenna Single-Carrier Case

In Gao et al. (2008), the authors considered the channel estimation of single-antenna single-carrier one-way relay channel with multiple relay nodes. Assuming that h_i and g_i denotes the channel from source node S to the i-th relay node D_i and the channel from the i-th relay node D_i to the destination node D, respectively. Instead of estimating h_i and g_i individually, the authors considered to estimate the combined channel $h_i g_i$. The authors studied two estimation criterions, least square (L-S) and minimum mean-square-error (MMSE), by separately treating the unknown channels as deterministic variables and statistical random variables. The estimations of combined channel vector $\mathbf{w}$ for LS and MMSE using the received signal at the destination node $\mathbf{d}_2$ can be expressed as

$$\hat{\mathbf{w}} = \mathbf{A}_{\mathrm{LS}}\mathbf{d}_2, \qquad \hat{\mathbf{w}} = \mathbf{A}_{\mathrm{MMSE}}\mathbf{d}_2 \tag{1}$$

where matrices $\mathbf{A}_{\mathrm{LS}}$ and $\mathbf{A}_{\mathrm{MMSE}}$ are related to the training signal and the beamforming matrix used at each relay node; furthermore, matrix $\mathbf{A}_{\mathrm{MMSE}}$ is also related to the statistical information of the noise and channel. According to estimation theory, the authors derived the estimation error covariance matrix of two criterions. The training design was further investigated with an aim to minimize the estimation error, i.e., the trace of the estimation error covariance matrix. Different from the point-to-point channel estimation, the training design in this work included source training sequence design and relay beamforming matrices design. From the problem formulation, it is found that the optimization of source training sequence design and relay beamforming matrices design can be combined together, which implies that only one matrix variable **C** needs to be equivalently optimized in the training design problem. For the LS estimation, the authors proved that the columns of **C** should be orthogonal with each other at the optimal solution, and optimal training design can be found. For the MMSE estimation, the authors transformed the training design problem into a convex semi-definite programming (SDP) problem and the optimal solution can be efficiently solved by modern interior point method based on existing convex optimization software.

Later on, the channel estimations of single-antenna single-carrier two-way relay channel were studied in Gao et al. (2009b) and Xie et al. (2014). In Gao et al. (2009b), the authors studied the two-way relay channel taking a time reciprocal property, which means that the channel from the source to the relay is equal to the channel from the relay to this source. With this assumption, the involved four unknown channels reduce to two unknown channels. Denote the channel from the source S_i to the relay node by h_i, similarly to the one-way relay channel estimation in Gao et al. (2008), the authors proposed to estimate the variables $|h_i|^2$ and $|h_1 h_2|$ at terminal S_i instead of estimating h_1 and h_2. Two channel estimation criterions, i.e., the maximum-likelihood (ML) and linear maximum average effective signal-to-noise ratio (LMSNR), were utilized to obtain the estimations. In specific, the ML estimation treats the unknown channels as two deterministic values and channel estimation is obtained by solving the following problem (take source S_1 as an example)

$$\max_{|h_1|^2, |h_1 h_2|} \log p\,(z_1 | h_1, h_2) \tag{2}$$

where z_1 is the received signal at source S_1 and $p\ (z_1|h_1,\ h_2)$ is the probability density function (PDF) of z_1 at given h_1 and h_2. The LMSNR estimation treats the channels as unknown random values with known statistical information, and the channels are estimated by maximizing the effective SNR. Moreover, the training sequences at two sources were designed aiming to minimize the Cramer-Rao lower bound (CRLB) and maximize the average effective SNR. The results of optimizations showed that the optimal training sequences at two sources should be orthogonal with each other. In Xie et al. (2014), the authors proposed to use the Bayesian approach to estimate the cascaded source-relay-destination channel. The maximum a posteriori (MAP)-based estimation schemes were developed to estimate the cascaded channel and the amplitude of individual source-relay channels with apriori knowledge of channel distribution information. Additionally, to deal with some practical constraints, an iterative least square-MAP algorithm was developed when noise variance was unknown.

Single-Antenna Multi-Carrier Case

The channel estimation of the single-antenna one-way relay channel was studied in Gao et al. (2011) and Wang et al. (2016) with the orthogonal frequency division multiplexing (OFDM) modulation. In this channel setup, the overall end-to-end channel from the source to the destination is the convolution of the channel **h** from the source node to the relay node and the channel **g** from the relay node to the destination node in the time domain. In Gao et al. (2011), to allow the destination node to estimate **h** and **g**, besides sending the training signals at the source node, the relay superimposes its own training signal to the received training signal and sends them to the destination node. In this case, the transmit signal $\mathbf{r}_t$ at the relay can be represented as

$$\mathbf{r}_t = \alpha \mathbf{r}_r + \mathbf{t}_r \tag{3}$$

where $\mathbf{r}_r$ is the received signal at the relay node, α is the scaling factor used at the relay to satisfy the power constraint, and $\mathbf{t}_r$ is the new training signal superimposed at the relay node. It was shown that the closed-form expressions of estimated channel are generally not available in OFDM setup. To obtain an accurate estimation, an iterative channel estimation was proposed where $\mathbf{h}$ and $\mathbf{g}$ were separately updated during the iteration. Different from Gao et al. (2011), the channel was estimated jointly with the unknown carrier frequency offset (CFO) and phase noise (PN) in Wang et al. (2016) under the OFDM framework. To enable the joint estimation of MIMO individual channel, CFO and PN at the destination, the training sequences are assumed to be transmitted at both the source and the relay. Let $\mathbf{y}^{[r]}$ denote the received signal at the destination when relay transmits the training signal and $\mathbf{y}^{[s]}$ denote the received signal at the destination when source transmits the training signal. According to the MAP criterion, the estimations of individual channel, CFO, and PN can be obtained by solving the following optimization problem

$$\left\{\hat{\phi}^{[s-d]}, \hat{\eta}^{[s-d]}, \hat{\mathbf{h}}, \hat{\mathbf{g}}\right\} \propto \arg \min_{\phi^{[s-d]}, \eta^{[s-d]}, \mathbf{h}, \mathbf{g}} p\left(\phi^{[s-d]}, \eta^{[s-d]}, \mathbf{h}, \mathbf{g} | \mathbf{y}^{[s]}, \mathbf{y}^{[r]}\right) \tag{4}$$

where $\phi^{[s-d]}$ and $\eta^{[s-d]}$ denote the combined CFO from source to destination and the combined PN from source to destination; $\left\{\hat{\phi}^{[s-d]}, \hat{\eta}^{[s-d]}, \hat{\mathbf{h}}, \hat{\mathbf{g}}\right\}$ denotes the estimated version of $\{\phi^{[s-d]}, \eta^{[s-d]}, \mathbf{h}, \mathbf{g}\}$; $p\left(\phi^{[s-d]}, \eta^{[s-d]}, \mathbf{h}, \mathbf{g} | \mathbf{y}^{[s]}, \mathbf{y}^{[r]}\right)$ denotes the posterior distribution of the parameters of interests given $\mathbf{y}^{[s]}$ and $\mathbf{y}^{[r]}$. The ambiguities among the estimated PN, CFO, and channels were analyzed and showed that the estimated source-relay channel suffers from a phase ambiguity. Based on this analysis, a hybrid Cramer-Rao lower bound (HCRLB) for analyzing the performance was derived, which can effectively avoid the estimation ambiguities.

Regarding the single-antenna and multi-carrier two-way relay channel, the channel estimation was studied in the framework of OFDM modulation in Gao et al. (2009a). Different from Gao et al. (2011), the authors assumed that the training sequences were only transmitted from two sources while no training sequence was superposed at the relay node. Two estimation schemes, i.e., block-based and pilot-tone-based, were proposed to estimate the cascaded source-relay-destination channel and the individual channels, respectively. The block-based estimation scheme uses all carriers in one or more OFDM blocks for channel estimation and generally applies to a scenario where the training sequence is long enough. The pilot-tone estimation scheme uses several pilots residing in one OFDM block to estimate the channel and applies to the scenario with a length-limited training sequence. The estimation ambiguities of two schemes were further analyzed. In specific, the authors showed that when the length of training sequence is larger than a threshold, only the sign ambiguity can be introduced and it does not affect the finally data decoding.

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Multi-Antenna Single-Carrier Case

When considering multiple antennas at each node, the channel estimation of single-carrier one-way relay channel was investigated in Rong et al. (2012) and Kong and Hua (2011). The challenge of estimating the multi-input multi-output (MIMO) channels lies in the fact that the estimation variables become unknown matrices, while not the unknown values as in the single-antenna case. In Rong et al. (2012), the MIMO channels in source-relay-destination link and the MIMO channel in direct link were estimated without knowledge of the channel statistical information. In particular, the MIMO channel in direct link was estimated using LS criterion. Regarding the source-relay-destination link, according to the parallel factor (PARAFAC) analysis, the bilinear alternating least-squares (BALS) algorithm was proposed to obtain individual MIMO channels for source-relay link and relay-destination link. It was shown that with a mild length of training sequence, the MIMO channel matrices of two hops can be estimated up to permutation and scaling ambiguities. Moreover, the authors proposed to exploit the knowledge of the relay factors to remove the permutation ambiguity. In Kong and Hua (2011), the authors assumed that the statistical channel information was known in prior, and then the linear MMSE (LMMSE) estimation method was proposed to estimate the MIMO channels. To estimate the individual MIMO channels in each hop of the source-relay-destination link, the authors proposed a two-step estimation strategy where in the first step, the MIMO relay-destination channel is estimated assuming that the relay node is able to transmit training sequences. With the estimated MIMO relay-destination channel, the MIMO source-relay channel is then estimated at the destination node utilizing the training sequence sent from the source. For the first step, the optimal structure of relay training sequence matrix was derived according to the statistical information of the relay-destination channel. While for the second step, an algorithm was developed to compute the optimal training sequence matrix used at the source and the optimal precoding matrix used at the relay.

Later on, the channel estimation of the MIMO single-carrier two-way relay channel was studied in Wang et al. (2015). Similar to Kong and Hua (2011), the authors assumed that the statistical channel information was known in prior under a Kronecker-correlation model. Additionally, the MIMO channels were estimated in a colored noise environment by considering the impact of the antenna correlation and the interference from neighboring users. To estimate each individual MIMO channel, the authors proposed to decompose the bidirectional transmission of two-way relay channel into two phases, i.e., MAC phase and the BC phase. The optimal LMMSE estimators were derived for each phase. Two iterative training design algorithms were further proposed to obtain the training sequences for the general conditions and they were verified to produce training sequences achieving near optimal channel estimation performance. For certain specific practical scenarios where the covariance matrices of the channel or disturbances are of particular structures, the optimal training sequence design guidelines were provided. To assess the estimation performance, the relationship between the estimation performance and the length of training sequences were established, which showed that when the training sequence length is shorter than the threshold, a lower bound of estimation performance exists no matter how to increase the powers.

Multi-Antenna Multi-Carrier Case

The MIMO channel estimation was extended to multi-carrier case for two-way relay channel in Kang et al. (2017). Instead of estimating the individual channels, the authors in this study proposed to estimate the convolution of two MIMO individual channels using the self-interfering link and information-bearing link under the LMMSE criterion. The training sequences were optimized with an aim to minimize the total MSE under the power constraints at the sources and the relay. To obtain the optimal training sequences, the authors derived optimal structure which then converted the training design optimization problem into a tractable convex form.

Key Applications

Wireless relay is one of the fundamental techniques in cellular wireless communications. It can be efficiently used to extend the wireless coverage and enhance the network throughput in harsh environments with low economy cost.

Cross-References

▶ Cooperative Communications
▶ MIMO-based Network
▶ Signal Processing for Wireless Network

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