Performance Analysis for Analog Network Coding with Imperfect CSI in FDD Two Way Channels

Xidan PENG

Jiangxi Electric Power Corporation, Nanchang 330077, China
E-mail: sharon_ly_zhan@163.com

Xiangyang LI

Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
E-mail: lixiangyang@sjtu.edu.cn

Abstract A time-division duplex (TDD) two-way channel exploits reciprocity to estimate the forward channel gain from the reverse link. Many previous works explore outage probabilities in the TDD system, based on the reciprocity property. However, a frequency-division duplex (FDD) system has no reciprocity property. In this letter, we investigate the impact of CSI estimation error on the performance of non-orthogonal and orthogonal analog network coding protocols in an FDD two-way system, where channel gains are independent of each other. Considering imperfect CSI, the closed-form expressions of outage probabilities by two protocols are derived in the high signal-to-noise ratio (SNR) regime, respectively. It is shown that the derived outage probabilities match results of Monte Carlo simulations in different communication scenarios. It is interesting that ANC in the FDD two-way channel is proved to outperform that in the TDD channel by the computer simulation.

Keywords two-way; ANC; imperfect CSI; FDD

1 Introduction

Cooperative relaying has been shown to be a practical technique to enhance the communication range of wireless networks. In some practical scenarios where data flows in both directions, a relay improves the performance of both transmission directions simultaneously. This pragmatic approach has been modeled as a two-way relay channel, and has recently attracted significant interests. Of particular interest is an analog network coding (ANC) protocol for this channel, which is a well-known amplify-and-forward (AF)-based two-way relaying protocol^[1, 2]. However, these works assume that receivers have the perfect knowledge of channel state information (CSI). With the impact of system noise and imperfect channel estimation algorithms, receivers hardly have the perfect knowledge of CSI. Therefore, performance analysis that take into account such CSI uncertainties play an important role in the design of practical systems.

Very recently, some related works on ANC have taken into consideration the impact of imperfect CSI^[3–5]. These works consider a time division duplexing (TDD) system, where any given node exploits reciprocity to estimate the forward channel gain from the reverse link. This

condition can't be met in the FDD system since all channel gains are independent of each other. Thereby results of TDD systems in [3–5] aren't generated to FDD systems either due to more random variables. To the best of our knowledge, a performance analysis in term of outage probability in the FDD two way channel is still an open issue.

In this letter, we investigate the outage performance for ANC with imperfect CSI in the two way channel with FDD. Approximating expressions of outage probabilities for non-orthogonal and orthogonal ANC are derived in the high SNR regime. It is validated that Monte Carlo simulation results are in agreement with the derived outage probabilities.

2 System Model

In this letter, we consider an FDD two-way system with two sources S_1 , S_2 and a relay R . Sources S_1 and S_2 desire to exchange their information with the help of relay R . We assume that all terminals are equipped with a single antenna and operate in a half-duplex mode. Suppose transmissions in this system suffer from frequency nonselective fading and additive noises. We denote channel gains from S_1 to R , S_2 to R , R to S_1 , and R to S_2 by h_{s_1r} , h_{s_2r} , h_{rs_1} and h_{rs_2} , respectively. They are modeled as zero-mean, circularly symmetric complex Gaussian random variables, denoted by $h_{s_1r} \sim \mathcal{CN}(0, \Omega_{h,s_1r})$, $h_{s_2r} \sim \mathcal{CN}(0, \Omega_{h,s_2r})$, $h_{rs_1} \sim \mathcal{CN}(0, \Omega_{h,rs_1})$ and $h_{rs_2} \sim \mathcal{CN}(0, \Omega_{h,rs_2})$. These channel gains are assumed to be independent of each other, i.e. any given node cannot exploit reciprocity to estimate the forward channel gain from the reverse link in the FDD system. Considering channel estimation errors, we denote the estimations of channel gains by $\hat{h}_{s_1r}$, $\hat{h}_{s_2r}$, $\hat{h}_{rs_1}$ and $\hat{h}_{rs_2}$, respectively. We model the channel estimation by $h_{ab} = \hat{h}_{ab} + e_{ab}$, where $a, b \in \{s_1, s_2, r\}$, $\hat{h}_{ab} \sim \mathcal{CN}(0, \Omega_{\hat{h},ab})$, $e_{ab} \sim \mathcal{CN}(0, \Omega_{e,ab})$ is estimation error for channel gain h_{ab} . We also assume that all channel gains estimation errors are independent of each other. Without loss of generality, the transmit power of each terminal is set to be P , each additive noise power is Ω_0 . We also assume source node S_i transmits with a fixed rate v_i bits/Sec/Hz.

2.1 Non-orthogonal ANC

Due to the half-duplex constraint and the complete separation between the two source nodes, the communication process of non-orthogonal ANC is organized into two transmission phases in Figure 1, where two different transmission phases work in different frequency bands.

Figure 1 The two-way system where sources S_1 and S_2 desire to exchange their information via a relay R

In the first phase, both source nodes transmit simultaneously. The received signal at the relay R is expressed as $Y_r = \sum_{i=1}^2 h_{s_i r} \sqrt{P} X_i + n_r$, where X_i is the unit energy transmit symbol from S_i and $n_r \sim \mathcal{CN}(0, \Omega_0)$ is an additive noise at relay R . In the other phase, the relay amplifies its received symbol Y_r and then broadcasts toward both source nodes. The received signal at the source node S_i is given by $Y_i = h_{r s_i} \alpha_n Y_r + n_i$, where α_n is a power-scaled gain at relay R and $n_i \sim \mathcal{CN}(0, \Omega_0)$ is an additive noise at source S_i . We consider the short-term power constraint at the relay node R , and thus the power-scaled gain, α_n , is written as

$$\alpha_n = \sqrt{\frac{P}{|\hat{h}_{s_1 r}|^2 P + |\hat{h}_{s_2 r}|^2 P + \Omega_{e, s_1 r} P + \Omega_{e, s_2 r} P + \Omega_0}} \quad (1)$$

The signal Y_i can be rewritten as

$$\begin{aligned} Y_i = & \hat{h}_{s_j r} \hat{h}_{r s_i} \alpha_n \sqrt{P} X_j \\ & + \hat{h}_{s_i r} \hat{h}_{r s_j} \alpha_n \sqrt{P} X_i \text{ (Self-interference term)} \\ & + (\hat{h}_{s_j r} e_{r s_i} \alpha_n + \hat{h}_{r s_i} e_{s_j r} \alpha_n + e_{s_j r} e_{r s_i} \alpha_n) \sqrt{P} X_j \\ & + (\hat{h}_{s_i r} e_{r s_i} \alpha_n + \hat{h}_{r s_i} e_{s_i r} \alpha_n + e_{s_i r} e_{r s_i} \alpha_n) \sqrt{P} X_i \\ & + \hat{h}_{r s_i} n_r \alpha_n + e_{r s_i} n_r \alpha_n + n_i \end{aligned} \quad (2)$$

where j is the other element in set $\mathcal{A} = \{1, 2\}$, with a given element $i \in \mathcal{A}$ (e.g., if $i = 1$, then $j = 2$). Note that the definitions of i and j are used throughout this letter. Here we assume that the estimation of channel gains $\hat{h}_{s_1 r}$, $\hat{h}_{s_2 r}$, $\hat{h}_{r s_i}$ are obtained at source S_i by using some channel estimation techniques. We assume both sources simultaneously transmit pilot symbols, and the relay amplifies and forwards the symbols to both sources. Source S_i simultaneously estimates $\hat{h}_{s_1 r}$, $\hat{h}_{s_2 r}$ and $\hat{h}_{r s_i}$ by using the received pilot symbols (Alternatively, the relay estimates $\hat{h}_{s_1 r}$ and $\hat{h}_{s_2 r}$ by using pilot symbols, then forwards them to both sources^[2]. Source S_i also obtains $\hat{h}_{r s_i}$ by using pilot symbols from the relay). The power scaled gain α_n is also derived according to (1). Therefore the self-interference term $\hat{h}_{s_i r} \hat{h}_{r s_j} \alpha_n \sqrt{P} X_i$ in (2) can be known and canceled at source S_i . Therefore, the mutual information per transmission from source S_j to S_i is given by

$$\mathcal{I}_{s_j s_i}^n = \frac{1}{2} \log \left(1 + \frac{|\hat{h}_{s_j r}|^2 |\hat{h}_{r s_i}|^2 P^2}{b_{1i} (|\hat{h}_{s_i r}|^2 + |\hat{h}_{s_j r}|^2) + b_{2i} |\hat{h}_{r s_i}|^2 + b_{3i}} \right) \quad (3)$$

where parameters b_{1i} , b_{2i} and b_{3i} are denoted by

$$\begin{aligned} b_{1i} &= \Omega_{e, r s_i} P^2 + \Omega_0 P \\ b_{2i} &= \Omega_{e, s_j r} P^2 + \Omega_{e, s_i r} P^2 + \Omega_0 P \\ b_{3i} &= \Omega_{e, s_j r} \Omega_{e, r s_i} P^2 + \Omega_{e, s_i r} \Omega_{e, r s_i} P^2 + \Omega_{e, r s_i} \Omega_0 P \\ &\quad + \Omega_{e, s_i r} \Omega_0 P + \Omega_{e, s_j r} \Omega_0 P + \Omega_0^2 \end{aligned} \quad (4)$$

2.2 Orthogonal ANC

The communication of Orthogonal ANC consists of three transmission phases in Figure 1. In the first two transmission phases, two sources transmit signal, respectively. When source S_j transmits symbol X_j , signal $Y_{s_j r}$ overheard at relay R and signal $Y_{s_j s_i}$ at source S_i are

expressed as

$$\begin{aligned} Y_{s_j r} &= (\hat{h}_{s_j r} + e_{s_j r})\sqrt{P}X_j + n_{jr} \\ Y_{s_j s_i} &= (\hat{h}_{s_j s_i} + e_{s_j s_i})\sqrt{P}X_j + n_{ji} \end{aligned} \quad (5)$$

where $n_{jr} \sim \mathcal{CN}(0, \Omega_0)$ and $n_{ji} \sim \mathcal{CN}(0, \Omega_0)$ are additive noises at relay R and source S_i , respectively. In the third transmission phase, relay R amplifies sum of signals $Y_{s_1 r}$ and $Y_{s_2 r}$, and forwards two sources. Source S_i receives

$$\begin{aligned} Y_{rs_i} &= \hat{h}_{s_j r} \hat{h}_{rs_i} \alpha_o \sqrt{P}X_j \\ &\quad + \hat{h}_{s_i r} \hat{h}_{rs_i} \alpha_o \sqrt{P}X_i \text{ (Self-interference term)} \\ &\quad + (\hat{h}_{s_j r} e_{rs_i} \alpha_o + \hat{h}_{rs_i} e_{s_j r} \alpha_o + e_{rs_i} e_{s_j r} \alpha_o) \sqrt{P}X_j \\ &\quad + (\hat{h}_{s_i r} e_{rs_i} \alpha_o + \hat{h}_{rs_i} e_{s_i r} \alpha_o + e_{rs_i} e_{s_i r} \alpha_o) \sqrt{P}X_i \\ &\quad + \hat{h}_{rs_i} n_{ir} \alpha_o + \hat{h}_{rs_i} n_{jr} \alpha_o + e_{rs_i} n_{ir} \alpha_o + e_{rs_i} n_{jr} \alpha_o + n_{ir} \end{aligned} \quad (6)$$

where α_o is the power scaled gain with the short-power constraint, denoted by

$$\alpha_o = \sqrt{\frac{P}{|\hat{h}_{s_1 r}|^2 P + |\hat{h}_{s_2 r}|^2 P + \Omega_{e, s_1 r} P + \Omega_{e, s_2 r} P + 2\Omega_0}} \quad (7)$$

Similar to non-orthogonal ANC, the self-interference term can be canceled at source S_i to obtain residual signal $Y_{rs_i}^c$. Jointly proceeding signals $Y_{s_j s_i}$ and $Y_{rs_i}^c$ with the maximum combine ratio technique, orthogonal ANC achieves the mutual information per transmission as

$$\begin{aligned} \mathcal{I}_{s_j s_i}^o &= \frac{1}{3} \log \left(1 + \frac{|\hat{h}_{s_j s_i}|^2 P}{\Omega_{e, s_j s_i} P + \Omega_0} \right. \\ &\quad \left. + \frac{|\hat{h}_{s_j r}|^2 |\hat{h}_{rs_i}|^2 P^2}{c_{1i} (|\hat{h}_{s_i r}|^2 + |\hat{h}_{s_j r}|^2) + c_{2i} \hat{h}_{rs_i} + c_{3i}} \right) \end{aligned} \quad (8)$$

where parameters c_{1i} , c_{2i} and c_{3i} are shown as

$$\begin{aligned} c_{1i} &= \Omega_{e, rs_i} P^2 + \Omega_0 P, \\ c_{2i} &= \Omega_{e, s_j r} P^2 + \Omega_{e, s_i r} P^2 + 2\Omega_0 P, \\ c_{3i} &= \Omega_{e, s_j r} \Omega_{e, rs_i} P^2 + \Omega_{e, s_i r} \Omega_{e, rs_i} P^2 + 2\Omega_{e, rs_i} \Omega_0 P \\ &\quad + \Omega_{e, s_i r} \Omega_0 P + \Omega_{e, s_j r} \Omega_0 P + 2\Omega_0^2 \end{aligned} \quad (9)$$

3 Outage Probability Analysis

As clearly shown in (3) and (8), the forms of mutual information per transmission are not easily tractable due to the existence of imperfect channel gains and thus we approximately analyze their outage probabilities.

We define the system suffers from an outage if there exists one of both source nodes which decodes its received signals with error, and denote outage probabilities achieved by non-orthogonal ANC and orthogonal ANC by $\mathcal{P}_{\text{out}}^n$ and $\mathcal{P}_{\text{out}}^o$, respectively. The outage probability is expressed as

$$\mathcal{P}_{\text{out}}^z \triangleq 1 - \Pr \left(\bigcap_{i=1,2} \mathcal{I}_{s_j s_i}^z \geq v_j \right) \quad (10)$$

where $x \in \{o, n\}$ and v_j denotes the transmission rate of source node S_j . In the high SNR regime, system outage probability is approximated by its upper bound^[6], i.e.,

$$\mathcal{P}_{\text{out}}^z = \sum_{i=1}^2 \Pr(\mathcal{I}_{s_j s_i}^z < v_j) \quad (11)$$

3.1 Non-orthogonal ANC

For convenience, we set parameters as follows

$$\begin{aligned} u &= \frac{b_{1i}\Omega_0}{b_{3i}P} |\hat{h}_{s_j r}|^2 & v &= \frac{b_{2i}\Omega_0}{b_{3i}P} |\hat{h}_{r s_i}|^2 \\ w &= \frac{b_{1i}\Omega_0}{b_{3i}P} |\hat{h}_{s_i r}|^2 & \delta &= \frac{\Omega_0}{P} \\ h(\delta) &= \frac{(4^{v_j} - 1)b_{1i}b_{2i}}{P^2 b_{3i}} \frac{\Omega_0}{P} \end{aligned} \quad (12)$$

With these parameters and (3), probability $\Pr(\mathcal{I}_{s_j s_i}^n < v_j)$ can be expressed as

$$\Pr(\mathcal{I}_{s_j s_i}^n < v_j) = \Pr\left(\frac{uv}{u+v+w+\delta} < h(\delta)\right) \quad (13)$$

Theorem 1 *If $h(\delta)$ is continuous with $h(\delta) \rightarrow 0$ as $\delta \rightarrow 0$, and variables u, v, w are exponentially distributed with parameters $\lambda_u, \lambda_v, \lambda_w$ respectively, then*

$$\begin{aligned} &\lim_{\delta \rightarrow 0} \frac{1}{h(\delta)} \Pr\left(\frac{uv}{u+v+w+\delta} < h(\delta)\right) \\ &= \lambda_u + \lambda_v - \left[c + \ln\left(\frac{\lambda_u \lambda_v h(\delta)}{\lambda_w}\right) \right] \frac{\lambda_u \lambda_v}{\lambda_w} \end{aligned} \quad (14)$$

where $c \approx 0.577$ is the Euler Lorenzo Mascheroni constant.

Proof Let $\mathcal{P}_e = \Pr\left(\frac{uv}{u+v+w+\delta} < h(\delta)\right)$ and $x = u - h(\delta)$. The probability density function (PDF) of x is written as

$$f(x) = \begin{cases} \lambda_u e^{-\lambda_u [x+h(\delta)]}, & x \geq -h(\delta) \\ 0, & x < -h(\delta) \end{cases} \quad (15)$$

Then it is given by

$$\begin{aligned} \lim_{\delta \rightarrow 0} \frac{\mathcal{P}_e}{h(\delta)} &= \lim_{\delta \rightarrow 0} \frac{1}{h(\delta)} \Pr[x \leq 0] \\ &+ \lim_{\delta \rightarrow 0} \frac{1}{h(\delta)} \Pr\left[v < \frac{(u+w+\delta)h(\delta)}{x}, x > 0\right] \\ &= \lim_{\delta \rightarrow 0} \frac{1}{h(\delta)} \left[1 - e^{-\lambda_u h(\delta)}\right] + g_1 \end{aligned} \quad (16)$$

Setting $g_2 = h(\delta) + \frac{[w+\delta+h(\delta)]h(\delta)}{x}$, $g_3 = \lambda_u x + \frac{\delta h(\delta) + h^2(\delta)}{x}$, then

$$\begin{aligned} g_1 &= \lim_{\delta \rightarrow 0} \frac{1}{h(\delta)} \Pr\left[v < \frac{(u+w+\delta)h(\delta)}{x}, x > 0\right] \\ &= \lim_{\delta \rightarrow 0} \frac{1}{h(\delta)} \left[\int_0^\infty \int_0^\infty (1 - e^{-\lambda_v g_2}) f(x) f(w) dx dw \right] \\ &= \lim_{\delta \rightarrow 0} \frac{1}{h(\delta)} \left[e^{-\lambda_v h(\delta)} - \lambda_u e^{-(\lambda_u + \lambda_v)h(\delta)} \right. \\ &\quad \left. \times \int_0^\infty \left(\frac{\lambda_w}{\lambda_w + \lambda_v h(\delta) x^{-1}} \right) e^{-g_3} dx \right] \end{aligned} \quad (17)$$

Let $\delta h(\delta) + h^2(\delta) = 0$ due to $\delta h(\delta) + h^2(\delta) = \mathcal{O}(\delta^2)$. It becomes

$$\begin{aligned}
 \lim_{\delta \rightarrow 0} \frac{\mathcal{P}_e}{h(\delta)} &= \lim_{\delta \rightarrow 0} \frac{1}{h(\delta)} \left[1 - e^{-(\lambda_u + \lambda_v)h(\delta)} \int_0^\infty \lambda_u e^{-g^3} dx \right. \\
 &\quad \left. + e^{-(\lambda_u + \lambda_v)h(\delta)} \int_0^\infty \left(\frac{\lambda_u \lambda_v h(\delta)}{\lambda_w x + \lambda_v h(\delta)} \right) e^{-\lambda_u x} dx \right] \\
 &= \lim_{\delta \rightarrow 0} \frac{1}{h(\delta)} \underbrace{\left[1 - e^{-(\lambda_u + \lambda_v)h(\delta)} \int_0^\infty \lambda_u e^{-g^3} dx \right]}_{=\lambda_u + \lambda_v \text{ (Please see Lemma 1.2 in [7])}} \\
 &\quad + \lim_{h(\delta) \rightarrow 0} \underbrace{\left[\int_{\lambda_u \lambda_v \lambda_w^{-1} h(\delta)}^\infty \frac{1}{x} e^{-x} dx \right]}_{=E_i \left(\frac{\lambda_u \lambda_v h(\delta)}{\lambda_w} \right) \frac{\lambda_u \lambda_v}{\lambda_w} \text{ (Please see Equation 4.331.2 in [9])}} \frac{\lambda_u \lambda_v}{\lambda_w}
 \end{aligned} \tag{18}$$

With Eq 4.331.2 in [9] and Lemma 1.2 in [7], it holds.

With (11), (13) and Theorem 1, probability $\mathcal{P}_{\text{out}}^n$ is derived in (19) in the high SNR regime ($\delta \rightarrow 0$).

$$\mathcal{P}_{\text{out}}^n = \sum_{i=1}^2 \frac{(4^{v_j} - 1) b_{1i} b_{2i} \Omega_0}{b_{3i} P^3} \left[\frac{b_{3i} P}{b_{1i} \Omega_0 \Omega_{\hat{h}, s_j r}} + \frac{b_{3i} P}{b_{2i} \Omega_0 \Omega_{\hat{h}, r s_i}} - \left(c + \ln \frac{(4^{v_j} - 1) b_{1i} \Omega_{\hat{h}, s_i r}}{P^2 \Omega_{\hat{h}, s_j r} \Omega_{\hat{h}, r s_i}} \right) \frac{b_{3i} P \Omega_{\hat{h}, s_i r}}{b_{2i} \Omega_0 \Omega_{\hat{h}, s_j r} \Omega_{\hat{h}, r s_i}} \right] \tag{19}$$

$$\begin{aligned}
 \mathcal{P}_{\text{out}}^o &= \sum_{i=1}^2 \frac{(8^{v_j} - 1)^2 c_{1i} c_{2i} \Omega_0 (\Omega_{e, s_j s_i} P + \Omega_0)}{2 c_{3i} \Omega_{\hat{h}, s_j s_i} P^4} \\
 &\quad \left[\frac{c_{3i} P}{c_{1i} \Omega_0 \Omega_{\hat{h}, s_j r}} + \frac{c_{3i} P}{c_{2i} \Omega_0 \Omega_{\hat{h}, r s_i}} - \left(c + \ln \frac{(8^{v_j} - 1) c_{1i} \Omega_{\hat{h}, s_i r}}{P^2 \Omega_{\hat{h}, s_j r} \Omega_{\hat{h}, r s_i}} \right) \frac{c_{3i} P \Omega_{\hat{h}, s_i r}}{c_{2i} \Omega_0 \Omega_{\hat{h}, s_j r} \Omega_{\hat{h}, r s_i}} \right]
 \end{aligned} \tag{20}$$

3.2 Orthogonal ANC

Here some parameters are denoted by

$$\begin{aligned}
 x &= \frac{c_{1i} c_{2i} \Omega_0 |\hat{h}_{s_j s_i}|^2}{c_{3i} (\Omega_{e, s_j s_i} P + \Omega_0) P^2}, & u &= \frac{c_{1i} \Omega_0}{c_{3i} P} |\hat{h}_{s_j r}|^2 \\
 v &= \frac{c_{2i} \Omega_0}{c_{3i} P} |\hat{h}_{r s_i}|^2, & w &= \frac{c_{1i} \Omega_0}{c_{3i} P} |\hat{h}_{s_i r}|^2 \\
 \delta &= \frac{\Omega_0}{P}, & h(\delta) &= \frac{(8^{v_j} - 1) c_{1i} c_{2i} \Omega_0}{P^2 c_{3i}} \frac{\Omega_0}{P}
 \end{aligned} \tag{21}$$

Then we have

$$\Pr(\mathcal{I}_{s_j s_i}^o < v_j) = \Pr \left(x + \frac{uv}{u + v + w + \delta} < h(\delta) \right) \tag{22}$$

Lemma 1 Let x be an exponential random variable with mean $1/\lambda_x$, δ be a small positive number, and $h(\delta)$ be a continuous function that $h(\delta) \rightarrow 0$ as $\delta \rightarrow 0$. Let r_δ be a multi-variate function that is independent of variable x , and it satisfies the condition that $\lim_{\delta \rightarrow 0} \frac{\Pr[r_\delta < h(\delta)]}{h(\delta)} = A$, where A is a positive constant. Then

$$\lim_{\delta \rightarrow 0} \frac{1}{h^2(\delta)} \Pr[x + r_\delta < h(\delta)] = \frac{A \lambda_x}{2} \tag{23}$$

Lemma 1.3 in [7] is a special form of Lemma 1, in which $r_\delta = \frac{yz}{y+z+\delta}$, with y and z being two independent exponentially-distributed random variables. We observe that Lemma 1 holds even if the constraint on r_δ in Lemma 1.3 is relaxed and the proof of Lemma 1 is the same as Lemma 1.3 in [7], and will not be repeated here. With Lemma 1 and Theorem 1, probability $\mathcal{P}_{\text{out}}^o$ is derived in (20).

4 Simulation Results

Consider a two-way network topology where the distance between two sources is 100m, and the relay node is located on the line segment between two source nodes. We assume that the distance from source S_1 to the relay node is L m, and thus the distance from source S_2 to the relay is $(100 - L)$ m. The signal fading follows the quasi-static Rayleigh distribution and the average channel gain equals $d^{-\beta}$ [8], where d denotes the distance from transmitter to receiver and β is the path loss index. Let the path loss index β be 3 and the additive noise power Ω_0 be -70 dbm. We also assume that ratio $\frac{\Omega_{h,ab}}{\Omega_{h,ab}} = 0.995$ for transmitter a and receiver b where $a \in \{S_1, S_2, R\}$ and $b \in \{S_1, S_2, R\}$ in this channel.

Figure 2 OP versus distance L for non-orthogonal and orthogonal ANC, where $P = 20$ dbm and $v_1 = v_2 = 0.5$ bits/Sec/Hz

Figure 2 shows the system outage performance (OP) versus distance L for non-orthogonal and orthogonal ANC, where $P = 20$ dbm and $v_1 = v_2 = 0.5$ bits/Sec/Hz. It is shown that the derived OP for the two protocols match the simulated results, which validates the accuracy of our derived expressions. We also observe that orthogonal ANC outperforms non-orthogonal ANC due to higher diversity gain by using the link between source S_i to S_j , and FDD system achieves lower OP than TDD for both the protocols. Figure 3 shows OP versus transmission power P in different transmission-rate scenarios, where $L = 50$ m. Our derived curves are in agreement with the Monte Carlo simulation results. It is feasible to achieve the lower OP with smaller transmission rates. We also observe that OP reaches a fixed level, called error floor, due to the imperfection in the channel estimation.

Figure 3 OP versus transmission power P in different transmission-rate scenarios, where $L = 50\text{m}$

5 Conclusion

We have investigated the impact of imperfect CSI on the performance of non-orthogonal and orthogonal ANC in the FDD two way channel. The closed-formed expressions of outage probabilities achieved by non-orthogonal and orthogonal ANC have been derived in the high SNR regime. By using Monte Carlo simulation, it validates that the simulation results are in agreement with the derived results, and FDD system outperforms TDD in terms of OP.

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