Full-Duplex Relay in High-Reliability Low-latency Networks Operating with Finite Blocklength Codes

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Abstract

We consider a full-duplex (FD) relaying network operating with finite blocklength (FBL) codes. Based on Polyanskiy's FBL model, we characterize the FBL reliability of the relaying network under both decode-and-forward (DF) and amplify-and-forward (AF) relaying schemes. Following the model, we provide reliability-optimal designs via optimal power allocation for both schemes. In particular, for the FD DF relaying scheme, we prove that the (tightly approximated) overall error probability is convex in the transmit power at the relay. In addition, we show that minimizing the overall error probability of the FD AF relaying is equivalent to maximizing the overall signal to interference plus noise ratio (SINR), and further prove that this SINR is pseudo-concave in the transmit power of the FD AF relay. Via numerical analysis, we validate our analytical model and illustrate the performance of the considered FD relaying networks with different latency constraints, power levels of the residual loop interference, and data packet sizes. Moreover, we compare the performances of FD AF and FD DF relaying schemes, while the performance of direct transmission is provided as a reference.

Index Terms

Finite blocklength, full-duplex, relaying, error probability.

I. INTRODUCTION

Relaying is known as a fundamental technique to enhance the performance of wireless networks. By deploying a third transceiver as the relay, the destination likely receives a much stronger signal forwarded by the relay in comparison to the direct transmission by the source. This leads to improvements in terms of coverage, throughput and transmission reliability [1]–[4]. On the other hand, for the transmissions of data packets with certain latency constraints, (if equal time division is considered) a two-hop relaying halves the transmission time (and therefore the blocklength) compared to the direct transmission. In other words, in comparison to the direct transmission, relaying actually introduces a tradeoff between the received signal power and transmission blocklengths.

In conventional relaying networks, the relay operates in a half-duplex mode [2]–[4], where the transmissions of the two hops (i.e., the transmission from the source to the relay and the transmission from the relay to the destination) are operated in different time-frequency resources. By applying advanced self-interference cancellation [5], [6], a full-duplex (FD) relay enables the transmission of the two hops simultaneously, i.e., in the same time-frequency resource. In particular, the FD relaying has been shown to be more promising to achieve higher throughput compared to conventional half duplex systems.

However, all the above performance advantages of relaying are conducted under the ideal assumption of communicating arbitrarily reliably at rates close to Shannon's channel capacity. They thus implicitly assume an infinite blocklength for the transmission, which does not allow for the accurate assessment of the performance in networks operating with short blocklengths to satisfy the low-latency requirements. In the finite blocklength (FBL) regime, the error probability in communication is not negligible. Early in 1962, a normal approximation of the coding rate was presented in [7]. Recently, an achievable upper bound on the coding rate is identified in [8] for a single-hop transmission system, taking the error probability into account. The FBL performance characterization of [8] has been extended to Gilbert-Elliott channels [9], quasi-static flat-fading channels [10]–[12], mutiple access networks [13]–[15]. More recently, the FBL performance of a half-duplex (HD) relay network was analytically investigated in [16]–[19].

Most existing studies addressing the FBL performance of relaying are under the assumption of a HD relaying principle, while the FBL performance analysis of FD relaying networks are missing. Nevertheless, the approximated FBL throughput has been recently addressed in [20], where the a linear approximation of the Q-function in the FBL error probability model is adopted, i.e., it approximates the error probability in the reliable region to zero. In other words, an fundamental FBL performance characterization of the FD relaying with respect to reliability (addressing the interests of high-reliability and low-latency networks) and the reliability-optimal resource allocation designs are still open problems.

In this work, we consider a FD relaying network supporting high-reliability low-latency communications, where the relay works under decode-and-forward (DF) and amplify-and-forward (AF) schemes. We characterize the reliability models for both the FD DF relaying and FD AF relaying and provide corresponding reliability-optimal designs by applying optimal power allocation. A numerical comparison between the two relaying schemes shows that the FD DF relaying generally provides a higher reliability than the FD AF relaying for applications with a small packet size and a low-latency (short blocklength) constraint, while FD AF relaying is more preferred for transmissions with relatively larger data packets.

The remaining of the paper is organized as follows. In Section II, we first describe our FD relaying system model and review the FBL performance model. Subsequently, in Section III we study the achievable reliability of both the FD DF relaying and FD AF relaying under certain latency and power constraints. The numerical results are presented in Section IV, and the whole work is summarized in Section V.

II. Preliminaries

In this section, we first describe our system model. Subsequently, the FBL performance model is reviewed.

A. System model

We consider a simple scenario with a source S, a destination D and a FD relay R as schematically shown in Fig. 1. It is assumed that the direct link from S to D is attenuated while the communication from S to D only be established via the two-hop relaying.

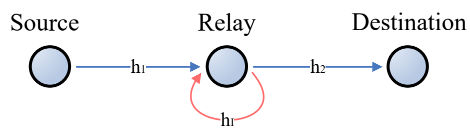

Fig. 1. Example of the considered two-hop FD relaying scenario.

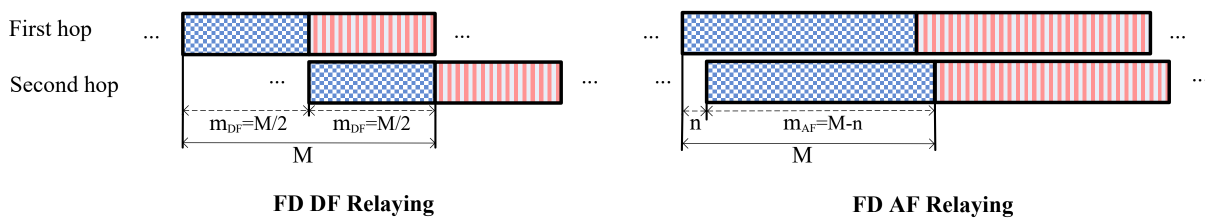

Fig. 2. Frame structures of the considered FD DF and DF AF relaying scenarios.

In a (two-hop) transmission period, a data packet with size D (bits) at S is transmitted. In particular, the data transmission is required to be finished under a latency constraint M (symbols). In addition, we consider a reliable transmission scenario, i.e., the error probability of the data transmission via the relay should be significantly lower than 10^{-1}.

In addition, both the AF and DF relaying schemes are considered, which result in different frame structures as shown in Fig. 2. The AF type of relay is also known as a repeater, which receives the radio frequency (RF) signals from the source, and amplifies and forwards the RF signals to the destination. Therefore, a FD AF relay could forward the received symbols of the code block immediately in a symbol level. Denoted by n the smallest amount of symbols can be recognized and forwarded by the FD AF relay. For a ideal case, the forwarding process of the FD AF relay operates per symbol, i.e., $n = 1$. In addition, we have $m_{\mathrm{AF}} = M - n$. Under the DF scheme, the relay needs to receive all the symbols of the first hop transmission for decoding and then forwards the data packet to the destination subsequently. This overcomes the drawback in the AF relaying of deteriorated received signal-to-interference-plus-noise ratio (SINR) caused by amplification of self-interference and noise [21]. On the other hand, the disadvantage of the FD DF relay is that it is not able to receive and forward the same data packet (carried by one codeword with a given length) at the same time. Hence, the blocklength of the two relaying hops under the DF scheme, denoted by m_{DF}, satisfies $2m_{\mathrm{DF}} = M$.

Denote by h_1 and h_2 the channel coefficients of the S-R backhaul link and R-D relaying link, and denote by L_i and z_i the gains of the path-loss and the channel fading. Then, we model $|h_i|^2 = L_i z_i, i = 1, 2$, where the fading gains are assumed to be constant in a transmission period. In addition, due to imperfect interference cancellation, the loop interference at the FD relay is significantly but not completely reduced. Denote by h_{RI} the residual loop interference at the relay. We assume perfect channel state information (CSI) at the receivers and in particular at the source. In addition, the total power budget/constraint for transmitting a data packet in a transmission period is P_{tot}, while the transmit power at the source and the relay are denoted by p_{S} and p_{R}, respectively.

For both the DF and AF schemes, the received signals (symbols) at R share the same expression, given by

$$y_1 = \sqrt{p_{\mathrm{S}}} h_1 x + \sqrt{p_{\mathrm{R}}} h_{\mathrm{RI}} x_{\mathrm{RI}} + w_1, \tag{1}$$

where x is the transmitted signal (symbol) and x_{RI} is the interference signal. Both x and x_{RI} have unit power. In addition, w_1 represents the additive white Gaussian noise (AWGN) in the S-R link with power σ_1^2. Then, the signal to interference plus noise ratio (SINR) at the relay is

$$\gamma_1 = \frac{p_{\mathrm{S}} |h_1|^2}{p_{\mathrm{R}} |h_{\mathrm{RI}}|^2 + \sigma_1^2} \tag{2}$$

On the other hand, the expressions of the received signals at D are different under the DF and AF schemes. In particular, the received signal at D under the DF scheme is given by[1]

$$y_{\mathrm{DF},2} = \sqrt{p_{\mathrm{R}}}h_2 x + w_2, \tag{3}$$

where w_2 is the AWGN in the S-R link with power σ_2^2. The SNR of $y_{\mathrm{DF},2}$ is given by

$$\gamma_{\mathrm{DF},2} = \frac{p_{\mathrm{R}}|h_2|^2}{\sigma_2^2}. \tag{4}$$

For the AF relaying case, the relay simply amplifies and forwards y_1, which results in a received signal at D given by

$$y_{\mathrm{AF},2} = \left(\sqrt{p_{\mathrm{S}}}h_1 x + \sqrt{p_{\mathrm{R}}}h_{\mathrm{RI}} x_{\mathrm{RI}} + w_1\right)\sqrt{G p_{\mathrm{R}}}h_2 + w_2, \tag{5}$$

where $G = \frac{1}{p_{\mathrm{S}}|h_1|^2 + p_{\mathrm{R}}|h_{\mathrm{RI}}|^2 + \sigma_2^2}$ is the gain of the amplifier. Hence, the SINR of the received signal at the destination is

$$\begin{aligned}\gamma_{\mathrm{AF},2} &= \frac{G p_{\mathrm{S}} p_{\mathrm{R}} |h_1|^2 |h_2|^2}{G p_{\mathrm{R}}^2 |h_{\mathrm{RI}}|^2 |h_2|^2 + G p_{\mathrm{R}} |h_2|^2 \sigma_1^2 + \sigma_2^2} \\ &= \frac{p_{\mathrm{S}} p_{\mathrm{R}} |h_1|^2 |h_2|^2}{p_{\mathrm{R}}^2 |h_{\mathrm{RI}}|^2 |h_2|^2 + p_{\mathrm{R}} |h_2|^2 \sigma_1^2 + \sigma_2^2\left(p_{\mathrm{S}}|h_1|^2 + p_{\mathrm{R}}|h_{\mathrm{RI}}|^2 + \sigma_2^2\right)}.\end{aligned} \tag{6}$$

B. The FBL performance model

In reference [8], the authors analyzed the performance in the FBL regime by applying the normal approximation. In comparison to the Shannon capacity bound, the finite blocklength model is more accurate when the blocklength is finite/short. In addition, the third-order term in the normal approximation for the AWGN channel is further addressed in [22]. For an AWGN channel, the coding rate r (in bits per channel use) with error probability $0 < \varepsilon < 1$, signal-to-noise ratio (SNR) γ, and blocklength m is shown to have the following asymptotic expression [22]:

$$r = \mathcal{R}(\gamma, \varepsilon, m) \approx \mathcal{C}(\gamma) - \sqrt{\frac{V(\gamma)}{m}} Q^{-1}(\varepsilon) + \frac{\log m}{m}, \tag{7}$$

where $\mathcal{C}(\gamma) = \log(1+\gamma)$, $V(\gamma) = \frac{\gamma(\gamma+2)}{(\gamma+1)^2}\log^2 e$ and $Q(x) = \int_x^\infty \frac{1}{\sqrt{2\pi}} e^{-t^2/2} dt$ is the Gaussian Q-function.

Form (7), the (block) error probability can be expressed as:

$$\varepsilon = \mathcal{P}(\gamma, r, m) \approx Q\left(\frac{\mathcal{C}(\gamma) + \frac{\log m}{m} - r}{\sqrt{V(\gamma)/m}}\right). \tag{8}$$

In this paper, we apply the above approximations for investigating the finite blocklength performance of the FD AF and FD DF relaying schemes. As these approximations have been shown to be accurate for a sufficiently large value of m [8], for simplicity we will employ them as the rate and error expressions in our analysis.

III. Achievable Reliability of FD Relaying under Latency and Power Consumption Constraints

In this section, we develop the reliability models of both FD DF and FD AF relaying schemes. In particular, we minimize the overall error probability of the two-hop transmission by applying optimal power allocation under a given latency constraint M and a power consumption constraint Mp_{tot}. We first discuss the FD DF relaying scheme and subsequently address the AF scheme.

A. Achievable FBL Reliability of FD DF Relaying

According to (2) and (8), the decoding error probability at the FD DF relay is obtained by $\varepsilon_{\mathrm{DF},1} = \mathcal{P}\left(\gamma_1, \frac{2D}{M}, \frac{M}{2}\right)$. Similarly, the decoding error probability at the destination is $\varepsilon_{\mathrm{DF},2} = \mathcal{P}\left(\gamma_{\mathrm{DF},2}, \frac{2D}{M}, \frac{M}{2}\right)$. Hence, the overall error probability of transmitting a data packet via the two-hop FD DF relaying is given by

$$\begin{aligned}\varepsilon_{\mathrm{DF}} &= \varepsilon_{\mathrm{DF},1} + \varepsilon_{\mathrm{DF},2} - \varepsilon_{\mathrm{DF},1}\varepsilon_{\mathrm{DF},2} \\ &\approx \varepsilon_{\mathrm{DF},1} + \varepsilon_{\mathrm{DF},2},\end{aligned} \tag{9}$$

while the approximation is tight due to the fact that $\varepsilon_{\mathrm{DF},1} + \varepsilon_{\mathrm{DF},2} \gg \varepsilon_{\mathrm{DF},1}\varepsilon_{\mathrm{DF},2}$ holds as we consider a high reliability network with $\max\{\varepsilon_{\mathrm{DF},1}, \varepsilon_{\mathrm{DF},2}\} < \varepsilon_{\mathrm{DF}} \ll 10^{-1}$. In the following, we consider minimizing $\varepsilon_{\mathrm{DF},1} + \varepsilon_{\mathrm{DF},2}$ to obtain the achievable reliability of the FD DF scheme.

[1] It should be pointed out that the DF relay only forwards the data packet to D when it decodes the signal form S successfully in the first hop. Due to the FBL, errors possibly occurs in this hop. The probability of the error will be later on discussed in Section III.

$$\frac{\partial w_{\mathrm{DF},i}}{\partial \gamma_i} = \frac{2\log^2 e}{M}\frac{(1+\gamma_i)^2 - \left(1+\log(1+\gamma_i)+\frac{\log(M/2)}{M/2}-\frac{2D}{M}\right)}{V(\gamma_i)^{\frac{3}{2}}(1+\gamma_i)^3} \geq \frac{2\log^2 e}{M}\frac{(1+\gamma_i)^2-(1+\log(1+\gamma_i))}{V(\gamma_i)^{\frac{3}{2}}(1+\gamma_i)^3}. \tag{13}$$

$$\begin{aligned}\frac{\partial w^2{}_{\mathrm{DF},i}}{\partial {\gamma_i}^2} &= \frac{4\log^4 e}{M^2}\left((1+\gamma_i)^2-1\right)^{\frac{1}{2}}\frac{\left((1+\gamma_i)^2-1\right)\left(2(1+\gamma_i)-\frac{1}{1+\gamma_i}\right)-3(1+\gamma_i)\left((1+\gamma_i)^2-1-\log(1+\gamma_i)-\frac{\log(M/2)}{M/2}+\frac{2D}{M}\right)}{V(\gamma_i)^3(1+\gamma_i)^6}\\ &= \frac{4\log^4 e}{M^2}\left((1+\gamma_i)^2-1\right)^{\frac{1}{2}}\frac{-(1+\gamma_i)^2+\frac{1}{(1+\gamma_i)^2}+3\left(\log(1+\gamma_i)+\frac{\log(M/2)}{M/2}-\frac{2D}{M}\right)}{V(\gamma_i)^3(1+\gamma_i)^5}\\ &\leq \frac{4\log^4 e}{M^2}\frac{\left((1+\gamma_i)^2-1\right)^{\frac{1}{2}}}{V(\gamma_i)^3(1+\gamma_i)^5}\left[-(1+\gamma_i)^2+\frac{1}{(1+\gamma_i)^2}+3\log(1+\gamma_i)\right].\end{aligned} \tag{14}$$

Obviously, $\varepsilon_{\mathrm{DF},1}+\varepsilon_{\mathrm{DF},2}$ is influenced by the choices of P_{S} and P_{R}. Note that under the power consumption constraint, we have $\frac{M}{2}P_{\mathrm{S}}+\frac{M}{2}P_{\mathrm{R}}=MP_{\mathrm{tot}}$, i.e., $P_{\mathrm{S}}+P_{\mathrm{R}}=2P_{\mathrm{tot}}$. Hence, the achievable reliability of the FD DF relaying can be obtained by solving the following optimization problem

$$\begin{aligned}\min_{P_{\mathrm{R}}} \quad & \varepsilon_{\mathrm{DF},1}+\varepsilon_{\mathrm{DF},2}\\ s.t. \quad & P_{\mathrm{S}}=2P_{\mathrm{tot}}-P_{\mathrm{R}}>0,\\ & P_{\mathrm{R}}>0.\end{aligned} \tag{10}$$

To solve Problem (10), we provide the following proposition

Proposition 1. *Considering a FD DF relaying network supporting a reliable transmission where target error probability $\varepsilon_{\mathrm{DF}} \leq 10^{-1}$ and the SNR/SINR of each link $\gamma_i \geq 0$ dB hold, the objective of Problem* (10) *is convex in P_{R}.*

Proof. According to (9), we prove the proposition by showing $\frac{\partial^2 \varepsilon_{\mathrm{DF},i}}{\partial {P_{\mathrm{R}}}^2} \geq 0$ for link i, $i=1,2$. Based on (8), we have

$$\frac{\partial \varepsilon_{\mathrm{DF},i}}{\partial \gamma_i} = \frac{1}{\sqrt{2\pi}}\exp\left(-\frac{w_{\mathrm{DF},i}^2}{2}\right)\frac{\partial w_{\mathrm{DF},i}}{\partial \gamma_i}, \tag{11}$$

$$\frac{\partial^2 \varepsilon_{\mathrm{DF},i}}{\partial {\gamma_i}^2} = \frac{1}{\sqrt{2\pi}}\exp\left(-\frac{w_{\mathrm{DF},i}^2}{2}\right)\left(w_{\mathrm{DF},i}\left(\frac{\partial w_{\mathrm{DF},i}}{\partial \gamma_i}\right)^2-\frac{\partial^2 w_{\mathrm{DF},i}}{\partial {\gamma_i}^2}\right), \tag{12}$$

where $w_{\mathrm{DF},i}(\gamma_i)=\frac{\mathcal{C}(\gamma_i)-2D/M}{\sqrt{2V(\gamma_i)/M}}$. In addition, the first and second order derivatives of $w_{\mathrm{DF},i}$ to γ_i are given in (13) and (14) on top of next page, where the inequalities hold due to that fact that according to (7) it holds $\mathcal{C}(\gamma)+\frac{\log m}{m}-r=\sqrt{\frac{V(\gamma)}{m}}Q^{-1}(\varepsilon)\geq 0$ for $\varepsilon<0.5$. Denote $f(x)=x^2+2x-\log(1+x), x\in[0,+\infty)$. Since $f(0)=0$ and $f'(x)=2x+2-1/(1+x)<0$ hold, we have $f(x)\geq 0, x\in[0,+\infty)$. Applying this to (13), we have $\frac{\partial w_{\mathrm{DF},i}}{\partial \gamma_i}\geq 0$, since $\gamma_i\in[0,+\infty)$ and therefore $(1+\gamma_i)^2-(1+\log(1+\gamma_i))={\gamma_i}^2+2\gamma_i-\log(1+\gamma_i)>0$. In addition, it can be also shown that $-(1+\gamma_i)^2+\frac{1}{(1+\gamma_i)^2}+3\log(1+\gamma_i)\leq 0$ for $\gamma_i>1$. Hence, $\frac{\partial w^2{}_{\mathrm{DF},i}}{\partial {\gamma_i}^2}\leq 0$ holds. Combining $\frac{\partial w_{\mathrm{DF},i}}{\partial \gamma_i}\geq 0$ and $\frac{\partial w^2{}_{\mathrm{DF},i}}{\partial {\gamma_i}^2}\leq 0$ to (11) and (12), $\frac{\partial \varepsilon_{\mathrm{DF},i}}{\partial \gamma_i}\geq 0$ and $\frac{\partial^2 \varepsilon_{\mathrm{DF},i}}{\partial {\gamma_i}^2}\geq 0$.

So far, we have studied the relationship between $\varepsilon_{\mathrm{DF,i}}$ and γ_i. Next, let us consider the relationship between γ_i and P_{R} for $i=1,2$. Combining $P_{\mathrm{S}}+P_{\mathrm{R}}=2P_{\mathrm{tot}}$ with (2), we have $\gamma_1=\frac{(2p_{\mathrm{tot}}-p_{\mathrm{R}})|h_1|^2}{p_{\mathrm{R}}|h_{\mathrm{RI}}|^2+\sigma_1^2}$. Then, $\frac{\partial^2 \gamma_1}{\partial {P_{\mathrm{R}}}^2}=\frac{\sigma_1^2|h_1|^2|h_{\mathrm{RI}}|^2+2p_{\mathrm{tot}}|h_1|^2|h_{\mathrm{RI}}|^4}{\left(p_{\mathrm{R}}|h_{\mathrm{RI}}|^2+\sigma_1^2\right)^4}\geq 0$ holds. In addition, based on (4), we have $\frac{\partial^2 \gamma_2}{\partial {P_{\mathrm{R}}}^2}=0$.

Combining the above results together, for $i=1,2$. we have

$$\frac{\partial^2 \varepsilon_{\mathrm{DF},i}}{\partial {P_{\mathrm{R}}}^2} = \underbrace{\frac{\partial^2 \varepsilon_{\mathrm{DF},i}}{\partial {\gamma_i}^2}}_{\geq 0}\underbrace{\left(\frac{\partial \gamma_i}{\partial P_{\mathrm{R}}}\right)^2}_{\geq 0}+\underbrace{\frac{\partial \varepsilon_{\mathrm{DF},i}}{\partial \gamma_i}}_{\geq 0}\underbrace{\frac{\partial^2 \gamma_i}{\partial {P_{\mathrm{R}}}^2}}_{\geq 0}\geq 0. \tag{15}$$

□

According to Proposition 1, there exists a global optimal solution to Problem (10), which can be solved efficiently via convex optimization tools [23].

B. Achievable FBL Reliability of FD AF Relaying

According to (8), the overall error probability of the transmission via a DF AD relay is given by

$$\varepsilon_{\mathrm{AF}} = \mathcal{P}\left(\gamma_{\mathrm{AF},2}, \frac{D}{M-n}, M-n\right). \tag{16}$$

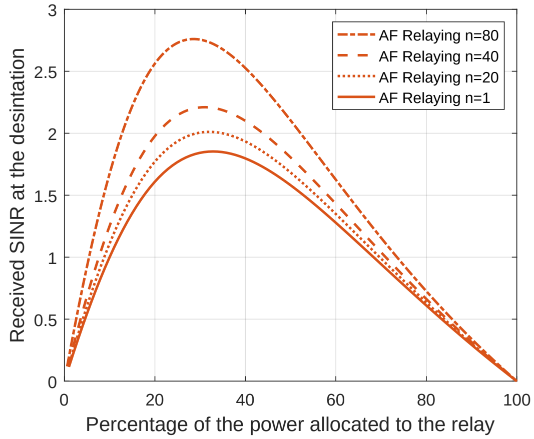

Fig. 3. The impact of power allocation on the SINR of FD AF relaying.

We consider to minimize the error probability by applying optimal power allocation, which is formulated as

$$\begin{aligned} \min_{p_{\mathrm{R}}} \quad & \varepsilon_{\mathrm{AF}} \\ s.t. \quad & p_{\mathrm{S}} = \tfrac{M}{M-n} p_{\mathrm{tot}} - p_{\mathrm{R}} > 0, \\ & p_{\mathrm{R}} > 0, \end{aligned} \tag{17}$$

where the first constraint is due to $(M-n)p_{\mathrm{S}} + (M-n)p_{\mathrm{R}} = Mp_{\mathrm{tot}}$.

According to the proof of Proposition 1, it is clear that the error probability given in (8) is decreasing in the corresponding SNR/SINR. Hence, the solution to Problem (17) is same as maximizing $\gamma_{\mathrm{AF},2}$, which is given by

$$\begin{aligned} \max_{p_{\mathrm{R}}} \quad & \gamma_{\mathrm{AF},2} \\ s.t. \quad & p_{\mathrm{S}} = \tfrac{M}{M-n} p_{\mathrm{tot}} - p_{\mathrm{R}} > 0, \\ & p_{\mathrm{R}} > 0. \end{aligned} \tag{18}$$

Proposition 2. *Problem* (18) *is a pseudo-convex problem.*

Proof. By substituting $p_{\mathrm{R}} = \frac{M}{M-n} p_{\mathrm{tot}} - p_{\mathrm{S}}$ into Equation (6), we have $\gamma_{\mathrm{AF},2} = \frac{A(p_{\mathrm{R}})}{B(p_{\mathrm{R}})}$ where $A(p_{\mathrm{R}}) = -{p_{\mathrm{R}}}^2 \cdot |h_1|^2 |h_2|^2 + p_{\mathrm{R}} \cdot \frac{M}{M-n} |h_1|^2 |h_2|^2 p_{\mathrm{tot}}$ and $B(p_{\mathrm{R}}) = p_{\mathrm{R}}^2 \cdot |h_{\mathrm{RI}}|^2 |h_2|^2 + p_{\mathrm{R}} \cdot \left(|h_2|^2 \sigma_1^2 - |h_1|^2 \sigma_2^2 + |h_{\mathrm{RI}}|^2 \sigma_2^2 \right) + \left(\frac{M}{M-n} p_{\mathrm{tot}} |h_1|^2 + \sigma_2^2 \right)$. Note that both $A(p_{\mathrm{R}})$ and $B(p_{\mathrm{R}})$ are quadratic functions with respect to p_{R}. It is easy to show that $A(p_{\mathrm{R}})$ is concave in p_{R} and $B(p_{\mathrm{R}})$ is convex in p_{R}, respectively. According to the results in Section 3.4.5 of [23], $\gamma_{\mathrm{AF},2}$ is pseudo-concave in p_{R} under the constraint $p_{\mathrm{S}} + p_{\mathrm{R}} = \frac{M}{M-n} p_{\mathrm{tot}}$. Hence, Problem (18) is pseudo-concave and can be efficiently solved by Dinkelbach algorithm (in polynomial time) [24]. □

IV. Numerical results

In this section, we provide numerical results to validate our analytical model and evaluate the system performance. In particular, the reliability performances of both the FD AF relaying and FD DF relaying are compared to the direct transmission with blocklength M, SNR $\gamma_{\mathrm{direct}} = \frac{p_{\mathrm{tot}} |h_{\mathrm{direct}}|^2}{\sigma_2^2}$, where the error probability of the direct transmission is given by $\varepsilon_{\mathrm{direct}} = \mathcal{P}\left(\gamma_{\mathrm{direct}}, \frac{D}{M}, M\right)$. In all our numerical analysis, we consider the following parameter setups: First, we set the distances from the source to the relay and from the relay to the destination to $d_1 = d_2 = 200$ m, and we assume a linear topology where the distance of the direct transmission is given by $d_1 + d_2 = 400$ m. In addition, we adopt the general pathloss model from [25], which is given by $L_i = L(d_0) + 10\alpha \cdot \log(\frac{d_i}{d_0})$, where $L(d_0)$ is determined by the free space pathloss at reference distance $d_0 = 100$m, and the pathloss exponent is set to $\alpha = 3.5$. Moreover, we consider the unit transmit power $P_{\mathrm{tot}} = 1$ and set the noise power to -100 dBm. The power of the residual loop interference is set to -95 dBm. Finally, we set $M = 200$ symbols and $D = 200$ bits (while we vary them in Fig. 5 and Fig. 7).

We start with Fig. 3 to study the impact of the power allocation on the SINR $\gamma_{\mathrm{AF},2}$ in the FD AF relaying scheme. As shown in the figure, the SINR is pseudo-concave in the percentage of power allocated to the relay, which confirms Proposition 2. In addition, a shorter length of n results in a lower SINR. This is due to the fact that the total power consumption for transmitting a packet with size D is limited by Mp_{tot}. A short n indicates a long blocklength of each hop of relaying, given by $M-n$, thus reducing the (per symbol) transmit power of the two hops, i.e., $p_{\mathrm{S}} + p_{\mathrm{R}} = \frac{M}{M-n} p_{\mathrm{tot}}$ is reduced as n deceases. As a result, the received SINR at the destination is weakened.

Then, we discuss the corresponding reliability results of Fig. 3. These results are provided in Fig. 4 where the performance of the FD DF relaying and the direct transmission are also presented. From the figure, we observe that the direct transmission

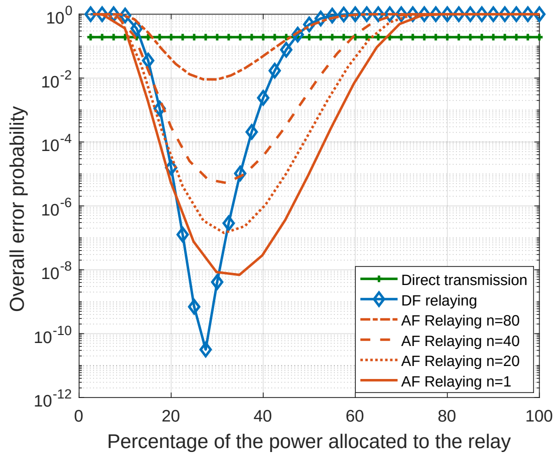

Fig. 4. The impact of power allocation on the overall error probability.

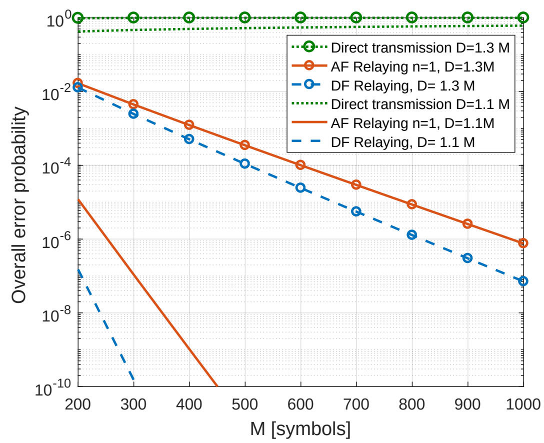

Fig. 5. The impact of latency constraint M on the achievable reliability.

is not preferred in a reliable transmission scenario. In addition, the overall error probabilities of FD AF relaying (with different lengths of n) are generally lower than the FD DF relaying. Moreover, it matches with Proposition 1 that the overall error probability of the FD DF relaying is convex in the power allocated to the relay. Furthermore, although it is shown in Fig. 3 that a small n results in a lower achievable SINR, having a small n leads also to a low coding rate (given by $D/(M-n)$) of each hop of the FD AF relaying. As a result, it can be observed from Fig. 4 that for the FD AF relaying, a shorter n makes the transmission more reliable. Actually, this indicates that it is a promising way to improve the reliability of the FD AF relaying by reducing n, i.e., the gain from decreasing the coding rate is higher than the loss of the SINR. Furthermore, under the FD AF scheme, the optimal decisions of power allocation are different for the scenarios with different values of n. In particular, a relatively lower p_{R} is preferred when n is short.

Next, we study the achievable (optimal) overall error probability over the power allocation in both the FD AF and FD DF relaying schemes. We vary the latency constraint M in Fig 5, while increasing the packet size with M, i.e., $D = k \cdot M, k = 1.1, 1.3$. On the one hand, the reliability of the direct transmission is relatively constant as M increases. On the other hand, all overall error probability curves of FD relaying are decreasing in M but with different slopes. In particular, the FD DF relaying is relatively more sensitive than the FD AF relaying in increasing M, i.e., the FD DF curves are relatively more steeper. In addition, for both FD AF and FD DF relaying schemes, the scenarios with relatively shorter packet sizes gain more from increasing M, i.e., curves representing the scenario with $D = 1.1M$ are steeper than the ones with $D = 1.3M$.

We investigate the impact of the residual loop interference on the reliability performance in Fig. 6, where we vary the power of the residual loop interference from -105 dBm to -90 dBm. Noting that the noise power in the simulation is set to -100 dBm, the figure actually illustrates the impacts of the residual interference when it is higher or lower than the noise power. First of all, as expected, a lower residual interference introduces a higher reliability for both the two FD relaying schemes. In particular, when the packet size is relatively smaller, the reliability enhancement by reducing the residual interference is more significant, i.e., the slopes of the curves with $D = 200$ bits are steeper than the curves with $D = 300$ bits. This results actually suggests for applications with small packets but high reliability requirements, it is more beneficial to spend additional cost to achieve a better interference cancellation. More surprisingly, we observe that when the packet size is relatively larger, the FD AF relaying becomes more reliable than the FD DF relaying.

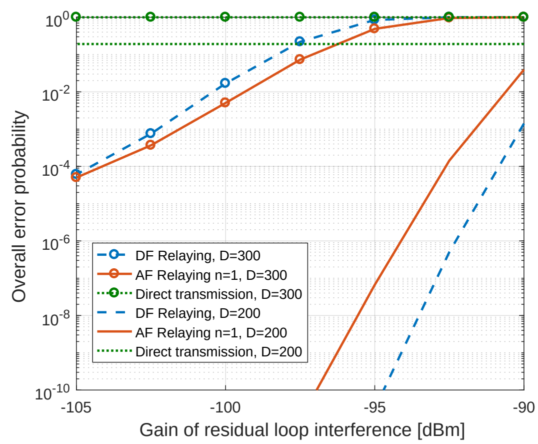

Fig. 6. The impact of the residual loop interference on the achievable reliability. In the simulation, we set $M = 200$ symbols.

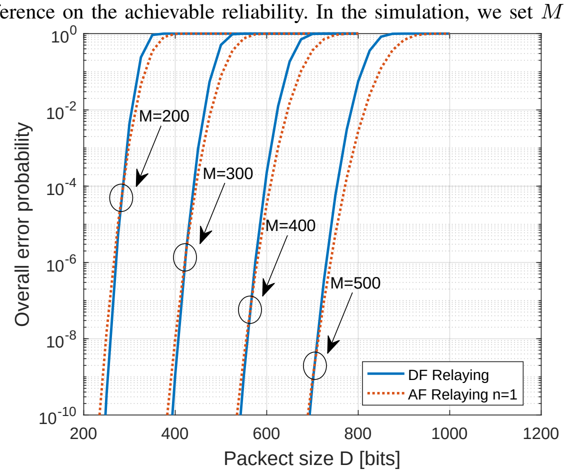

Fig. 7. The impact of the packet size on the achievable reliability. In the simulation, we set the residual loop interference to -100 dBm.

The results in Fig. 6 actually indicate that the relationship between the FD AF relaying and FD DF relaying is strongly influenced by the packet size. This motivates us to further compare the two relaying schemes in Fig. 7 by varying the packet size, while different setups of M are considered. It matches well with Fig. 6 that the FD AF relaying is possible to be more reliable than the FD DF relaying. In particular, the FD DF relaying is more reliable in the relatively lower error probability region. At the same time, when the coding rate is such high that the system becomes relatively less highly reliable, the FD AF relaying is more preferred, i.e., in the region above the crossing point between the curves in each pair. Finally, it should pointed out that the region (in which the FD AF relaying is in a dominant position) expands as M increases, i.e., the crossing point between the curves of the two relaying schemes is moving to the lower error probability region as M increases.

V. Conclusion

In this work, we characterized the reliability in the FBL regime for a network operating with FD DF and FD AF relaying schemes. Following the characterizations, we provided optimal power allocation designs for both the two relaying schemes to minimize the overall error probability under latency and power constraints. In particular, we have proved that under the FD DF relaying scheme the (approximated) overall error probability is convex in the transmit power at the relay. In addition, we showed that minimizing the overall error probability of the FD AF relaying is equivalent to maximizing the overall SINR, and this SINR has been proved to be a pseudo-convex function of the transmit power at the FD AF relay. All the provided analytical models have been validated by numerical results. In particular, by numerical analysis, the direct transmission has been shown to be not preferred in reliable transmission scenarios. Moreover, the FD DF relaying generally provides a higher reliability performance than the FD AF relaying for applications with a small packet size and a low-latency constraint (corresponding to a short blocklength). In particular, the region, within which the FD DF relaying outperforms the FD AF relaying, is squeezed as the latency constraint becomes loose.

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