On the Performance Advantage of Relaying under the Finite Blocklength Regime

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***Abstract*—We consider a two-phase relaying system with finite blocklengths. We study the performance difference of relaying under the finite blocklength regime as well as under the Shannon capacity regime. Most importantly, we are interested in the conditions that lead to a higher performance of relaying under the finite blocklength regime. We find that these situations are characterized by error probabilities of relaying, e.g., the overall error probability of relaying and the error probability of the bottleneck link of relaying. We identify scenarios where relaying outperforms direct transmission under the finite blocklength regime even if their performances are similar under the Shannon capacity regime. Moreover, we prove that under these scenarios the performance advantage of relaying is more significant with short blocklengths. Finally, numerical results are provided and discussed.**

***Index Terms*—Finite blocklength, relaying, coding rate, error probability.**

I. INTRODUCTION

Under the ideal assumption of communicating arbitrarily reliably at Shannon capacity, existing works [1]–[5] show that relaying is a promising technique to improve the performance of wireless networks. However, the error-free communication is generally achieved under an infinite blocklength assumption which clearly is over-optimistic in practice. By considering the (block) error probability of finite blocklength (FB) codes, [6] identifies a tight bound of the coding rate (in bits per channel use) for a single-hop transmission system. A considerable performance loss [6] is introduced in this case in comparison to the Shannon capacity regime. Moreover, this performance loss increases as the blocklength decreases. This motivates us to consider the performance of relaying under the FB regime as (if equal time division is considered) relaying halves the transmission time (and therefore the blocklength) compared to direct transmission. As a result, relaying potentially introduces an additional performance loss.

In our recent work [7] under the assumption that the channel gain of the direct link is extremely low, in general we address analytical performance models for relaying with FBs. Through simulations it is observed in [7] that the performance loss (due to finite blocklength) of relaying is much smaller than expected, while the performance loss of direct transmission is larger. This observation seems counterintuitive as relaying halves the blocklength. Thus, in this letter we consider a more general scenario where we do not have any specific assumptions on the direct link. We first analyze theoretically the performance difference between relaying under the FB regime and under the Shannon capacity regime. Moreover, we investigate the theoretical conditions under which relaying outperforms direct transmission under the FB regime. Finally, numerical results are provided and discussed.

II. SYSTEM MODEL

We consider a simple scenario with a source S, a destination D and a decode-and-forward (DF) relay R as schematically shown in Fig. 1. Time is divided into frames, and in the direct transmission case each frame is used to transmit a data block from the source to the destination using $2m$ symbols. For relaying, each frame is divided into two phases (each with length m) which are referred to as broadcasting phase and relaying phase. In the broadcasting phase, the source sends a data block to the relay and the destination. Afterwards, if the relay decodes the block successfully, it forwards the block to the destination in the subsequent relaying phase. We also consider real channels and denote the channel vectors of the S-D direct link, the S-R backhaul link and the R-D access link by h_1, h_2 and h_3. In addition, the transmit power at the relay and the source is denoted by p_{tx}. Hence, the received signals at the destination and the relay in a broadcasting frame are given by: $\mathbf{y}_1 = h_1\mathbf{x} + \mathbf{n}_1$ and $\mathbf{y}_2 = h_2\mathbf{x} + \mathbf{n}_2$. Next, if the data is decoded correctly and forwarded by the relay, the received signal at the destination in a relaying frame is given by $\mathbf{y}_3 = h_3\mathbf{x} + \mathbf{n}_3$. The transmitted signal $\mathbf{x}$ and received signals $\mathbf{y}_1, \mathbf{y}_2$ and $\mathbf{y}_3$ are real m-dimensional vectors. Furthermore, $\mathbf{n}_k, k = 1, 2, 3$ represents the real Gaussian noise vector $\mathbf{n}_k \sim \mathcal{N}\left(\mathbf{0}, \sigma^2\mathbf{I_m}\right)$, where $\mathbf{I}_m$ denotes an $m \times m$ identity matrix. We assume perfect channel state information (CSI) at the receivers and in particular at the source. In addition, we assume the destination to apply maximum ratio combining (MRC) based on the CSI where the combined channel gain is given by $h_1^2 + h_3^2$.

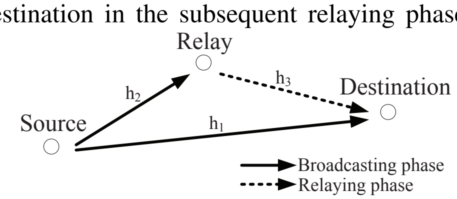

Fig. 1. Example of the considered DF relaying scenario.

III. PERFORMANCE OF DIRECT TRANSMISSION WITH FB

For the real additive white Gaussian noise channel, [6] derives a tight bound for the coding rate of a single-hop transmission system. With blocklength m and (block) error probability ε, the coding rate (in bits per channel use) is:

$$\mathrm{R}(h^2,\varepsilon,m) = \mathrm{C}(h^2) - \sqrt{\left(1-2^{-4\,\mathrm{C}(h^2)}\right)/2m}\,Q^{-1}(\varepsilon)\log_2 e, \quad (1)$$

where $Q^{-1}(\cdot)$ is the inverse Q-function and as usual the Q-function is given by $Q(w) = \int_w^\infty \frac{1}{\sqrt{2\pi}} e^{-t^2/2} dt$. In addition, $\mathrm{C}(h^2)$ is the Shannon capacity function of the gain h^2 of a real channel: $\mathrm{C}(h^2) = \frac{1}{2}\log_2\left(1+h^2 p_{\text{tx}}/\sigma^2\right)$. Based on the above result, the coding rate of direct transmission with blocklength $2m$ and error probability ε_{D} is (in bit/ch.use):

$$\begin{aligned} r_{\mathrm{D}} &= \mathrm{R}(h_1^2,\varepsilon_{\mathrm{D}},2m) \\ &= \mathrm{C}(h_1^2) - \sqrt{\left(1-2^{-4\,\mathrm{C}(h_1^2)}\right)/4m} \cdot Q^{-1}(\varepsilon_{\mathrm{D}})\log_2 e. \end{aligned} \tag{2}$$

Therefore, with blocklength $2m$ and coding rate r_{D}, if the source has perfect CSI, the decoding error probability at the destination of direct transmission is given by:

$$\varepsilon_{\mathrm{D}} = \mathrm{P}^{\mathrm{e}}(h_1^2,r_{\mathrm{D}},2m) = Q\left(\frac{\mathrm{C}(h_1^2) - r_{\mathrm{D}}}{\sqrt{\left(1-2^{-4\,\mathrm{C}(h_1^2)}\right)/4m \cdot \log_2 e}}\right). \tag{3}$$

IV. Relaying Performance with FB

In the assumed relaying system, as we consider MRC at the receiver, the coding rate on the different links need to be the same. This coding rate is determined by the source based on the CSI of all the links and in particular of the bottleneck link of relaying. The bottleneck link of two-phase relaying (with MRC) is either the backhaul link or the combined link (by MRC over the direct link and the relaying link). Hence, the equivalent coding rate of two-phase relaying is half of the single-phase coding rate of the bottleneck link. With blocklength m at each phase, the equivalent coding rate of relaying is given by (in bit/ch.use):

$$r_{\mathrm{R}} = \frac{\mathrm{R}(h_\star^2, \varepsilon_\star, m)}{2} = \frac{\mathrm{C}(h_\star^2)}{2} - \sqrt{\frac{1-2^{-4\,\mathrm{C}(h_\star^2)}}{8m}} Q^{-1}(\varepsilon_\star)\log_2 e, \tag{4}$$

where $\star$ is the indicator of the bottleneck link of relaying and therefore $\varepsilon_\star$ represents the corresponding error probability and $h_\star^2$ represents the corresponding channel gain: $h_\star^2 = \min\{h_2^2, h_1^2 + h_3^2\}$.

Similar to (3), the decoding error probability at the relay is given by $\varepsilon_2 = \mathrm{P}^{\mathrm{e}}(h_2^2, 2r_{\mathrm{R}}, m)$. In addition, the error probability at the destination (which applies MRC) is obtained as $\varepsilon_{\mathrm{MRC}} = \mathrm{P}^{\mathrm{e}}(h_1^2 + h_3^2, 2r_{\mathrm{R}}, m)$. Obviously, we have $\varepsilon_\star = \max\{\varepsilon_2, \varepsilon_{\mathrm{MRC}}\}$. Similarly, the error probability of the direct link is given by $\varepsilon_1 = \mathrm{P}^{\mathrm{e}}(h_1^2, 2r_{\mathrm{R}}, m)$. Therefore, the overall error probability results from the error probability of each link and is given by:

$$\varepsilon_{\mathrm{R}} = \varepsilon_1 \left[\varepsilon_2 + (1-\varepsilon_2)\,\varepsilon_{\mathrm{MRC}}\right]. \tag{5}$$

As $(1-\varepsilon_2)(1-\varepsilon_{\mathrm{MRC}}) \geq 0$, we immediately have $\varepsilon_{\mathrm{R}} \leq \varepsilon_1$. In addition, ε_{R} is also upper-bounded by: $\varepsilon_{\mathrm{R}} = \varepsilon_1\varepsilon_2(1-\varepsilon_{\mathrm{MRC}}) + \varepsilon_1\varepsilon_{\mathrm{MRC}} \leq \varepsilon_1\varepsilon_2 + \varepsilon_1\varepsilon_{\mathrm{MRC}} \leq 2\varepsilon_1\varepsilon_\star$. Moreover, we also have a lower bound of ε_{R}, given by: $\varepsilon_{\mathrm{R}} = \varepsilon_1\varepsilon_2 + \varepsilon_1\varepsilon_{\mathrm{MRC}} - \varepsilon_1\varepsilon_2\varepsilon_{\mathrm{MRC}} \geq \max\{\varepsilon_1\varepsilon_2, \varepsilon_1\varepsilon_{\mathrm{MRC}}\} = \varepsilon_1\varepsilon_\star$. Summarizing, ε_{R} is bounded by:

$$\varepsilon_1\varepsilon_\star \leq \varepsilon_{\mathrm{R}} \leq \varepsilon_1 \cdot \min\{2\varepsilon_\star, 1\}. \tag{6}$$

In particular, we have $\varepsilon_\star > \varepsilon_{\mathrm{R}}$ if $\varepsilon_1 < 0.5$.

V. Performance Advantage of Relaying with FB

In this section, we study the performance difference of relaying under the FB regime and under the Shannon capacity regime. We first study this performance difference by considering a scenario where relaying and direct transmission have equivalent Shannon capacity. Afterwards, in this specific scenario we analyze the conditions under which relaying is more efficient in the FB regime than in the Shannon capacity regime, i.e., relaying has a higher FB-limited performance than direct transmission. Finally, we discuss the performance advantage of relaying under more general scenarios.

The equivalent Shannon capacity of two-phase relaying is $c_{\mathrm{R}} = \mathrm{C}(h_\star^2)/2$, where $\mathrm{C}(h_\star^2)$ is the Shannon capacity of the bottleneck link. Accordingly, the Shannon capacity of direct transmission is $c_{\mathrm{D}} = \mathrm{C}(h_1^2)$. Therefore, if relaying and direct transmission have the same performance under the Shannon capacity regime, we have $\mathrm{C}(h_\star^2)/2 = \mathrm{C}(h_1^2)$. Next, we study the performance difference (between relaying in the FB regime and relaying in the Shannon capacity regime) by comparing the (equivalent) coding rates between relaying and direct transmission. To make a fair comparison, the error probability of direct transmission and the overall error probability of relaying are assumed to be the same, i.e., $\varepsilon_{\mathrm{D}} = \varepsilon_{\mathrm{R}}$.

Therefore, the performance gap between the coding rate of relaying with blocklength m at each phase and the coding rate of direct transmission with blocklength $2m$ is given by:

$$\begin{aligned} &r_{\mathrm{R}} - r_{\mathrm{D}} = r(h_\star^2, \varepsilon_\star, m)/2 - r(h_1^2, \varepsilon_{\mathrm{D}}, 2m) \\ &= \mathrm{C}(h_\star^2)/2 - \sqrt{\left(1 - 2^{-4\,\mathrm{C}(h_\star^2)}\right)/8m} \cdot Q^{-1}(\varepsilon_\star)\log_2 e \\ &\quad - \mathrm{C}(h_1^2) + \sqrt{\left(1 - 2^{-4\,\mathrm{C}(h_1^2)}\right)/4m} \cdot Q^{-1}(\varepsilon_{\mathrm{D}})\log_2 e \\ &= \mathrm{C}(h_1^2) - \sqrt{\left(1 - 2^{-8\,\mathrm{C}(h_1^2)}\right)/8m} \cdot Q^{-1}(\varepsilon_\star)\log_2 e \\ &\quad - \mathrm{C}(h_1^2) + \sqrt{\left(1 - 2^{-4\,\mathrm{C}(h_1^2)}\right)/4m} \cdot Q^{-1}(\varepsilon_{\mathrm{R}})\log_2 e \\ &= A \cdot B, \end{aligned} \tag{7}$$

where $A = \sqrt{\left(1-2^{-4\,\mathrm{C}(h_1^2)}\right)/8m}\,\log_2 e$ and $B = \sqrt{2}Q^{-1}(\varepsilon_{\mathrm{R}}) - \sqrt{1 + 2^{-4\,\mathrm{C}(h_1^2)}} \cdot Q^{-1}(\varepsilon_\star)$. Under the above assumptions, it follows that for $A \cdot B \neq 0$ there is a performance difference between the two schemes. In particular, if $A \cdot B > 0$, this indicates that relaying is more efficient in the FB regime than in the Shannon capacity regime. Obviously, A is positive and decreasing in m. On the other hand, B is not dependent on m. Hence, we have the following proposition:

Proposition 1. *Under the FB regime, the performance gap between relaying and direct transmission, i.e., the absolute value of $r_R - r_D$, increases as the blocklength decreases. However, the blocklength does not influence if relaying or direct transmission has a better performance.*

Proposition 1 implies that if relaying outperforms direct transmission, i.e., $A \cdot B > 0$, the shorter the blocklength is, the bigger the performance gap is. This is an unexpected insight that relaying is more beneficial with shorter blocklengths. We further investigate the condition where relaying outperforms direct transmission based on the following error scenarios:

- **Common error scenario[1]:** The (block) error probability of each link of relaying is lower than 0.5, i.e., $\max\{\varepsilon_1, \varepsilon_\star\} < 0.5$. Hence, $Q^{-1}(\varepsilon_\star) > 0$ and $\frac{\sqrt{2}Q^{-1}(\varepsilon_{\mathrm{R}})}{Q^{-1}(\varepsilon_\star)}$

[1] In practice, the (block) error probabilities of transmissions are generally expected to be much lower than 0.5, e.g., an error probability in the range of 0.3-0.5 is normally regarded as relatively high. The common error scenario in this paper refers to error probabilities in the range of 0-0.5. It is actually the complement of the extreme error scenario.

is decreasing in ε_{R}. Next, we prove that $A{\cdot}B > 0$ to show that relaying is definitely superior to direct transmission under this error scenario.

Proof. $\max\{\varepsilon_1, \varepsilon_\star\} < 0.5$
$\Rightarrow$ based on (6) we have $\varepsilon_{\mathrm{R}} < \varepsilon_\star < 0.5$
$\Leftrightarrow Q^{-1}(\varepsilon_{\mathrm{R}}) > Q^{-1}(\varepsilon_\star) > 0$
$\Rightarrow \frac{\sqrt{2}Q^{-1}(\varepsilon_{\mathrm{R}})}{Q^{-1}(\varepsilon_\star)} > \sqrt{2} > \sqrt{1+\frac{1}{[1+\mathrm{SNR}(h_1^2)]^2}} = \sqrt{1+2^{-4\,\mathrm{C}(h_1^2)}}$
$\Rightarrow B > 0$ and $A \cdot B > 0$. □

- **Extreme error scenario**[2]**:** The error probability of at least one link of relaying is higher than 0.5, i.e., $\max\{\varepsilon_1, \varepsilon_\star\} > 0.5$. In the following, we prove that the condition $\varepsilon_{\mathrm{R}} < \varepsilon_\star$ is sufficient to have $A \cdot B > 0$ under this scenario.

  Proof. Under the condition $\varepsilon_{\mathrm{R}} < \varepsilon_\star$, if $\varepsilon_\star < 0.5$, we have $\varepsilon_{\mathrm{R}} < \varepsilon_\star < 0.5$. Therefore, the rest of the proof is similar to the one above (starting from the second step) for the common error scenario. Hence, here we mainly consider the other situation where $\varepsilon_\star > 0.5$:
  $\varepsilon_{\mathrm{R}} < \varepsilon_\star$ and $\varepsilon_\star > 0.5$
  $\Leftrightarrow \varepsilon_{\mathrm{R}} < \varepsilon_\star$ and $\frac{\sqrt{2}Q^{-1}(\varepsilon_{\mathrm{R}})}{Q^{-1}(\varepsilon_\star)}$ is increasing in ε_{R}
  $\Rightarrow \frac{\sqrt{2}Q^{-1}(\varepsilon_{\mathrm{R}})}{Q^{-1}(\varepsilon_\star)} < \sqrt{2}$

$$\Rightarrow \begin{aligned}\sqrt{2}Q^{-1}(\varepsilon_{\mathrm{R}}) > \sqrt{2}Q^{-1}(\varepsilon_\star) &> \sqrt{1+\frac{1}{[1+\mathrm{SNR}(h_1^2)]^2}}\,Q^{-1}(\varepsilon_\star) \\ &= \sqrt{1+2^{-4\mathrm{C}(h_1^2)}}\,Q^{-1}(\varepsilon_\star)\end{aligned}$$

  $\Rightarrow B > 0$ and $A \cdot B > 0$. □

Summarizing, under the common error scenario (or under the extreme error scenario with $\varepsilon_{\mathrm{R}} < \varepsilon_\star$) relaying is definitely superior to direct transmission in the FB regime even if their performance is the same under the Shannon capacity regime, i.e., $c_{\mathrm{R}} = c_{\mathrm{D}}$. Note that under the common error scenario (based on (6)) we definitely have $\varepsilon_{\mathrm{R}} < \varepsilon_\star$. Hence, $\varepsilon_{\mathrm{R}} < \varepsilon_\star$ is actually a sufficient but not necessary condition to make relaying outperform direct transmission.

Based on Proposition 1, (if $A \cdot B > 0$) the performance advantage of relaying increases as the blocklength decreases. This actually can be explained based on the condition $\varepsilon_{\mathrm{R}} < \varepsilon_\star$. The above analysis shows that with the same (overall) error probability ($\varepsilon_{\mathrm{D}} = \varepsilon_{\mathrm{R}}$) relaying can operate with a higher error probability per phase (i.e., $\varepsilon_{\mathrm{R}} < \varepsilon_\star$) and hence set the coding rate more aggressively. Note that the fundamental difference between Shannon capacity and FB regime is the consideration of error probabilities int he latter case. Therefore, the performance loss (if comparing the FB coding rate to the Shannon capacity) is caused by the error probability. However, relaying can compensate the performance loss/decrease by operating with a higher error probability than direct transmission. One could also say that relaying simply has a lower performance decrease, and that leads to a relative performance advantage of relaying in comparison to direct transmission. If the blocklength is long and only introduces a slight performance loss under the FB regime, the advantage of relaying is not significant. However, a relatively short blocklength leads to a significant performance loss. Then, in case of relaying the performance loss is lower which leads to a higher coding rate in comparison to direct transmission.

[2]Based on (3), the extreme error scenario corresponds to the case where the Shannon capacity of at least one link of relaying is lower than the coding rate (at each phase). We provide an example to clarify that this scenario is also feasible in practice. Recall that the source determines the coding rate based on the channel gain of the bottleneck link (either h_2^2 or $h_1^2 + h_3^2$). Therefore, it is possible that this coding rate is higher than the Shannon capacity of the direct link (with channel gain h_1^2).

So far we analyzed the advantage of relaying under the condition $c_{\mathrm{R}} = c_{\mathrm{D}}$, i.e., $\mathrm{C}(h_\star^2)/2 = \mathrm{C}(h_1^2)$. In the following, we consider the other channel conditions. Based on (2), r_{D} is decreasing in $\mathrm{C}(h_1^2)$. Therefore, if $\varepsilon_{\mathrm{R}} < \varepsilon_\star$ and $\mathrm{C}(h_\star^2)/2 > \mathrm{C}(h_1^2)$ (which means that $\mathrm{C}(h_1^2)$ becomes smaller in comparison to the scenario $\mathrm{C}(h_\star^2)/2 = \mathrm{C}(h_1^2)$), under the FB regime relaying is definitely superior to direct transmission, too. Moreover, recall that the condition $\varepsilon_{\mathrm{R}} < \varepsilon_\star$ is sufficient but not necessary to let $A \cdot B > 0$. This indicates the possibility that relaying could still be a better choice even if $\mathrm{C}(h_\star)/2 < \mathrm{C}(h_1)$. For example, relaying is more likely to be superior to direct transmission if $\mathrm{C}(h_\star)/2$ is just slightly lower than $\mathrm{C}(h_1)$.

Therefore, the performance comparison between relaying and direct transmission can be summarized in the following proposition with respect to various channel conditions:

Proposition 2. *Under the common error scenario (or under the extreme error scenario with $\varepsilon_R < \varepsilon_\star$), we have:*

- $c_R > c_D \Rightarrow r_R > r_D$.
- $c_R = c_D \Rightarrow r_R > r_D$.
- *Even if $c_R < c_D$, it is possible that $r_R > r_D$.*

This proposition clearly shows the performance advantage of relaying under the FB regime in comparison to the Shannon capacity regime. In fact, based on Proposition 2 the performance advantage of relaying leads to a broader spatial area for selecting/deploying a relay in the FB regime as shown in Fig. 2. In the figure, if a relay is deployed in region A, relaying outperforms direct transmission under both the FB regime and the Shannon capacity regime. On the other hand, if a relay is deployed in the (ring shaped) region B, relaying has a higher FB-limited performance but a lower Shannon capacity in comparison to direct transmission. From a perspective of topology, the key contribution of this work can be understood as that we analyzed the conditions under which region B exists.

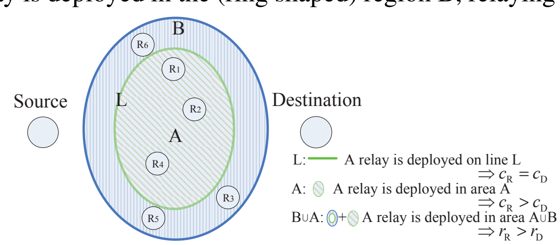

Fig. 2. The performance advantage of relaying under the FB regime (from a perspective of topology).

VI. Numerical Results and Discussion

In this section, we present numerical results to illustrate our analytical model. As both the FB coding rates and Shannon capacities vary in SNR, to investigate the difference between the performances (of either relaying or direct transmission) under the FB regime and under the Shannon capacity regime, we observe the ratio (ρ) of the (equivalent) coding rate to the (equivalent) Shannon capacity: $\rho_{\rm R} = r_{\rm R}/c_{\rm R}$ for relaying and $\rho_{\rm D} = r_{\rm D}/c_{\rm D}$ for direct transmission. In Fig. 3 we compare the performance ratios $\rho_{\rm R}$ and $\rho_{\rm D}$ for different error probabilities and different transmit powers while setting $c_{\rm R} = c_{\rm D}$ and $\varepsilon_{\rm R} = \varepsilon_{\rm D}$. The figure demonstrates our analytical finding that relaying is superior to direct transmission if the error probability is not extremely high. From the figure, we observe that only under extreme error scenario, e.g., $\varepsilon_{\rm R} = \varepsilon_{\rm D} = 10^{-0.3} \approx 0.501$, the performance ratio of direct transmission is slightly higher.

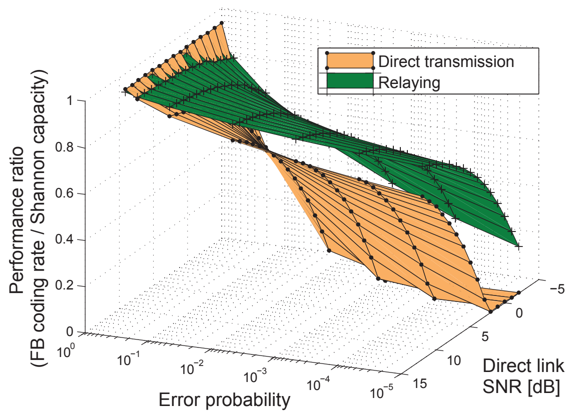

Fig. 3. Performance ratios of relaying and direct transmission while the blocklength of each phase of relaying and the blocklength of direct transmission are 100 and 200. We vary $p_{\rm tx}$ to obtain different SNR while setting $c_{\rm R} = c_{\rm D}$.

We further investigate the performance advantage of relaying by observing $\rho_{\rm R}/\rho_{\rm D}$ in Fig. 4. In the figure, the abscissa is the blocklength at each phase of relaying while the blocklength of direct transmission is twice as large. The

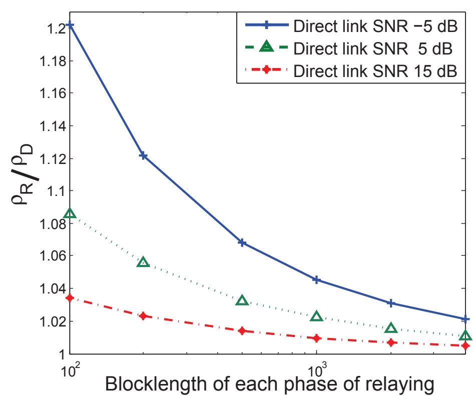

Fig. 4. Performance advantage ratio of relaying to direct transmission ($\varepsilon_{\rm R} = \varepsilon_{\rm D} = 10^{-3}$).

figure illustrates Proposition 1, i.e., the performance advantage of relaying under the FB regime is more significant with short blocklengths in comparison to direct transmission. Moreover, the performance advantage of relaying is higher under poor channel conditions.

In addition, we provide the corresponding absolute values of the second case in Fig. 4 where the SNR of the direct link is about 5 dB. We show these values in Fig. 5. This figure illustrates our analysis in Proposition 2 that (although having a slightly lower Shannon capacity) the coding rate of relaying in Fig. 5 shows a significantly higher performance than direct transmission. For example, when the blocklength of each phase of relaying equals 500 (at the same time, the blocklength of direct transmission is 1000), the coding rate of direct transmission is only about 89% of the corresponding Shannon capacity while for relaying this ratio increases to 94%.

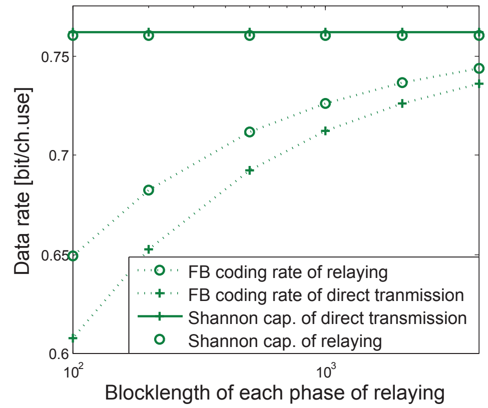

Fig. 5. The comparison between relaying and direct transmission with FBs while the SNR of the direct link is 5 dB and $\varepsilon_{\rm R} = \varepsilon_{\rm D} = 10^{-3}$.

VII. Conclusion

In this letter, we studied performance difference between relaying under the FB regime and under the Shannon capacity regime. We proved that relaying is definitely superior to direct transmission under the FB regime if the error probability of the bottleneck link of relaying is higher than the overall error probability of relaying (even relaying and direct transmission have the same Shannon capacity). In particular, for the common error scenario, relaying is definitely superior to direct transmission under the FB regime. This performance advantage of relaying under the FB regime is more significant with short blocklengths. From a perspective of topology, this performance advantage of relaying leads to a broader area for selecting/deploying a relay. Finally, we showed a nice match between our analytical model and the numerical results.

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