Implications Of The Half-Duplex Constraint On Relay-Aided Cooperation Using Rateless Codes

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***Abstract*—The half-duplex constraint, which mandates that a cooperative relay cannot transmit and receive simultaneously, considerably simplifies the demands made on the hardware and signal processing capabilities of a relay. However, the very inability of a relay to transmit and receive simultaneously leads to a potential under-utilization of time and bandwidth resources available to the system. We analyze the impact of the half-duplex constraint on the throughput of a cooperative relay system that uses rateless codes to harness spatial diversity and efficiently transmit information from a source to a destination. We derive closed-form expressions for the throughput of the system, and show that as the number of relays increases, the throughput approaches that of a system that uses more sophisticated full-duplex nodes. Thus, half-duplex nodes are well suited for cooperation using rateless codes despite the simplicity of both the cooperation protocol and the relays.**

***Index Terms*—Cooperative communications, rateless codes, fading channels, half-duplex relays, selection**

I. Introduction

In a cooperative communication system, the source transmits information to the destination with the help of one or more relays. Cooperation exploits the broadcast nature of wireless channel and harnesses the spatial diversity inherent in a network consisting of multiple geographically separated relays [1], [2]. Several cooperation protocols have been proposed to try to meet the twin goals of (i) being practically simple and robust in design and (ii) using only simple, single antenna, and low cost relays for this [3]–[7].

The first goal of robust and simple protocol design has led to the development of selection-based techniques in systems with multiple relays. In these, only one relay among the many available relays is selected on the basis of its current channel state to the source and/or destination to forward information to the destination [4], [8], [9]. Selection is attractive because it circumvents the practical difficulties associated with ensuring tight synchronization among multiple transmitting relays.

The same goal has also motivated the development of efficient rateless codes based cooperation protocols [10]–[14], which do not require the transmitting source and relays to have any instantaneous channel state information (CSI) of the channels they are transmitting on [15], [16]. This is an important advantage of rateless codes since acquisition of CSI requires extra time and energy, and complicates the protocol design. For example, [17] showed that the time and energy cost of this additional overhead severely limits the number of relays that should cooperatively beamform.

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Unlike conventional codes, in which a finite number of parity bits are transmitted along with information bits, rateless codes generate a potentially unbounded number of coded parity bits for each packet of information bits. The source transmits these coded bits until it receives an acknowledgment from one of the relays that it has successfully decoded the packet. The relay, which is of the decode-and-forward type, then transmits the packet to the destination using a rateless code again, and does so until it receives an acknowledgment from the destination.

Even though it is impossible to generate universal codes that are simultaneously optimal at all rates, rateless codes can be found that come close to the optimal rate [18]. *Thus, the realized rate, which is the number of information bits divided by the total time taken to transmit a sufficient number of coded bits so that the receiver can successfully decode the packet, is just marginally lower than the mutual information of the channel conditioned on the instantaneous channel fade(s).* This adaptation of the realized rate to the channel fade, without requiring CSI at the transmitter, has also been called as Continuous Incremental Redundancy in [10]. In effect, the receiver accumulates mutual information from the received signal over time and can successfully decode it once its accumulated mutual information exceeds the entropy of the source's packet. While rateless codes were initially proposed for erasure channels, extensions have also been considered for Gaussian channels [19], [20] and fading channels [10], [11], which will be the focus of this paper.

The second goal of using simple, low cost relays has motivated protocols that use half-duplex relays, which can transmit and receive but not simultaneously [5]–[7]. This restriction reduces the hardware and signal processing capabilities required of the relays. For example, if the channels over which a relay transmits and receives are separated in frequency, the half-duplex constraint eliminates the need for a radio frequency duplexer component that would otherwise be required to isolate the transmit and receive signals [5], [21]. In half-duplex relays that transmit and receive in the same band, there is no need to employ advanced signal isolation techniques to prevent transmit signal leakage from drowning out the weak received signal [22].

However, the use of half-duplex relays is not without its costs. In conventional fixed code rate systems, it incurs a 50% loss in spectral efficiency since two time slots are required to transmit a packet from the source to the destination via a relay. This was studied in detail for amplify-and-forward relays with conventional coding in [23]. A corresponding evaluation of the performance penalty when rateless codes are used instead has not been done in the literature to the best of our knowledge. While the protocols studied in [12], [13] work with half-duplex relays, the impact of the half-duplex constraint was not quantified. In [14], only one relay was considered.

The characterization of performance of a two-hop cooperative system that uses rateless codes for transmission and in which multiple half-duplex relays are present shall, therefore, be the focus of this paper. To this end, we develop new closed-form expressions for the throughput achieved by system, and quantify the extent to which the half-duplex constraint leads to an under-utilization of the time and bandwidth resources by the cooperative system. We show a surprising result that the limitations imposed by the constraint disappear as the number of relays increases. The throughput of the system, in fact, approaches that of a system that employs more sophisticated full-duplex relays.

The paper organized as follows. In Sec. II, we set up the system model. Section III analyzes the performance of the system. Results are presented in Sec. IV and are followed by our conclusions in Sec. V.

II. System Model

As shown in Fig. 1, we consider a two-hop network in which a source, S, has a continuous stream of packets to transmit to a destination, D, via N decode-and-forward half-duplex relays, $R_1, \ldots, R_N$.

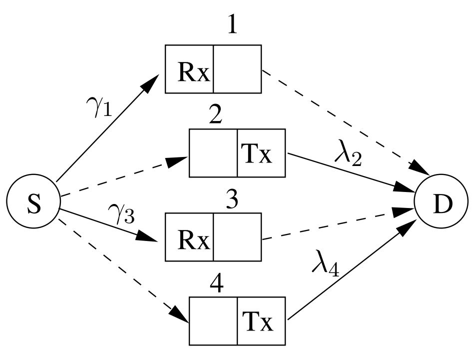

Fig. 1. A two-hop cooperative relay network consisting of a source, a destination, and $k = 4$ half-duplex relays. Dotted lines (- -) indicate links that are inactive due to the half-duplex constraint at some time instant.

The wireless channels between the different nodes are assumed to be frequency-flat, block-fading Rayleigh channels. Different channels are independent of each other. Each channel is assumed to remain constant over the duration of transmission of a packet. It changes to an independent value thereafter.[1] The noise variance is normalized to unity without loss of generality. Therefore, we use the terms signal to noise ratio (SNR) and channel power gain interchangeably. The instantaneous receive SNRs of the S-to-R_i link and the R_i-to-D links are denoted by γ_i and λ_i, respectively. From the Rayleigh fading assumption, it follows that they are exponentially distributed random variables, with means denoted by $\overline{\gamma}_{\text{SR}}$ and $\overline{\lambda}_{\text{RD}}$, respectively.

A. Transmission Protocol and the Half-Duplex Constraint

The source as well as relays transmit over pre-assigned orthogonal frequency bands, each of bandwidth W Hz, that do not interfere with each other. A relay can in one of two states: either it can receive a signal from the source or it can transmit to the destination. As soon as one of the receiving relays has accumulated sufficient mutual information, it successfully decodes the source's packet. It then sends an acknowledgment back to the source, reencodes the packet, and starts transmitting it to the destination. It can not receive the source's signal until it completes transmitting its packet to the destination. A transmitting node, which can be the source or a relay, times out if it does not receive an acknowledgment within a duration T_{out}, and drops the packet.

Once the source receives an acknowledgment, it starts transmitting the next packet. All the other relays thereafter discard all the mutual information they might have accumulated for this decoded packet, and start receiving the next packet from the source.[2] This protocol is similar to the two step rateless code based cooperation protocols considered in [12], [13].

Since the realized rate is close to the mutual information of the channel, the time taken by a receiver to decode a packet consisting of B information bits from the transmitter is

$$\frac{B(1+\delta)}{\frac{W}{2}\log_2(1+\text{SNR})} = \frac{\tilde{B}}{\log_e(1+\text{SNR})}, \qquad (1)$$

where δ is the inefficiency of a practical implementation of the rateless code, and $\tilde{B} = 2B(1+\delta)/W$. Since the SNR depends on fading, the transmission times of different packets are different.

B. Comments About Model and Generalizations

No knowledge is required about the SR channels at the source and the RD channels at the relays since they transmit using rateless codes. Since the channels are orthogonal, the relays can transmit and receive independently of each other in a decentralized manner, which simplifies protocol design. For the same reason, it does not matter whether the source and relays use the same rateless code or not. To simplify the theoretical treatment, we shall assume that the direct source-destination link is weak or blocked enough to be ignorable.

Note that relay selection and, thus, the harnessing of spatial diversity happen automatically since the relay that first decodes the packet is the one with the highest SR channel SNR among the receiving relays.[3] Note also that at any point in time the N relays may be transmitting up to N different packets in parallel

[1]For rateless code this assumption is valid when the time-out period is less than the channel coherence time. This approximation ensures analytical tractability, and has also been made, for example, in [12], [13].

[2]Since only one bit of feedback is needed in an acknowledgment, it can be sent on an error-free low bandwidth channel with negligible delays. A relay can either over hear an acknowledgment sent by another relay, or get to know about it directly from the source when it starts transmitting the next packet.

[3]This can be achieved in multiple ways. For example, the relays can overhear the acknowledgment. Or, the source itself can inform all the relays once it receives the acknowledgment and starts transmitting the next packet.

to the destination. The relays that are not transmitting, receive and try to decode the source's transmission.

The analysis can be extended to the asymmetric case, in which the different channels are statistically non-identical. Another interesting extension is the case where the half-duplex relays transmit and receive over the same band. These are not treated here due to space constraints.

III. Analysis

We shall use the following notation henceforth. Let $T^{\text{SR}}(L)$ denote the time taken by the source to transmit a packet (including those that are dropped due to the transmission time exceeding T_{out}) when L relays are receiving. Similarly, let T_i^{RD} denote the time taken by a relay to transmit a packet to the destination. $\mathbf{E}[X]$ shall denote the expected value of a random variable X, and $\Pr(A)$ shall denote the probability of event A. The relay index i will often not matter in the results below because the SR channels are i.i.d., and so are the RD channels.

Result *1:* The average rate at which the packets transmitted by the source are successfully received by any one of the relays, Λ_S, is

$$\Lambda_s = \sum_{L=0}^{N} \Pr(L \text{ relays receive}) \frac{\left(1 - O^{\text{SR}}(L)\right)}{\mathbf{E}\left[T^{\text{SR}}(L)\right]}. \quad (2)$$

Here, $O^{\text{SR}}(L)$ is the probability that the source times out and drops a packet given that L relays are receiving. It equals

$$O^{\text{SR}}(L) = \left(1 - \exp\left(\frac{1 - e^{\frac{\tilde{B}}{T_{\text{out}}}}}{\overline{\gamma}_{\text{SR}}}\right)\right)^L. \quad (3)$$

And, $\mathbf{E}\left[T^{\text{SR}}(L)\right]$ is given by

$$\mathbf{E}\left[T^{\text{SR}}(L)\right] = O^{\text{SR}}(L) T_{\text{out}} + \frac{\tilde{B}L}{\overline{\gamma}_{\text{SR}}} \sum_{i=0}^{L-1} (-1)^i \binom{L-1}{i} \psi\left(\frac{\overline{\gamma}_{\text{SR}}}{i+1}, \frac{\tilde{B}}{T_{\text{out}}}\right), \quad (4)$$

where

$$\psi(a, u) = \int_u^\infty \frac{1}{y} \exp\left(y + \frac{1}{a}\left(1 - e^y\right)\right) dy. \quad (5)$$

Proof: The proof is relegated to Appendix A. ■

Result *2:* The average rate at which the destination successfully receives packets, Λ_D, is

$$\Lambda_D = pN \frac{\left(1 - O_i^{\text{RD}}\right)}{\mathbf{E}\left[T_i^{\text{RD}}\right]}, \quad (6)$$

where i indexes an arbitrary relay, p is the probability that a relay is transmitting,

$$O_i^{\text{RD}} = 1 - \exp\left(\frac{1 - e^{\frac{\tilde{B}}{T_{\text{out}}}}}{\overline{\lambda}_{\text{RD}}}\right), \quad \text{and} \quad (7)$$

$$\mathbf{E}\left[T_i^{\text{RD}}\right] = O_i^{\text{RD}} T_{\text{out}} + \frac{\tilde{B}}{\overline{\lambda}_{\text{RD}}} \psi\left(\overline{\lambda}_{\text{RD}}, \frac{\tilde{B}}{T_{\text{out}}}\right). \quad (8)$$

Proof: The proof is given in Appendix B. ■

In general, the event that a relay is receiving depends on the channel fades that have occurred thus far for all the SR and RD links. This is because of three reasons: (1) The transmission time of a packet by the source depends on the instantaneous SR link gains of all the relays that are receiving; (ii) Only the first relay to decode the packet from the source forwards it to the destination; and (iii) The coupling introduced between a relay's reception and transmission processes by the half-duplex constraint. Therefore, determining the joint probability that L out of N relays are receiving is analytically intractable. We circumvent this difficulty by introducing a simple *decoupling approximation, which assumes that the event that a relay is receiving is independent of whether other relays are receiving or not.* The next section verifies the accuracy of this approximation. This approximation is similar to the collision decoupling approximation used to great effect in analyzing the distributed coordination function of IEEE 802.11 [24]. Hence,

$$\Pr(L \text{ relays receive}) \approx \binom{N}{L} (1-p)^L p^{N-L}. \quad (9)$$

A Fixed Point Equation for p: A packet that is transmitted by the source and is successfully received by a Relay i either reaches the destination or gets dropped, with probability O_i^{RD}, during transmission by the relay. Therefore, $\Lambda_S(1 - O_i^{\text{RD}}) = \Lambda_D$. Using Results 1 and 2 and the decoupling approximation, we then get the following fixed point equation in terms of p:

$$\sum_{L=0}^{N} \binom{N}{L} (1-p)^L p^{N-L} \frac{\left(1 - O^{\text{SR}}(L)\right)}{\mathbf{E}\left[T^{\text{SR}}(L)\right]} - \frac{pN}{\mathbf{E}\left[T_i^{\text{RD}}\right]} = 0. \quad (10)$$

The above equation always has a solution in $(0, 1)$. This is because when $p = 0$, the left term of (10) equals $\frac{\left(1 - O^{\text{SR}}(N)\right)}{\mathbf{E}\left[T^{\text{SR}}(N)\right]} > 0$. When $p = 1$, the left term equals $\frac{-N}{\mathbf{E}\left[T_i^{\text{RD}}\right]} < 0$, since $O^{\text{SR}}(0) = 1$. The solution is easily found numerically using standard packages such as Matlab or Mathematica. Having found p, the throughput of the system in bits/sec is simply $B\Lambda_D$, where Λ_D in packets/sec is given by (6).

IV. Simulations

We now plot the results from the analysis and verify them using Monte Carlo simulations that use 20,000 packets. The results are shown for the following parameter values: $B = 4096$ bits/packet, $W = 2$ MHz, $\overline{\gamma}_{\text{SR}} = 10$ dB, $\delta = 0$, and $T_{\text{out}} = 10$ msec.

Figure 2 plots the average throughput, Λ_D, as a function of the average SNR of the RD channel, $\overline{\lambda}_{\text{RD}}$, for different numbers of half-duplex relays, N, in the system. We see that the throughput increases as either N or $\overline{\lambda}_{\text{RD}}$ increases, which makes intuitive sense. Notice the good match between the simulations and analytical results for all values of N and $\overline{\lambda}_{\text{RD}}$. This validates the decoupling approximation used in the analysis. The accuracy of the approximation increases as the number of relays increases.

Next, we compare in Fig. 3, the performance of the half-duplex relay system with that of a similar system that uses the

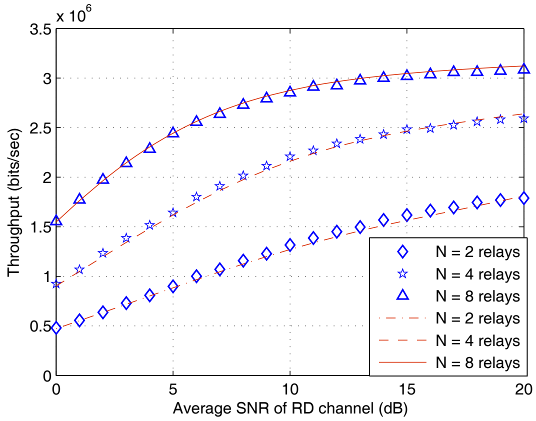

Fig. 2. Throughput as a function of the RD channel quality and the number of half-duplex relays. Analytical results are shown using lines and simulation results using markers ($\diamond$, $\triangle$, and $\star$).

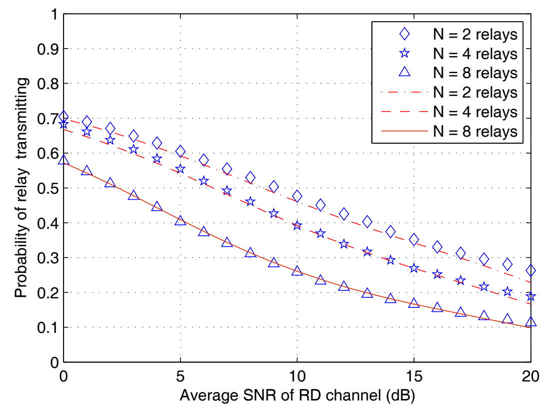

Fig. 4. Probability that a half-duplex relay is busy transmitting. Analytical results are shown using lines and simulation results using markers ($\diamond$, $\triangle$, and $\star$).

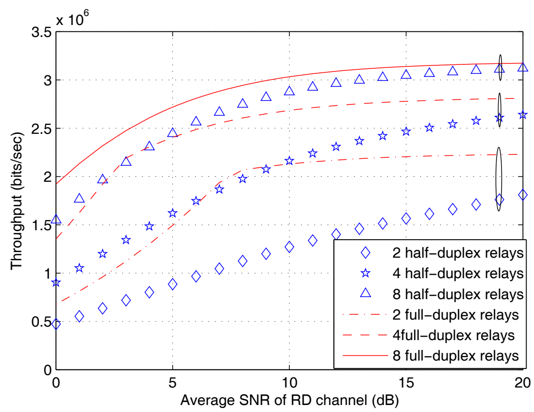

Fig. 3. Comparison of systems that use full-duplex relays (with buffers) and simple half-duplex relays.

same number of full-duplex relays, which can transmit and receive simultaneously [25]. The full-duplex relays are also allowed to buffer packets in their queues. This is necessary since the SR and RD channels of a relay are independent of each other; the buffer helps balance the packet arrival and departure processes at a relay. No such buffer is necessary for a half-duplex relay since it does not receive another packet until it has finished transmission of its current packet. As expected, a higher throughput is achieved by using full-duplex relays. Interestingly, the performance difference between the two systems decreases as the number of relays increases or the mean RD channel SNR, $\overline{\lambda}_{\mathrm{RD}}$, increases. This is because each half-duplex relay is prevented from receiving for smaller fractions of time as either N or $\overline{\lambda}_{\mathrm{RD}}$ increases.

To understand this important observation better, we plot in Fig. 4 the probability, p, that a half-duplex relay is busy transmitting as a function of the mean RD channel gain and the number of relays. We observe that p decreases as N increases. This is because of the diminishing returns from the increased spatial diversity that arise when there are more relays. As N increases, the average time taken by the source to transmit a packet decreases. However, for Rayleigh fading, the average time does not decrease at a rate as fast as $1/N$. At the same time, as N increases, each relay only receives, on average, only $1/N$th of the packets from the source. Therefore, each relay spends a smaller fraction of its time transmitting. Similarly, p decreases when $\overline{\lambda}_{\mathrm{RD}}$ increases because the mean time taken by a relay to transmit a packet to the destination decreases. The figure again shows a good match between the simulation and analytical results, which are obtained by solving (10).

V. Conclusions

We analyzed the throughput of a typical two-hop cooperative communications system that uses simple half-duplex relays and rateless codes to transmit information from the source to the destination over wireless Rayleigh fading channels. We observed that despite the half-duplex constraint and not requiring any instantaneous channel state information at the transmitting nodes, the system was able to exploit spatial diversity. In fact, as the number of relays increased or the quality of the relay-to-destination channels improved, the throughput of the system approached that of a system that used the same number of full-duplex relays, which require more sophisticated hardware and signal processing capabilities. Thus, the half-duplex constraint has only a marginal impact on the throughput benefits possible from relay-aided cooperation using rateless codes. Future work involves modifying the transmission policy of the relays to further improve throughput, and generalizing the study to multi-hop relay networks.

Appendix

A. *Proof of Result 1*

Conditioned on the event that L relays are receiving, the probability that a packet is dropped because the source times out is $O^{\mathrm{SR}}(L)$. The average rate at which the source transmits packets is $1/\mathbf{E}\left[T^{\mathrm{SR}}(L)\right]$. Therefore, (2) follows from the law of total expectation and the weak law of large numbers.

We now derive expressions for $O^{\mathrm{SR}}(L)$ and $\mathbf{E}\left[T^{\mathrm{SR}}(L)\right]$. For notational convenience, let $R_1, \ldots, R_L$ be the L receiving relays. Let t_i^{SR} denote the time taken by R_i to receive a packet from the source. Since the source times out after a duration T_{out}, we have $T^{\text{SR}}(L) = \min\left\{T_{\text{out}}, t_1^{\text{SR}}, \ldots, t_L^{\text{SR}}\right\}$. Clearly, $\Pr\left(T^{\text{SR}}(L) > x\right) = 0$, for $x > T_{\text{out}}$.

For $0 \leq x \leq T_{\text{out}}$, it follows that $\Pr\left(T^{\text{SR}}(L) > x\right) = \Pr\left(t_1^{\text{SR}} > x, \ldots, t_L^{\text{SR}} > x\right)$. From (1), we get $\Pr\left(t_i^{\text{SR}} > x\right) = \Pr\left(\gamma_i < e^{\frac{\tilde{B}}{x}} - 1\right)$. Since the channels are Rayleigh fading, γ_i is an exponential RV with mean $\overline{\gamma}_{\text{SR}}$. Therefore, $\Pr\left(\gamma_i < e^{\frac{\tilde{B}}{x}} - 1\right) = 1 - \exp\left(\frac{1-e^{\frac{\tilde{B}}{x}}}{\overline{\gamma}_{\text{SR}}}\right)$. Since the various SR channels are independent, we have

$$\Pr\left(T^{\text{SR}}(L) > x\right) = \left(1 - \exp\left(\frac{1-e^{\frac{\tilde{B}}{x}}}{\overline{\gamma}_{\text{SR}}}\right)\right)^L, \; 0 \leq x \leq T_{\text{out}}. \tag{11}$$

Therefore, the probability that the source times out is $O^{\text{SR}}(L) = \Pr\left(T^{\text{SR}}(L) \geq T_{\text{out}}\right) = \left(1 - \exp\left(\frac{1-e^{\frac{\tilde{B}}{T_{\text{out}}}}}{\overline{\gamma}_{\text{SR}}}\right)\right)^L$.

Differentiating (11), we get the probability density function of $T^{\text{SR}}(L)$, which we denote by $f_L^{\text{SR}}(x)$. Clearly, $f_L^{\text{SR}}(x) = 0$, for $x > T_{\text{out}}$. For $0 \leq x \leq T_{\text{out}}$, we get the following from (11):

$$f_L^{\text{SR}}(x) = O^{\text{SR}}(L)\delta(x - T_{\text{out}}) + \frac{L\tilde{B}}{\overline{\gamma}_{\text{SR}}x^2}\left[1 - \exp\left(\frac{1-e^{\frac{\tilde{B}}{x}}}{\overline{\gamma}_{\text{SR}}}\right)\right]^{L-1} \exp\left(\frac{\tilde{B}}{x} + \frac{1-e^{\frac{\tilde{B}}{x}}}{\overline{\gamma}_{\text{SR}}}\right), \tag{12}$$

where $\delta(.)$ is the Dirac delta function.

Finally, $\mathbf{E}\left[T^{\text{SR}}(L)\right] = \int_0^{T_{\text{out}}} x f_L^{\text{SR}}(x)\, dx$. Expanding the terms in (12) and using the variable substitution $y = \tilde{B}/x$ leads to the desired result in (4).

B. Proof of Result 2

The probability that a relay drops a packet because it times out is O_i^{RD}. The average rate at which the relay transmits packets to the destination, including the ones that are dropped, is $1/\mathbf{E}\left[T_i^{\text{RD}}\right]$. However, a relay transmits for only a fraction p of the time. Therefore, the destination successfully receives packets from each relay at an average rate of $p\left(1 - O_i^{\text{RD}}\right)/\mathbf{E}\left[T_i^{\text{RD}}\right]$. Summing over all the N relays yields (6).

Due to time-out, the time taken by R_i to transmit a packet to the destination equals $T_i^{\text{RD}} = \min\left\{T_{\text{out}}, \frac{\tilde{B}}{\log_e(1+\lambda_i)}\right\}$, where λ_i is an exponential RV with mean $\overline{\lambda}_{\text{RD}}$. Therefore, for $0 \leq x \leq T_{\text{out}}$, $\Pr\left(T_i^{\text{RD}} \geq x\right) = \Pr\left(\lambda_i < e^{\frac{\tilde{B}}{x}} - 1\right)$. Since the RD channels are Rayleigh fading with mean power gain $\overline{\lambda}_{\text{RD}}$, the outage probability $O_i^{\text{RD}} = \Pr\left(T_i^{\text{RD}} \geq T_{\text{out}}\right)$ evaluates to (7).

As in Appendix A, the probability density function of T_i^{RD}, which we denote by $g_i^{\text{RD}}(x)$, is obtained by differentiating the expression derived above for $\Pr\left(T_i^{\text{RD}} \geq x\right)$. For $x > T_{\text{out}}$, $g_i^{\text{RD}}(x) = 0$. And, for $0 \leq x \leq T_{\text{out}}$, we have

$$g_i^{\text{RD}}(x) = \frac{\tilde{B}}{\overline{\lambda}_{\text{RD}}x^2} \exp\left(\frac{1-e^{\frac{\tilde{B}}{x}}}{\overline{\lambda}_{\text{RD}}}\right) e^{\frac{\tilde{B}}{x}} + O_i^{\text{RD}}\delta(x - T_{\text{out}}). \tag{13}$$

Upon substituting (13) in the integral $\mathbf{E}\left[T_i^{\text{RD}}\right] = \int_0^{T_{\text{out}}} x g_i^{\text{RD}}(x)\, dx$, we get the desired result in (8). This is along lines similar to Appendix A.

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