Energy-Efficient Buffer-Aided Relaying Relying on Non-Linear Channel Probability Space Division

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***Abstract*—A buffer-aided two hop link is studied, where the RN is capable of temporarily storing the received packets. We commerce by defining the concept of a two-dimensional Channel Probability Space (CPS) based on the source-relay and relay-destination channel. Specifically, a non-linear CPS division method is proposed, which partitions the CPS into several regions representing the quality of the specific channels plus an outage region. Then the best channel is activated for the sake of minimizing the system's energy dissipation. Finally, the proposed buffer-aided transmission scheme relying on our non-linear CPS division regime is investigated and the results show that at given average end-to-end energy dissipation, the outage probability was reduced by** 33.5% **compared to the benchmark scheme.**

***Index Terms*—Cooperative communication, opportunistic routing, buffer, energy consumption, energy dissipation, channel space.**

I. Introduction

Minimizing the energy consumption of a relay-aided wireless communication system is still an open problem at the time of writing. Employing a relay between the Source Node (SN) and the Destination Node (DN) is one of the most basic methods that can be used for minimizing the energy consumption. It is traditionally assumed that a packet is transmitted from the SN to the DN via the Relay Node (RN) sequentially . For the convenience of description, we refer to this as "*the conventional transmission scheme*" in our forthcoming discourse. This transmission scheme results in a range of advantages over conventional single-hop communications. These advantages may include an extended coverage area, an improved link performance and high-flexibility network planning, etc. [2–4]. However, this transmission scheme has its drawback, namely its limited diversity order. Let us discuss this drawback in detail in order to conceive possible solutions.

The drawback in the conventional transmission is specifically the Bit Error Ratio (BER)/outage performance, which cannot benefit from the maximum achievable diversity order. This is because there is no channel selection scheme, since the channel to be activated at a specific time instant is predefined and it is activated regardless of its instantaneous Channel Quality (CQ). In order to improve the achievable performance of relaying systems, novel signalling schemes have been proposed [2, 5, 6], which require the nodes to have a store-and-wait capability. Additionally, our previous contributions [7–9] proposed a buffer-aided transmission scheme, namely the Multihop Diversity (MHD) transmission, philosophically which relies on temporarily storing the received packets and on activating the channel having the highest instantaneous SNR. Both our simulation results and theoretical analysis demonstrated that MHD transmissions are capable of a substantial selection diversity gain. Recently, a relay-relation scheme was proposed in [10], while full-duplex relaying was discussed in [11]. As a further advance, adaptive link selection was proposed in [12].

The motivation behind this paper is to fully exploit the advantages of buffer-aided transmissions. Without loss of generality, let us consider a single-relay-aided network scenario, where the SN-RN distance is lower than the RN-DN distance. Even though the SN-RN distance may be different from the RN-DN distance, the probability of either of those two hops being selected should be the same, otherwise the system becomes unstable, which results in a buffer-overflow at the RN. In order to solve this problem, a new channel activation scheme relying on buffer-aided transmissions is proposed. We assumed that the link between the SN and the DN is of low quality, which is hence ignored at the DN's receiver. Hence, there are only two channels constituted by the SN-RN and RN-DN links, which form a 2D Channel Probability Space (CPS). In a specific Time Slot (TS), the instantaneous CQ values may be directly mapped to a specific point in this 2D channel space. Our buffer-aided transmission scheme relies on the channel quality at this specific point for selecting the most appropriate channel for its next transmission. *The new contributions of this paper are summarized as follows:*

1. The concept of non-linear channel space partitioning is proposed.

2. The normalized end-to-end energy dissipation and the OP are analyzed.

The rest of this paper is organized as follows. Section II presents our system model and our assumptions, while Section III introduces the CPS concept and proposes our new channel activation regime. In Section IV, we provide our numerical and simulation results. Finally, our conclusions are offered in Section V.

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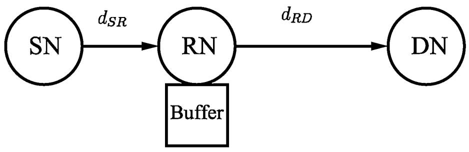

Fig. 1. System model for a buffer-aided three-node network, where SN sends messages to DN via RN.

II. System Model

Fig. 1 shows our single-relay-aided network considered in this contribution, which consists of a SN, a buffer-aided RN and a DN. The distances between corresponding pairs of nodes are d_{SR} and d_{RD}. Before explaining more about the details of this paper, we list the assumptions relevant to the physical layer schemes as below:

- The classic Decode-and-Forward (DF) protocol [13] is employed for relaying the signals;
- Each node is capable of adjusting its transmit power between zero and the maximum transmit power P_{max} for ensuring that the required SNR of γ_{Th} is achieved at the receiver;
- The signals are transmitted on the basis of TSs having a duration of T seconds;
- The channels are assumed to experience independent block-based flat Rayleigh fading, where the complex-valued fading envelope of a hop remains constant within a TS, but it is independently faded for different TSs;
- The pathloss is assumed to obey the negative exponential law of $d^{-\alpha}$, where α is the pathloss exponent;
- The instantaneous CQ of TS t between each node pairs is denoted by γ_{SR}, and γ_{RD}. The instantaneous transmit power of each node $\mathcal{E}_{RD}$ or $\mathcal{E}_{RD}$ can then be calculated with the aid of $\kappa = 9.895\times10^{-05}$ and the noise power for $N = 10^{-14}W$ which corresponds to a receiver sensitivity of $-110\ dBm$. An example of calculating $\mathcal{E}_{SR}$ is given by

$$\mathcal{E}_{SR} = \frac{\gamma_{Th}}{\gamma_{SR}}\frac{d_{SR}^{\alpha}N}{\kappa}, \mathcal{E}_{SR} \leq P_{max}, \tag{1}$$

and the outage threshold of this channel is

$$\gamma_{SR}^{out} = \frac{\gamma_{Th}}{P_{max}}\frac{d_{SR}^{\alpha}N}{\kappa}. \tag{2}$$

Additionally, we give the assumptions of the transmission scheme as follows:

- The SN always has packets to send, which hence facilitates for the single-relay-aided network to operate in its steady state.
- Both the SN and DN are capable of storing an infinite number of packets. By contrast, the RN can only store a maximum of B packets.
- In each TS, only a single packet is transmitted, when the corresponding link is activated.
- Our buffer-aided transmission scheme with non-linear CPS division provides every node with the global CQ knowledge and buffer fullness knowledge of the RNs within a given TS. All the operations are assumed to have been carried out without a delay and without errors.

III. The Node Activation Scheme with Non-Linear Channel Probability Space

In this section, our channel selection regime is introduced, which takes into account both the instantaneous and the expected transmission energy dissipation. Then, both the theoretical energy dissipation and the Outage Probability (OP) performance bounds are derived. Finally, a low-complexity algorithm is conceived for the estimation of the energy efficiency.

A. Channel Selection Criteria

Our goal is to activate that particular transmitter, which minimizes the expected end-to-end Packet-Energy-Dissipation (PED). Let us define that the total PED of the SN-RN-DN route is the sum of that in each hop. When the SN-RN channel is activated, the PED of the SN-RN hop ($\mathcal{E}_{SR}$) and of the RN-DN hop ($\mathcal{E}_{RD}$) takes place in two different Time Slots (TSs). Although $\mathcal{E}_{SR}$ may be known based on the current channel condition, $\mathcal{E}_{RD}$ of the RN-DN hop is unknown in the current TS. Therefore, we use the expected PED $\bar{\mathcal{E}}_{RD}$ for estimating $\mathcal{E}_{RD}$. Hence, when SN-RN channel is activate in TS t, the expected end-to-end PED becomes:

$$\mathcal{E}_{SR-\bar{RD}} = \frac{\gamma_{Th}}{\gamma_{SR}}\frac{d_{SR}^{\alpha}N}{\kappa} + \bar{\mathcal{E}}_{RD}. \tag{3}$$

When the RN-DN Channel is activated in TS t, the expected end-to-end PED is:

$$\mathcal{E}_{\bar{SR}-RD} = \bar{\mathcal{E}}_{SR} + \frac{\gamma_{Th}}{\gamma_{RD}}\frac{d_{RD}^{\alpha}N}{\kappa}. \tag{4}$$

Therefore, the minimum expected end-to-end PED, which is dissipated by any particular activated channel in each TS, is formulated as

$$\mathcal{E} = \min\{\mathcal{E}_{SR-\bar{RD}}, \mathcal{E}_{\bar{SR}-RD}\}, \tag{5}$$

which is the selection criteria of the simulation. In the remained part of this section, the theoretical energy dissipation and outage probability performance bound will be analyzed.

B. The concept of Channel Probability Space Division

The analysis starts from the concept of the CPS. As seen from Fig. 2, assuming that there is a two-dimensional space $\mathbb{S}$, a specific point associated with the coordinates $(\gamma_{SR}\ \gamma_{RD})$ in $\mathbb{S}$ represents the corresponding instantaneous channel condition of the system, hence $\mathbb{S}$ represents the CPS of the system. The outage SNR-threshold associated with each coordinate γ_{SR}^{out} and γ_{RD}^{out} dissects each coordinate into two segments, hence $\mathbb{S}$ is cut into $2^2 = 4$ subspaces. Fig. 2 shows the resultant CPS. A system outage occurs, when we have $\gamma_{SR} < \gamma_{SR}^{out}$ and $\gamma_{RD} < \gamma_{RD}^{out}$. The outage probability is denoted by P_{out} (which is represented by the square defined by the points ACDO in Fig. 2), yielding

$$P_{out} = (1 - e^{-\gamma_{SR}^{out}})(1 - e^{-\gamma_{RD}^{out}}). \tag{6}$$

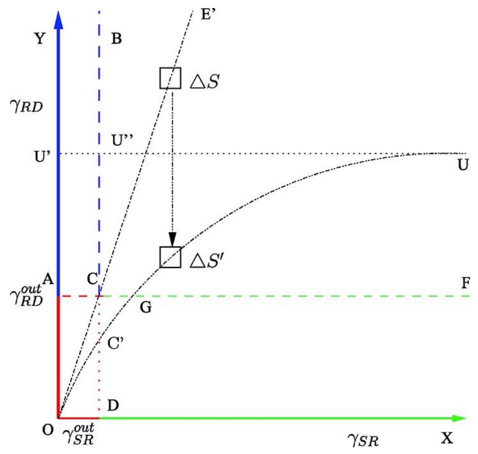

Fig. 2. A plane in CPS which shows that the channel selection is only between SN-RN hop and RN-DN hop.

Let P_{SR} and P_{RD} represent the probability that the corresponding channel is selected. Naturally, we expect $P_{SR} + P_{RD} + P_{out} = 1$. A subscript $\{\bullet\}$ in curly blackets represents that the instantaneous SNR of the set of channels is higher than the corresponding outage threshold. For example, $P_{SR\{SR\ RD\}}$ represents the probability of the channel SR being activated when we have $\gamma_{SR} \geq \gamma_{SR}^{out}$ and $\gamma_{RD} \geq \gamma_{RD}^{out}$. Naturally, we have $P_{SR} = P_{SR\{SR\}} + P_{SR\{SR\ RD\}}$ and the same properties are valid for P_{RD}. If there is only a single instantaneous CQ above the corresponding outage threshold, the system will choose that particular channel. For example, $P_{SR\{SR\}}$ is the probability represented by the prism defined by the points CDXF in Fig. 2. The corresponding probabilities are

$$P_{SR\{SR\}} = e^{-\gamma_{SR}^{out}}(1 - e^{-\gamma_{RD}^{out}}), \tag{7}$$

$$P_{RD\{RD\}} = (1 - e^{-\gamma_{SR}^{out}})e^{-\gamma_{RD}^{out}}. \tag{8}$$

Having introduced the concept of CPS and the calculation of the probabilities of P_{out}, $P_{SR\{SR\}}$ and $P_{RD\{RD\}}$, the more complicated scenarios, $P_{SR\{SR\ RD\}}$ and $P_{RD\{SR\ RD\}}$ are discussed in the next section.

C. The Energy Efficiency Factor E_{ffe}

Our main assumption is that the number of packets conveyed from SN to RN should be the same as those transmitted from RN to DN, which implies that the SN-RN channel and RN-DN channel should have the same probability of being activated. This assumption is automatically satisfied for $d_{SR} = d_{RD}$, since we have identical channel conditions in both hops. However, since P_{SR} may not equals P_{RD}, an energy efficiency factor E_{ffe} is introduced to balance the activation probability of the SN-RN channel and the RN-DN channel, as seen in Fig. 2. The associated activation process can be applied under diverse channel selection scenarios represented by this system model.

Explicitly, our goal is to find the activation boundary between the region (FCB) of activating the SR and RD links. As seen in Fig. 2, the line CE' represents the scenario, where the SR and RD channels have the same received SNR, which results in the lowest energy dissipation. However, the probability P_{SR} of activating the SR link may not be the same as P_{RD} due to the fact that d_{SR} may not be the same as d_{RD}. Without loss generality, let us assume that we have $d_{SR} < d_{RD}$, which results in $P_{SR} > P_{RD}$.

In order to deal with the problem of $P_{SR} > P_{RD}$, some of the regions that used to correspond to the activation of the SR hop have to be reassigned, so that they belong to the RD hop. However, this adjustment imposes extra energy consumption. Hence, the activation regions are carefully reassigned based on the associated energy efficiency factor E_{ffe}, which is defined as the ratio of the extra energy consumption. This process is detailed below.

Let us denote the probability of a small region ΔS in the surface OCE of Fig. 2 by $p_{\Delta S}$. The coordinates of ΔS are $(\gamma_{\Delta S_{SR}}, \gamma_{\Delta S_{RD}})$. When the region ΔS belongs to the SR hop and the SR hop is activated, then the expected end-to-end energy dissipated upon encountering the region ΔS is calculated from (3), yielding

$$\mathcal{E}_{\Delta S \in SR} = p_{\Delta S}(\frac{\gamma_{Th} d_{SR}^{\alpha} N}{\gamma_{\Delta S_{SR}} \kappa} + \bar{\mathcal{E}}_{\mathcal{RD}}). \tag{9}$$

By contrast, when the region ΔS belongs to the RD hop and the RD hop is activated, the expected end-to-end energy dissipated upon encountering the region ΔS is calculated from (4), yielding

$$\mathcal{E}_{\Delta S \in RD} = p_{\Delta S}(\frac{\gamma_{Th} d_{RD}^{\alpha} N}{\gamma_{\Delta S_{RD}} \kappa} + \bar{\mathcal{E}}_{\mathcal{SR}}). \tag{10}$$

If the region ΔS is reassigned from the SR hop to the RD hop, the extra energy dissipation becomes

$$\Delta \mathcal{E}_{\Delta S} = p_{\Delta S} \left(\frac{\gamma_{Th} d_{RD}^{\alpha} N}{\gamma_{\Delta S_{RD}} \kappa} + \bar{\mathcal{E}}_{\mathcal{SR}} - \frac{\gamma_{Th} d_{SR}^{\alpha} N}{\gamma_{\Delta S_{SR}} \kappa} - \bar{\mathcal{E}}_{\mathcal{RD}} \right). \tag{11}$$

Hence, if we know the probability $p_{\Delta S}$ of encountering the region ΔS of Fig. 2, E_{ffe} is defined as

$$E_{ffe} = \frac{\gamma_{Th} d_{RD}^{\alpha} N}{\gamma_{\Delta S_{RD}} \kappa} + \bar{\mathcal{E}}_{\mathcal{SR}} - \frac{\gamma_{Th} d_{SR}^{\alpha} N}{\gamma_{\Delta S_{SR}} \kappa} - \bar{\mathcal{E}}_{\mathcal{RD}}. \tag{12}$$

The specific value of E_{ffe} can be found using Equations (13) to (24), whilst a practical algorithm will be provided for solving these equations in Section III-D for the sake of making energy-efficient channel-activation decisions. In the remainder of this section, E_{ffe} is considered to be a known parameter.

D. Finding E_{ffe}

Having introduced E_{ffe}, this subsection explores the boundary of two activation regions. Explicitly, the three unknowns to be determined are $\bar{\mathcal{E}}_{\mathcal{SR}}$, $\bar{\mathcal{E}}_{\mathcal{RD}}$ and E_{ffe}, where we have:

$$\bar{\mathcal{E}}_{SR} = \frac{\mathcal{E}_{SR}}{P_{SR}} = \frac{\mathcal{E}_{SR\{SR\}} + \mathcal{E}_{SR\{SR\ RD\}}}{P_{SR\{SR\}} + P_{SR\{SR\ RD\}}} \tag{13}$$

$$\bar{\mathcal{E}}_{RD} = \frac{\mathcal{E}_{RD}}{P_{RD}} = \frac{\mathcal{E}_{RD\{RD\}} + \mathcal{E}_{RD\{RD\ SR\}}}{P_{RD\{RD\}} + P_{RD\{RD\ SR\}}} \tag{14}$$

$$\begin{aligned} P_{SR} &= P_{SR\{SR\}} + P_{SR\{SR\ RD\}} \\ =&P_{RD} = P_{RD\{RD\}} + P_{RD\{RD\ SD\}}. \end{aligned} \tag{15}$$

The channel-activation probabilities $P_{SR\{SR\}}$ and $P_{RD\{RD\}}$ have been formulated in (7) and (8), where the associated energy-dissipations $\mathcal{E}_{SR\{SR\}}$ and $\mathcal{E}_{RD\{RD\}}$ are

$$\begin{aligned} \mathcal{E}_{SR\{SR\}} &= \int_{\gamma_{SR}^{out}}^{\infty} e^{-\gamma_{SR}} \frac{\gamma_{Th}}{\gamma_{SR}} \frac{d_{SR}^{\alpha} N}{\kappa} d\gamma_{SR} \\ &= \frac{\gamma_{Th} d_{SR}^{\alpha} N}{\kappa} (-Ei(-\gamma_{SR}^{out})), \end{aligned} \tag{16}$$

$$\mathcal{E}_{RD\{RD\}} = \frac{\gamma_{Th} d_{RD}^{\alpha} N}{\kappa} (-Ei(-\gamma_{RD}^{out})), \tag{17}$$

with Ei being defined in [14](8.211.1). Now the variables $P_{SR\{SR\ RD\}}$, $P_{RD\{SR\ RD\}}$, $\mathcal{E}_{SR\{SR\ RD\}}$, $\mathcal{E}_{RD\{SR\ RD\}}$ should be found. However, owing to the limited length of this paper, we only consider $P_{SR\{SR\ RD\}}$ and $\mathcal{E}_{SR\{SR\ RD\}}$ as examples, noting that the expressions of $P_{SR\{SR\ RD\}}$ and $\mathcal{E}_{SR\{SR\ RD\}}$ are similar.

Explicitly, the boundary along the line of GU in Fig. 2 is expressed with the aid of $\gamma_{SR\{SR\ RD\}}$ and $\gamma_{RD\{SR\ RD\}}$ instead of $\gamma_{\Delta S_{SR}}$ and $\gamma_{\Delta S_{RD}}$. Given E_{ffe} in (12), the relationship between $\gamma_{SR\{SR\ RD\}}$ and $\gamma_{RD\{SR\ RD\}}$ is shown below

$$\gamma_{RD\{SR\ RD\}} = f_{\{SR->RD\}}(\gamma_{SR\{SR\ RD\}}) \tag{18}$$

$$= \frac{\gamma_{Th} d_{RD}^{\alpha} N}{E_{ffe}\kappa + \bar{\mathcal{E}}_{RD}\kappa - \bar{\mathcal{E}}_{SR}\kappa + \frac{\gamma_{Th} d_{SR}^{\alpha} N}{\gamma_{SR\{SR\ SD\}}}}, \tag{19}$$

where the domain of definition for $\gamma_{RD\{SR\ RD\}}$ is $(\gamma_{RD}^{out}, \infty)$[1] (CB in Fig. 2), and hence that for $\gamma_{SR\{SR\ RD\}}$ is $(\gamma_{SR\{SR\ RD\}}^{min}, \gamma_{SR\{SR\ RD\}}^{max})$ (GF in Fig. 2), yielding

$$\gamma_{SR\{SR\ RD\}}^{min} = \max\{\gamma_{SR}^{out}, f_{\{SR->RD\}}^{-1}(\gamma_{RD}^{out})\} \tag{20}$$

$$\gamma_{SR\{SR\ RD\}}^{max} = f_{\{SR->RD\}}^{-1}(\infty). \tag{21}$$

If $f_{\{SR->RD\}}^{-1}(\infty)$ has no positive solution[2], we have $\gamma_{RD\{SR\ RD\}}^{max} = \infty$. A specific example of $E_{ffe} > 0$ is shown in Fig. 2, where γ_{SR}^{out} is at point C and $f_{\{SR->RD\}}^{-1}(\gamma_{RD}^{out})$ is at point G. Hence $\gamma_{SR\{SR\ RD\}}^{min}$ is at point G, while $f_{\{SR->RD\}}^{-1}(\infty)$ has no solution, therefore we have $\gamma_{RD\{SR\ RD\}}^{max} = \infty$. Finally, the boundary for this example between activating the two hops is the curve GU.

[1]When $\gamma_{RD} > \gamma_{RD}^{out}$, the RD link has a certain probability to be selected. Now we want to find this probability. On the other hand, if a channel has an infinite SNR, this channel will be definitely activated. Hence, the the domain of definition of this input value is $(\gamma_{RD}^{out}, \infty)$.

[2]This principle is suitable for all functions $f_{\{\bullet\}}^{-1}(\infty)$, regardless of the sign of E_{ffe}.

Now the link activation probability $P_{SR\{SR\ RD\}}$ and the energy dissipation $\bar{\mathcal{E}}_{SR\{SR\ RD\}}$ of the SR link (region FGU in Fig. 2) may be formulated as (22) and (23)[3]:

$$\begin{aligned} &P_{SR\{SR\ RD\}} \\ =&\int_{\gamma_{SR\{SR\ RD\}}^{min}}^{\gamma_{SR\{SR\ RD\}}^{max}} e^{-\gamma_{SR}} \int_{\gamma_{RD}^{out}}^{f_{\{SR->RD\}}(\gamma_{SR})} e^{-\gamma_{RD}} d\gamma_{RD} d\gamma_{SR} \\ =&e^{-\gamma_{RD}^{out}} (e^{-\gamma_{SR\{SR\ RD\}}^{min}} - e^{-\gamma_{SR\{SR\ RD\}}^{max}}) \\ &- \int_{\gamma_{SR\{SR\ RD\}}^{min}}^{\gamma_{SR\{SR\ RD\}}^{max}} e^{-\gamma_{SR} - f_{\{SR->RD\}}(\gamma_{SR})} d\gamma_{SR} \end{aligned} \tag{22}$$

Upon substituting (7), (8), (16)-(23) into (13)-(15), the three unknowns $\bar{\mathcal{E}}_{\mathcal{SR}}$, $\bar{\mathcal{E}}_{\mathcal{RD}}$ and E_{ffe} can be found. However, it is not practical to directly solve these integral equations. Hence, we conceive a simple algorithm for finding the solution.

The basic principle is that of employing an exhaustive search for finding the optimal E_{ffe}. All energy dissipations and activation probabilities as well as (13) and (14) can be evaluated for a specific E_{ffe}. Therefore, we search for specific E_{ffe} values in the interval starting from zero and terminating when (15) is satisfied. Finally, the end-to-end PED bound is

$$\bar{\mathcal{E}} = \bar{\mathcal{E}}_{SR} + \bar{\mathcal{E}}_{RD}. \tag{24}$$

Algorithm 1: The algorithm of finding E_{ffe}.

```
E_ffe = 0;
Calculate all activation probabilities and energy
  dissipations;
Update Ē_SR and Ē_RD based on (13) and (14);
while P_SR ≠ P_RD do
    Increase E_ffe;
    Calculate all selection probabilities and energy
      consumptions;
    Update Ē_SR and Ē_RD based on (13) and (14);
end
```

IV. Performance results

In this section, we build up two network topologies for the sake of illustrating the effect of the RN's position on both the energy dissipation and the OP. More specifically, given the proposed channel selection criteria detailed in Section III-A, the non-linear CPS division method discussed throughout Section III-B to Section III-D can be applied. We set the SN to position $(100m, 100m)$ and the DN to position $(900m, 100m)$. We consider two scenarios, where the RN is set to the position of $(400m, 100m)$ for the first topology, while to the position of $(300m, 100m)$ for the second topology. The effect of the buffer size B of the RN is also investigated, which ranges from $B = 1$ to $B = 256$ packets. In all experiments, the parameters of N and κ are $N = -110$ dBm and $\kappa = 9.895 \times 10^{-05}$.

[3]Note that, some integrals derived in this paper cannot be expressed in closed-form. However, all formulas can be simplified to a single integral. The infinite value of the channel SNR may be considered as a large finite value, such as say 10. Therefore, a finite single integral can be efficiently evaluated by commercial software, such as MATLAB®, Maple® and Mathematica®.

$$\bar{\mathcal{E}}_{SR\{SR\ RD\}} = \int_{\gamma^{min}_{SR\{SR\ RD\}}}^{\gamma^{max}_{SR\{SR\ RD\}}} \frac{\gamma_{Th}}{\gamma_{SR}} \frac{d^{\alpha}_{SR}N}{\kappa} e^{-\gamma_{SR}} \int_{\gamma^{out}_{RD}}^{f_{\{SR->RD\}}(\gamma_{SR})} e^{-\gamma_{RD}} d\gamma_{RD} d\gamma_{SR}$$
$$= \frac{\gamma_{Th} d^{\alpha}_{SR}N}{\kappa} e^{-\gamma^{out}_{RD}} \left((-Ei(-\gamma^{min}_{SR\{SR\ RD\}}) + Ei(-\gamma^{max}_{SR\{SR\ RD\}})) - \int_{\gamma^{min}_{SR\{SR\ RD\}}}^{\gamma^{max}_{SR\{SR\ RD\}}} \frac{e^{-\gamma_{SR} - f_{\{SR->RD\}}(\gamma_{SR})}}{\gamma_{SR}} d\gamma_{SR} \right) \quad (23)$$

For convenience, "normalized energy dissipation" refers to the "Average normalized end-to-end energy dissipation per packet", which is the optimization objective of this paper. The first topology is represented by 'T1', while the second one by 'T2'. Moreover, 'non-linear-CPS' denotes the proposed buffer-aided transmission scheme associated with our non-linear CPS division. 'MHDCDF' represents the transmission scheme proposed in [1] where the system activates the specific channel, whose SNR cumulative distribution function (CDF) gives the highest ordinate value amongst all the available hops. 'Conv.' indicates the conventional relay-aided scheme, where a packet is transmitted from the SN to DN via the RN sequentially in two hops without buffering. Finally, 'Bound' represents the theoretical value, which assumes that the RN always has packets to transmit or it is capable of receiving packets in any TS, while 'sim' indicates the simulation based values relying on a sufficiently high number of packets.

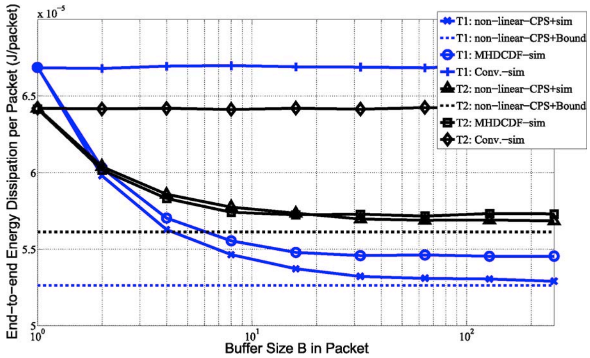

Fig. 3. Average normalized end-to-end energy dissipation per packet as defined in Section III-A when the pathloss factor is $\alpha = 2$. The theoretical curve was evaluated from (24).

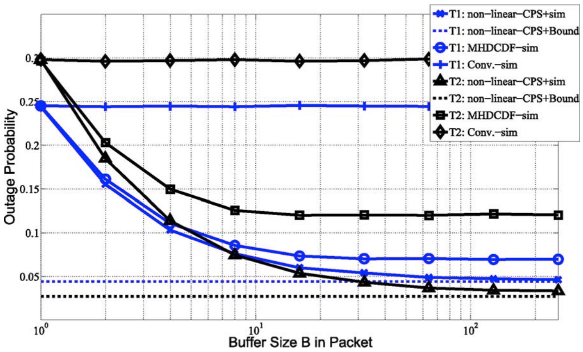

Fig. 4. The simulated and theoretical outage probability evaluated from (6).

Fig. 3 and Fig. 4 compare both the normalized energy dissipation and of the OP for various transmission schemes. For 'T1', it can be seen that the 'non-linear-CPS' scheme has both a lower normalized energy dissipation and a lower OP, when compared to that of the 'MHDCDF-sim' scheme. By contrast, for 'T2', both the 'non-linear-CPS' and 'MHDCDF-sim' schemes have a similar normalized energy dissipation. However, the OP performance of 'non-linear-CPS' is significantly lower than that of the 'MHDCDF-sim' scheme. By contrast, 'Conv.' is shown to perform the worst amongst the three schemes. The reason of why 'non-linear-CPS' has the best performance is because it is capable of identifying the highest-quality channel to be activated. To elaborate a little further, as expected, the energy dissipation and the OP have an inverse relationship, albeit their quantitative relationship is beyond the scope of this paper.

V. Conclusions

We proposed a buffer-aided transmission scheme relying on our non-linear CPS concept and investigated its performance in terms of both the normalized energy dissipation and the outage probability. A range of formulas have been obtained under the assumption that the packets can be correctly received, provided that the received SNR was in excess of a certain threshold. Our analysis and performance results showed that the proposed scheme results in a significant reduction of the energy dissipation, where the theoretical bound may be closely approached by employing a sufficiently large buffer at the RN. Our future research will consider the benefits of channel space division in higher dimensions associated with more nodes.

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