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Optimization of Split-and-Combine Relaying

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Abstract— **Relays play an important role for increasing rate and reducing energy consumption of wireless networks. In this paper we consider a three-node network (source, relay, destination) in which we want to minimize total energy consumption for a given transmission rate. We analyze and optimize the *Split-Combine-Relaying* (SCR) protocol that for many typical parameter settings performs better than traditional decode-and-forward. SCR splits a data packet into two fragments, which are then transmitted in two phases. In the first phase of transmission, the source sends the first fragment to the relay. In the second phase of the transmission, the source sends the second fragment to the destination, while, at the same time, the relay forwards the first fragment to the destination. We provide an optimization framework to decide the amount of data in each fragment, the amount of time spent in each of the phases, and the corresponding transmission powers. We also show that an extension of SCR that employs Slepian-Wolf coding of the fragments leads to further reduction of energy consumption.**

I. INTRODUCTION

Relays play an important role for improving the performance of wireless systems. They can serve to increase the range, and/or increase the capacity of a wireless ad-hoc networks as well as cellular networks. Furthermore, they can also be used to reduce total energy consumption; this is very important because on one hand, it implies longer battery life for mobile wireless devices; on the other hand, it implies the decrease in the amount of interference that a transmission produces, which in turns improves the overall signal to interference and noise ratio (SINR) in a network.

In the current paper we will consider the "canonic" network consisting of just one source, one relay, and one destination.[1] It is important for several reasons: (i) it gives fundamental insights into the design and performance limits of relay networks; (ii) such canonic networks actually have practical applications in cellular networks, e.g., the IEEE 802.16j (WiMAX) standard [1]; (iii) it serves as "building block" of larger relay networks [2].

The information-theoretic limits of relay channels have been explored since the classical papers of van der Meulen [3] and Cover and Thomas [4]. A number of different relaying schemes have been proposed, including (i) Amplify-and-Forward (AF) relaying, which can achieve gains with a simple power boosting circuit, (ii) Decode-and-Forward (DF), where the relay decodes the original message (thus eliminating noise effects), and then re-encodes and retransmits it, and (iii) Compress-and-Forward (CF) [5] where the source transmits a packet to both the relay and destination simultaneously during the first phase, and the relay transmits a quantized (compressed) version of its received signal to the destination during the second phase. Such energy accumulation schemes can reduce the total energy required to deliver the message from the source to the destination. A large number of papers, including the seminal works of Kramer and coworkers [2] and Laneman and Wornell [6] investigated the performance of various protocols.

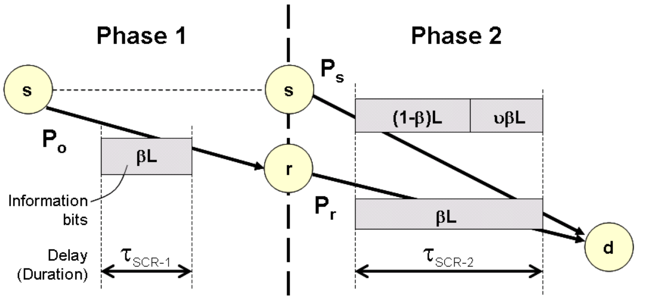

Fig. 1. An example of SCR transmission. L is the total number of bits to be sent from s to d. β is the packet splitting ratio. The parameter $\nu = 0$ corresponds to basic SCR, and $\nu > 0$ corresponds to Slepian-Wolf empowered SCR.

In this paper, we analyze a relaying scheme we call Split-and-Combine Relaying (SCR) [7]–[10]. An example of SCR with notations used throughout this paper is shown in Fig. 1. SCR takes a data packet unit and splits it into two fragments (not necessarily of equal length), which are then transmitted in two phases. In the first phase of transmission, the source sends the first fragment to the relay. In the second phase of the transmission, the source sends the second fragment to the destination, while, at the same time, the relay forwards the first fragment to the destination.

The key novel aspect of our work is that we optimize the energy consumption of the system for a prescribed rate (latency); the parameters we optimize are the powers of source and relay, as well as the duration of the two transmission phases; to the best of our knowledge, such optimization was not previously addressed in the literature. Willems and van

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[1] To simplify notation, we just call it "relay network" in the remainder of the paper. Extensions to larger networks are beyond the scope of this paper.

der Meulen studied memoryless multiple access channel with cribbing encoders over two decades ago [7], but did not optimize power allocation. While [8] studies SCR with power control, it assumes that the duration of the first and second phases of SCR are fixed independent of the link qualities, and as a matter of fact are equal. Finally, Erkip and coworkers [9], [10] analyzed the tradeoff between transmit power and rate of different cooperative techniques in the context of delay-limited capacity in which partial channel state information is known in a time-varying channel. The total energy consumptions of different schemes are not considered.

Another contribution of our paper is the extension of the SCR technique to consider the fact that the source knows the fragment of data that is being sent by the relay in the second phase. We show that this scheme can further reduce the total energy consumption by 16% in a specific scenario. While [11] introduced the concept of Slepian-Wolf cooperation, it did not allow for simultaneous transmission of the source and relay, and thus is different from the Slepian-Wolf empowered SCR scheme considered in this paper.

The remainder of the paper is organized as follows. The system model is described in Sec. II. In Sec. III, we describe the fundamental SCR technique, provide a framework to find its optimal parameters and compare its performance to traditional schemes. We also extend SCR to Slepian-Wolf empowered SCR. Finally, we provide numerical results and discussions in Sec. IV, and conclude in Sec. V.

II. SYSTEM MODEL

We consider the problem of unicast traffic in a wireless network that consists of a source node, s, a destination node, d, and an intermediate relay node, r, which operates in Decode-and-Forward (DF) mode. The source has a total of L bits of data to deliver to the destination. All nodes have a single antenna for transmission and reception, and operate in half-duplex mode (either transmitting or receiving, but not both simultaneously). The channels between the nodes are quasi-static AWGN (additive white Gaussian noise) channels; occasional link updates reflect possible changes of the channel states. Let $V = \{s, r, t\}$ be the set of nodes in the networks. For $u, v \in V$, let $|h_{uv}|^2$ be the channel (power) gain between the nodes u and v. The source node s knows the channel state information $|h_{sr}|^2$, $|h_{sd}|^2$ and $|h_{rd}|^2$, while the relay node r only knows $|h_{rd}|^2$. The receiver makes use of h_{sd} and h_{rd} for optimal combining of received signals. We assume the block-fading model [12] where the channels are fixed for the duration of a single transmission, and the scheme is implemented for each fading state separately.

When the source transmits a packet, it can only be addressed to either the relay or the destination - but not to both. We consciously ignore here the "broadcast effect", i.e., the case that the destination overhears the transmission from the source to the relay. This assumption is motivated by the fact that the energy needed to power the receiver circuits can be larger than the savings obtained from "overhearing" the direct transmission. For this reason, we will exclude schemes such as CF relaying from our comparison. The relay node operates in half-duplex mode, i.e., it can only receive or transmit signal at a given moment in time.

The relay can forward a message only reliable decoding, i.e., if the checksum of that message is correct. The contents of packets are received successfully when its transmission rate satisfies the information theoretic bounds for Gaussian channels. For example, when the source transmits the packet to the relay, a packet is received successfully if and only if its transmission rate R_{sr} satisfies[2] $R_{sr} \leq C(|h_{sr}|^2 P_s)$, where

$$C(x) = \frac{W}{2} \log\left(1 + \frac{x}{\sigma^2}\right) \tag{1}$$

W is system bandwidth available for use within this network, P_s is the transmission power of the source node, σ^2 is the receiver noise power, and $\log$ denotes the logarithm of base 2 is used.

We furthermore assume that the receiver has advanced multi-packet reception (MPR) capabilities. When both the source and relay transmits packets simultaneously to the destination, *both* packets are received successfully if and only if the transmission rate of the packet from the source, R_{sd-mpr}, and the transmission rate of the packet from the relay, R_{rd-mpr}, satisfy the information theoretic bounds for the multiple access channel [13]

$$R_{sd-mpr} \leq C(|h_{sd}|^2 P_s) \tag{2}$$

$$R_{rd-mpr} \leq C(|h_{rd}|^2 P_r) \tag{3}$$

$$R_{sd-mpr} + R_{rd-mpr} \leq C(|h_{sd}|^2 P_s + |h_{rd}|^2 P_r), \tag{4}$$

where P_s and P_r are the transmission power of the source and relay node, respectively.

III. SPLIT-AND-COMBINE RELAYING

It is well understood that the multiple access capacity region of two nodes transmitting simultaneously is larger than that of time sharing the channel between the two node [13]. The multiple access capacity region is described mathematically in (2)-(4), and is shown graphically as regions I and II in Fig. 2.

Since the message originally is present at the source only, multiple access from the source and relay can be used only after the source first passes a fraction of its data to the relay. The SCR technique proceeds in two phases as follows:

- **Phase 1:** The source transmits a fraction of the whole data content (βL bits, where β is the packet splitting factor, $0 < \beta < 1$) to the relay. The relay decodes the βL bits.
- **Phase 2:** The source transmits the remaining $(1-\beta)L$ bits of data to the destination while, at the same time, the relay forwards its received βL bits of data to the destination. The MPR-enabled destination decodes the transmission from both the source and the relay.

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[2] The information theoretical bound cannot be achieved using finite block length, but LDPC code with block sizes about $10,000$ bits get very close to the theoretical limit. One may also multiply all capacity result by a constant factor to approximate the effect due to finite block length.

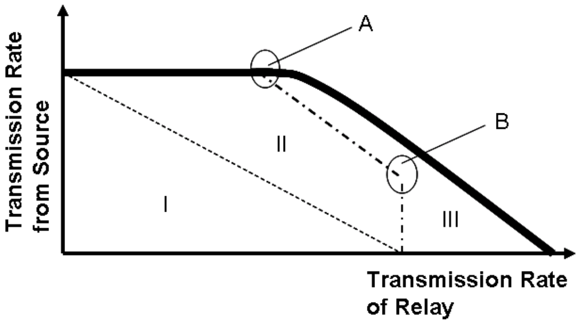

Fig. 2. Capacity of time-sharing (region I), multiple access channel (regions I and II) and Slepian-Wolf channel (regions I and II and III).

Let the source uses transmission power P_0 during Phase 1 of SCR. Hence, the delay (duration) of Phase 1 is $\tau_{SCR-1} = \frac{\beta L}{R_{sr}}$, where $R_{sr} = \frac{W}{2} \log\left(1 + \frac{|h_{sd}|^2 P_0}{\sigma^2}\right)$. The energy consumption is $E_{SCR-1} = \frac{\beta L P_0}{R_{sr}}$. Let the source and relay use transmission powers P_s and P_r, respectively, during Phase 2 of SCR. Then the delay of Phase 2 is

$$\tau_{SCR-2} = \max\left\{\frac{\beta L}{R_{rd-mpr}}, \frac{(1-\beta)L}{R_{sd-mpr}}\right\}, \tag{5}$$

where R_{sd-mpr} and R_{rd-mpr} are any positive values that satisfy (2)-(4), and the total energy consumption is $E_{SCR-2} = \frac{\beta L P_r}{R_{rd-mpr}} + \frac{(1-\beta)L P_s}{R_{sd-mpr}}$.

We now give a series of lemmas that govern the behavior of the SCR algorithm. First, we show that by reducing the transmission power, the total energy consumption of data transmission reduces.

Proposition 1: The total energy consumption of data transmission decreases when the transmission power decreases.

Proof: The energy for transmitting a packet at power P is

$$E = \frac{2LP}{W \log\left(1 + \frac{|h|^2 P}{\sigma^2}\right)}, \tag{6}$$

where $|h|^2 > 0$ is the channel (power) gain. This function is monotonically increasing. ■

Using the proposition, we can show that for minimum energy consumption, during phase 2 of SCR, the transmission delays for sending data from the source and relay, respectively, to the destination should be the same.

Lemma 1: The energy consumption of SCR is optimal (minimized) only if $\frac{\beta}{R_{rd-mpr}} = \frac{1-\beta}{R_{sd-mpr}}$.

Proof: Let us first consider the case $\frac{\beta L}{R_{rd-mpr}} > \frac{(1-\beta)L}{R_{sd-mpr}}$. Since the delay is given by (5), we can decrease R_{sd-mpr} by reducing the transmission power of the source during phase 2 of SCR, and the overall transmission delay would not be affected. By Proposition 1, decreasing transmission power decreases overall energy. Hence, the same overall transmission rate can be achieved using less total energy. A similar argument can be used for $\frac{\beta L}{R_{rd-mpr}} < \frac{(1-\beta)L}{R_{sd-mpr}}$. ■

Now, consider phase 2 of the communication protocol. For optimal performance, the transmission rates of source and relay should be chosen in the segment between points A and B in Fig. 2.

Lemma 2: The energy consumption during phase 2 of SCR is optimal (minimized) when the transmission rates of the source and relay are set such that (4) is satisfied with equality.

Proof: We prove this lemma by contradiction. If (4) is not satisfied with equality, it means that we can reduce the transmission power of either the source or the relay (or both) without affecting the overall delay. By Proposition 1, decreasing transmission power decreases overall energy. Hence, this strategy is not optimal. ■

Given the previous Lemmas, and the maximum rates R_{sd-mpr} and R_{rd-mpr} given in (2)-(3), we can find the bounds to β, and the corresponding values for R_{sd-mpr} and R_{rd-mpr}.

Lemma 3: For optimal SCR, the packet splitting factor is $1 - \frac{C(|h_{sd}|^2 P_s)}{C(|h_{sd}|^2 P_s + |h_{rd}|^2 P_r)} \leq \beta \leq \frac{C(|h_{rd}|^2 P_r)}{C(|h_{sd}|^2 P_s + |h_{rd}|^2 P_r)}$, and the optimal transmission rates in the second phase are

$$R_{sd-mpr} = (1-\beta)\, C(|h_{sd}|^2 P_s + |h_{rd}|^2 P_r) \tag{7}$$

$$R_{rd-mpr} = \beta C(|h_{sd}|^2 P_s + |h_{rd}|^2 P_r). \tag{8}$$

Proof: From Lemma 1, we know that

$$\beta = 1 - \frac{R_{sd}}{R_{sd} + R_{rd}} = \frac{R_{rd}}{R_{sd} + R_{rd}}. \tag{9}$$

We also know the upperbound for R_{sd-mpr} and R_{rd-mpr} in (2)-(3). The bounds on β follow. Furthermore, the transmission rates follow by manipulating the equality constraints in Lemmas 1 and 2. ■

A. Optimal SCR

Theorem 1: For optimal SCR, choose P_0, P_s and P_r, as a function of $|h_{sr}|^2$, $|h_{rd}|^2$, $|h_{sd}|^2$ and an objective overall transmission rate R, from the following optimization:

$$\min_{P_0, P_s, P_r} \frac{\beta L P_0}{C(|h_{sr}|^2 P_0)} + \frac{L(P_s + P_r)}{C(|h_{sd}|^2 P_s + |h_{rd}|^2 P_r)} \tag{10}$$

subject to $P_0, P_s, P_r > 0$ and

$$\beta = 1 - \frac{C(|h_{sd}|^2 P_s)}{C(|h_{sd}|^2 P_s + |h_{rd}|^2 P_r)} \tag{11}$$

$$R = \frac{C(|h_{sr}|^2 P_0)}{\beta} + C(|h_{sd}|^2 P_s + |h_{rd}|^2 P_r). \tag{12}$$

Proof: Given (7) and (8), we find that the total energy consumption and rate in the second phase of SCR are the second terms of (10) and (12), respectively, which do not depend on β. The energy consumption and rate in the first phase of SCR are the first terms of (10) and (12). As β decreases, the rate increases while the total energy decreases. Hence, in order to minimize total energy and delay of SCR, one should use the minimum value of β in the range given in Lemma 3, which is (11). ■

The optimization in Theorem 1 can be done readily using standard optimization techniques. Once the optimal power allocations are found, the transmission rates can be computed using the capacity formulas. The optimal transmission rates in phase 2 correspond to point A in Fig. 2.

B. Extension using Slepian-Wolf Coding

So far, we model the second phase of SCR using a multiple access channel. In fact, in the first phase, the source passes the information to be transmitted in the second phase to the relay; the data that the source and relay transmit in the second phase can therefore be correlated. This falls into the class of Slepian-Wolf [14] problems in information theory. Specifically, the capacity region of the second phase of SCR is [15]

$$0 \le R_{sd-sw} \le I(X_s; Y|X_r) \tag{13}$$

$$R_{sd-sw} + R_{rd-sw} \le I(X_s, X_r; Y), \tag{14}$$

where R_{uv-sw} denotes the transmission rate between the respective nodes u and v using coding for the Slepian-Wolf channel, $I(\cdot;\cdot)$ is the mutual information, X_u is the transmitted signal from node u, and $Y = X_s + X_r + N$ is the received signal at the destination, where N is the receiver noise.

We choose X_r as zero-mean Gaussian distributed with variance $|h_{rd}|^2 P_r$, and $X_s = W_s + \nu X_r$ where W_s is zero-mean Gaussian distributed with variance $|h_{sd}|^2 P_s - \nu^2 |h_{rd}|^2 P_r$, and ν is a control parameter that specifies, out of the βL bits of information that the source has already sent to the relay, the amount of this information the source also sends to the destination directly. By expanding the mutual information in (13)-(14) with this strategy, we obtain the following achievable rates: $R_{sd-sw} \le C(|h_{sd}|^2 P_s - \nu^2 |h_{rd}|^2 P_r)$, and $R_{sd-sw} + R_{rd-sw} \le C(|h_{sd}|^2 P_s + (1 + 2\nu)|h_{rd}|^2 P_r)$, for $0 \le \nu \le \sqrt{\frac{P_s |h_{sd}|^2}{P_r |h_{rd}|^2}}$.

The capacity region of the Slepian-Wolf channel is shown as regions I, II and III in Fig. 2. Compared to multiple access channel, the Slepian-Wolf channel increases the achievable region by region III in the figure. Intuitively, since the relay does not have any information on the content of the source in the second phase, the relay cannot help improve the transmission of the source. Hence, the maximum transmission rate of the source remains the same as that in the multiple access channel. However, by choosing the parameter ν, the source can allocate a different fraction of its power resource to help the data that is transmitted by the relay. As a result, the relay can transmit at higher data rate even when it uses the same transmission power as that in the multiple access channel.

In terms of power profiles and power splitting ratio, Slepian-Wolf empowered SCR introduces an additional variable, ν, into the optimization problem. Nonetheless, for a given ν, all the derivations for the optimal SCR in the previous section hold.

Theorem 2: For optimal Slepian-Wolf empowered SCR, choose P_0, P_s, P_r and ν as a function of $|h_{sr}|^2$, $|h_{rd}|^2$, $|h_{sd}|^2$ and an objective overall transmission rate R, from the following optimization:

$$\min_{P_0, P_s, P_r, \nu} \frac{\beta L P_0}{C(|h_{sr}|^2 P_0)} + \frac{L(P_s + P_r)}{C(|h_{sd}|^2 P_s + (1+\nu^2)|h_{rd}|^2 P_r)} \tag{15}$$

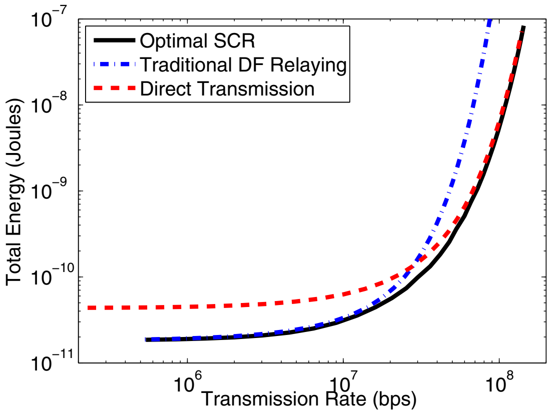

Fig. 3. Transmission Rate and energy consumption of direct transmission, traditional DF relaying and optimal SCR.

subject to $P_0, P_s, P_r > 0$ and

$$0 \le \nu \le \sqrt{\frac{|h_{sd}|^2 P_s}{|h_{rd}|^2 P_r}} \tag{16}$$

$$\beta = 1 - \frac{C(|h_{sd}|^2 P_s - \nu^2 |h_{rd}|^2 P_r)}{C(|h_{sd}|^2 P_s + (1+\nu^2)|h_{rd}|^2 P_r)} \tag{17}$$

$$R = \frac{C(|h_{sr}|^2 P_0)}{\beta} + C(|h_{sd}|^2 P_s + (1+\nu^2)|h_{rd}|^2 P_r). \tag{18}$$

The corresponding optimal rates are:

$$R_{sr} = C(|h_{sr}|^2 P_o) \tag{19}$$

$$R_{sd-sw} = C(|h_{sd}|^2 P_s - \nu^2 |h_{rd}|^2 P_r) \tag{20}$$

$$R_{rd-sw} = \frac{W}{2} \log\left(1 + \frac{(1+2\nu^2)|h_{rd}|^2 P_r}{|h_{sd}|^2 P_s - \nu^2 |h_{rd}|^2 P_r + \sigma^2}\right). \tag{21}$$

IV. NUMERICAL RESULTS AND DISCUSSIONS

A. Optimal SCR

We show the energy-rate tradeoff of DT, traditional DF relaying, and the optimal SCR scheme (introduced in Sec. *III*), in a three-node network scenario with $\alpha = 4$, $d_{sd} = 50$ m, $d_{sr} = 40$ m, $d_{rd} = 10$ m, $L = 10000$ bits of information, system bandwidth $W = 20$ MHz, and effective noise power $\sigma^2 = -100$ dBm. The channel gain between any nodes u and v is $|h_{uv}|^2 = 1/d_{uv}^{\alpha}$, where channel path loss exponent $\alpha = 4$.

The comparison DF relaying scheme optimizes total energy consumption given a target delay using $\tau_{DF} = \frac{L}{C(|h_{sr}|^2 P_s)} + \frac{L}{C(|h_{rd}|^2 P_r)}$, and $E_{DF} = \frac{L P_s}{C(|h_{sr}|^2 P_s)} + \frac{L P_r}{C(|h_{rd}|^2 P_r)}$.

From Fig. 3, we note that optimal SCR achieves better performance compared to both DT and DF relaying, regardless of what the transmission rate is.

In Fig. 4, we show the corresponding optimal power allocation of the optimal SCR. The circle (o) and cross (x) markers denote the transmit powers at the source during phase one and two of SCR, respectively. At high transmission rate, the optimal transmit power of the source at the two phases are about the same. At low transmission rate, optimal SCR

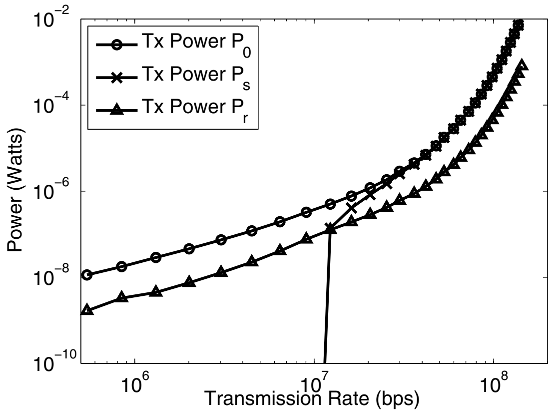

Fig. 4. The power allocation that achieves optimal SCR for a specific target transmission rate.

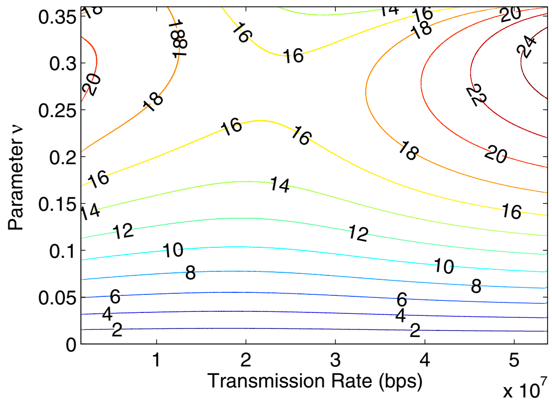

Fig. 5. The percentage reduction of total energy consumption of Slepian-Wolf empowered SCR and basic SCR (using equal transmission power) as a function of parameter ν and transmission rate. The result uses the following parameters: $d_{sd} = 50$ m, $d_{sr} = 20$ m, $d_{rd} = 30$ m. The contours denote the equal energy saving percentage.

achieves overall energy saving by reducing the transmission power of the source during the second phase. However, in reality, the receiver sensitivity constraint requires the transmit power to be above a certain threshold. Also, small P_s in the second phase implies β is close to one, and it becomes impractical to apply channel codes to the $(1-\beta)L$ bits efficiently. Hence, one should revert to using traditional DF relaying for low rate applications.

B. Slepian-Wolf Empowered SCR

In Fig. 5, we show how the parameter ν that enables Slepian-Wolf coding affects the overall energy consumption of SCR. The result assumes $P_0 = P_s = P_r$. This implies $0 \leq \nu \leq \sqrt{\frac{|h_{sd}|^2}{|h_{rd}|^2}} = 0.36$. In the figure, we see that, for the specific case considered, Slepian-Wolf Empowered SCR can reduce total energy consumption by as much as over 16%, for ν at about 0.25. That is, about 25% of data sent to the relay in the first phase is retransmitted in the second phase to the destination.

V. CONCLUSIONS

In this paper, we analyzed the Split Combine Relaying (SCR) technique in 3-node relay networks. The technique allows to minimize the total transmit power given a transmission rate constraints. We presented the fundamental optimization framework to obtain power and rate allocation and the corresponding packet splitting ratio for optimal SCR. We also investigated an extension that employs Slepian-Wolf encoding, and found that it can further reduce the total energy consumption.

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