Energy Efficient Relay Selection for Cooperative Relaying in Wireless Multimedia Networks

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***Abstract*—In existing wireless networks, supporting multimedia services is becoming more popular and important. In general, wireless multimedia networks should require energy efficiency and reliable transmission while keeping satisfactory quality of services. In this respect, cooperative communications have been considered as an efficient approach to address these demands by offering significant diversity gains over single antenna systems without increasing requirements on radio resources. In this paper, we propose a power-allocation method to optimize the decode-and-forward (DF) cooperative transmission for source and relay nodes as a means to reduce the total power consumption, while maintaining the required quality of services, and investigate fundamental characteristics of cooperative transmission in terms of power efficiency. Moreover, for a network with multiple cooperative nodes, we also propose energy efficient relay-selection rule to offer fairness at each node and implement it into a practical routing protocol. Our performance analysis is supplemented by simulation results to illustrate the significant energy savings of the proposed methods.**

***Index Terms*—Relaying, energy efficiency, reliability, QoS, multimedia**

I. Introduction

Future wireless networks are expected to support the mixture of real-time applications, such as monitoring [1] and multimedia streams [2], [3], and non-real-time data applications, such as web browsing, messaging and file transfers. Compared with wired environments, the associated communication channels and traffic patterns in mobile wireless networks are more unpredictable. Hence all of these applications impose stringent and diversified Quality-of-Service (QoS) requirements, which cannot be satisfactorily addressed through the traditional communication system. Recently, the availability of low-cost and high processing capability hardware which is capable of delivering multimedia content from the environment has fostered the development of wireless multimedia networks [4]–[7], i.e., networks of resource-constrained wireless devices that can retrieve and deliver multimedia content such as voice and video streams, still images, messaging and file transfer. As a result, it is predicted that wireless multimedia networks should maintain both transmission reliability and energy efficiency while keeping satisfactory quality of services.

Towards this goal, multiple-input multiple-output (MIMO) has received significant attention, which can provide spatial diversity and hence represents a powerful technique for interference mitigation and reduction [8], [9]. Although MIMO systems can show their huge benefit in cellular base scenarios, they may face challenges when it comes to their deployment in mobile devices. In particular, the typically small-size of wireless devices makes it impractical to deploy multiple antennas. To overcome this drawback, the concept of cooperative communication mechanisms have been proposed as an effective way of exploiting spatial diversity to improve the quality of wireless links [10]–[14]. The key idea is to have multiple wireless devices in different locations cooperatively share their antenna resources and aid each other's wireless transmission effectively to form virtual and distributed antenna arrays.

In cooperative communication, the term "cooperation" refers to a node's willingness to share its own resource (e.g., energy, transmission opportunity) for the benefit of other nodes. It is thus important to understand how much resource must be consumed to reap the benefits of the cooperative communication. In our previous work [15], we have shown that it is advantageous to employ cooperative transmission in a network with multiple, mutually cooperative nodes, which can significantly reduce the total power consumption while maintaining a given level of quality of service (QoS). However, there is no clear answer about whether cooperative communication requires more (or less) overall resources than conventional, non-cooperative communication to achieve the same level of wireless link quality? If so, how much resource we can best save when employing cooperative communication? What is the impact of each node's "willingness" to cooperate on energy efficiency when selfish and unselfish natures are imposed to individuals? What are the applicable scenarios and how to incorporate the proposed solution into practical routing protocol to support multimedia services? This paper is our answers to these questions, with particular focus on the energy consumption issues in cooperative communication to support multimedia services with stringent QoS requirements.

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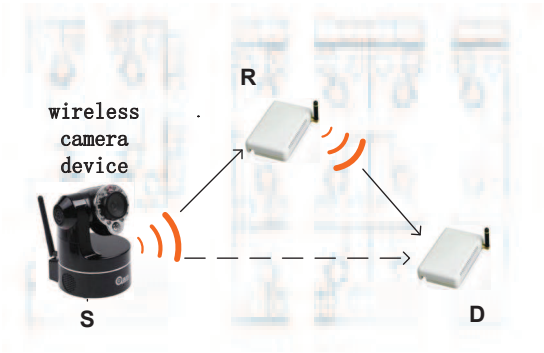


Fig. 1. An example of a wireless cooperative link

We consider in this paper the decode-and-forward (DF) cooperative communication. Fig. 1 illustrates the concepts of DF, where the transmission of a source (S) to a destination (D) is aided by a relay (R). While there are variants of cooperative communication, depending on how the relay cooperates to the source's transmission, R's action in DF is to overhear the packet transmitted by S, decode it, and retransmit it to D, improving the reception quality of the (combined) signal at D. This cooperative scheme lends itself to a relatively easy implementation in hardware and software. Moreover, it is shown in [11] that such a cooperative scheme can achieve full second-order diversity and therefore provides significant improvement to reception reliability.

Specifically, we explore the energy consumption aspect of DF cooperative communications (CC) from various angles. First, we look at how much transmit powers are required for the source and the relay respectively in the cooperative transmission for a given requirement on the link quality. This result is then used to investigate how much and in which case the power can be saved by using the cooperative communication, compared to conventional and (non-cooperative) direct communication. Based on these analytical results, we propose the strategy for a resource allocation problem in networks of multiple cooperative nodes, namely the energy-efficient relay-selection rule for each packet transmission. In order to study the achievable energy savings due to cooperative communications at a fundamental level, we assume throughout the paper that a predefined QoS requirement in terms of the transmission rate and the outage probability is given.

The following summarizes our contributions and key results:

- We derive a closed-form solution for the optimal transmission power required by each source and relay node in DF cooperative communication under a Rayleigh fading channel model to achieve the given QoS requirements. Under the optimal power allocation, our analysis shows that the required transmission power of the relay is always smaller than that of the source, a result which lays a foundation to encourage the cooperative behaviors as this means that the helping party (relay) only needs to spend relatively small amount of energy than the one seeking help from others (source).
- We analyze the power consumption in the optimal cooperation scheme and compare its performance with both direct transmission and conventional cooperation where both source and relay power are considered as identical. Specifically, we define the term of power efficiency and investigate the best relay location to achieve the minimum power consumption as well as derive the bound performance compared with conventional cooperation.
- By utilizing the optimal results, we propose adaptive relay selection rule that will help select appropriate relays for the fairness and maximal energy saving of each node in a multi-node environment and analyze node's "willingness" to cooperate when selfish and unselfish natures are imposed to individuals as well as incorporate them into the implementation of a practical machine-to-machine (M2M) routing protocol. Simulation results are supplemented to illustrate the significant energy savings of the proposed relays selection rules in providing reliable services.

This paper is organized as follows. The literature review of related work is given in Section II. The system model and optimal power consumption are introduced and analyzed in Section III. The analysis of the optimal cooperation scheme is presented in Section IV. The energy-efficient relay-selection rules and their practice in the M2M routing protocol are proposed in Section V and VI, respectively. Simulation results are provided in Section VII. Finally, concluding remarks are given in Section VIII.

II. Related work

Cooperative diversity has largely been considered by physical layer researchers as a low-cost way to achieve spatial diversity. The key feature of cooperative transmission is to encourage multiple single-antenna users/sensors to share their antennas cooperatively. There have been intensive studies on the physical layer techniques of cooperative communication, we refer the interested reader to some state-of-art works [10], [11] for a preliminary understanding of cooperative transmission at physical layer.

In general, there are two common approaches to cooperative diversity: amplify-and-forward (AF) and decode-and-forward (DF) [16]. The first scheme can be viewed as repetition coding from two separate transmitters, except that the relay transmitter amplifies its own receiver noise. While for the second scheme, the relay fully decodes and retransmits the received signal to the destination (and possibly transmits decoding errors). The destination can employ a variety of combining techniques to achieve diversity gain from cooperation. Due to the enhanced performance and relatively easy implementation in hardware and software, we explore the decode-and-forward scheme [11] in this work.

A. Fundamental understanding of cooperative benefits

More recent works in the literature shows that cooperative communication can significantly improve the overall quality of the wireless transmission. Min *et al.* in [17] consider energy efficient relay selection for two-way relay channel using analog

network coding. Yinman *et al.* in [18] examine the symbol-error-rate (SER) performance of decode-and-forward (DF) cooperative communications with multiple Dual-Hop relays over Nakagami-m fading Channels and show that SER performance is significantly improved with channel conditions or fading parameters, because of the increased diversity order. Vahid *et al*. in [19] also consider in spectrum sharing systems the error performance of cognitive (secondary) user's communication can be significantly improved by implementing the partial relay selection using DF without affecting the performance of licensed (primary) users. Meanwhile, Meixia *et al*. in [20] address an optimization problem involving transmission mode selection (direct or cooperative transmission), relay selection as well as subcarrier assignment to maximize throughput in cooperative OFDMA networks. It shows that the proposed algorithm can enhance throughput performance by more than 75% compared to direct transmission. Mohamed *et al*. in [21] propose an energy efficient routing protocol for cooperative networks by employing relay clusters along a non-cooperative path and reveal that the proposed cooperative transmission protocol can save up to 40% of energy compared with the disjoint-paths and the one-path scheme using only direct transmission.

There are also existing works on the analysis of delay and network capacity of wireless networks by using the concept of cooperation. Mao *et al*. in [22] measure queuing delay in two-user cooperation system and the proposed scheduling policy is proven to greatly reduce the delay unbalance between users. Also Sanquan *et al*. in [23] show that the connectivity of wireless networks can be significantly improved through collaboration. Furthermore, the collaborative networks require less power than non-collaborative networks in order to maintain connectivity of the whole network.

B. Cross-layer approach to achieve energy efficiency

Although various cooperative transmission schemes have been developed to increase the bandwidth efficiency, most of existing literatures focus on physical layer techniques and there is lack of understanding of cooperative benefits at upper layers, e.g., routing and applications. In this paper, we take a cross layer approach to tackle cooperative efficiency from physical layer up to network and application layers. Specifically, by proposing efficient relay selection rules, we evaluate the performance of cooperative diversity in wireless networks to satisfy the stringent requirements imposed by multimedia services.

In the latest work of relay selection, Ritesh *et al.* in [24] consider to employ a varying subset (and number) of relay nodes to cooperatively beamform at any given time to achieve energy efficiency. Ramin *et al.* in [25] propose an optimization problem to find a number of relay along the path with the minimum end-to-end outage probability from source to destination. The proposed solution requires an optimization over all the paths connecting source-destination subject to a fixed total power constraint. Salama *et al.* in [13] investigate the performance of the best-relay selection and show that the best-relay selection not only reduces the amount of required resources but also can maintain a full diversity order. Sung-Rae *et al.* in [26] also propose a best relay selection scheme to ensure minimum outage probability given a Poisson field of relay nodes and the presence of path loss and fading, and argue that relays geographically closing to the source and destination are preferred to others.

Different to the above literatures, our contribution in this paper is that we consider power efficiency as a main object in relay selection to sure QoS requirements. Moreover, the proposed relay selection rules can help achieve the global energy efficiency as well as reliability in wireless multimedia networks. Hence these results will potentially have a broad impact across a range of industry areas, including M2M and home automation, etc.

III. System model and optimal DF cooperation

We consider a cooperative network in Fig. 1: source node (S), destination node (D), and a relay node (R), which overhears S's transmission to D, retransmits or *relays* the received signal to D, improving the reception quality of the (combined) signal at D. Our scheme employs two transmission slots: In the first time slot, the source broadcasts its data to the relay and the destination. In the second time slot, the relay transmits the signal it received in the previous time slot, if the SNR exceeds a threshold; otherwise, the source retransmits the signal. We thus implicitly assume a mini-slot at the beginning of the second slot during which ACKs are sent error-free from the relay to the source. Two time slots are used to transmit and relay a given data signal to avoid RF capture effects when simultaneously transmitting and receiving in the same frequency band. As a result, the destination receives two independent copies of the same packets transmitted through different wireless channels. Diversity gain can be achieved by combining the data copies using one of a variety of combining techniques, e.g., the Maximum Ratio Combining (MRC) where the received signals are weighted with respect to their SNR and then summed together.

A detailed system assumptions are summarized as follows:

- The channel model incorporates both path loss and Rayleigh fading.
- The channel gain $\mathrm{a}_{s,d}$ between the nodes s and d is modelled as $\mathrm{a}_{s,d} = h_{s,d}/d_{s,d}^{\alpha/2}$, where $h_{s,d}$ captures the channel fading characteristics, $d_{s,d}$ is the distance between the nodes s and d and α is the path-loss exponent.
- The channel fading parameter $h_{s,d}$ is assumed to be complex Gaussian with zero mean and unit variance, and independent and identically distributed (i.i.d.) across times slots, packets and across links.
- b is defined as a desired data rate in the unit of bit/s/Hz, p and q denote the source and relay power, respectively.
- Additive white Gaussian noise is also assumed with the same variance σ_n^2 at both relay and destination.
- Outage probability is defined as the probability that a given data rate cannot be supported because of channel variations.

- A QoS is decided by the target outage probability η and transmission data rate b, which is required by multimedia service applications.

A. Direct transmission

We start with direct transmission, the received signal at a destination d is modeled as

$$y_d[n] = \mathrm{a}_{s,d} x_s[n] + n_d[n] \tag{1}$$

where $x_s[n]$ is the signal transmitted by a source s, $n \in [1, ..., N]$ is the index of the transmitting packet and $n_d[n]$ is additive white Gaussian noise, with variance σ_n^2, at the receiver.

The channel capacity between the source s and the destination d is

$$I_{s,d} = \log(1 + p|\mathrm{a}_{s,d}|^2) \tag{2}$$

where $p = E_b/N_0$ is defined as the normalized transmission power. Since for Rayleigh fading, $|\mathrm{a}_{s,d}|^2$ is exponentially distributed with parameter $d_{s,d}^{\alpha}$. The outage probability satisfies

$$\begin{aligned} \epsilon^{out} = \Pr[I_{s,d} < b] &= 1 - \exp\left(-\frac{(2^b - 1) d_{s,d}^{\alpha}}{p}\right) \\ &\approx d_{s,d}^{\alpha}\left(\frac{2^b - 1}{p}\right) \end{aligned} \tag{3}$$

for large p. Here b is a desired data rate in the unit of bit/s/Hz, which is defined by QoS requirements. We then have the normalized transmission power for direct transmission

$$p_D = d_{s,d}^{\alpha}\left(\frac{2^b - 1}{\epsilon^{out}}\right). \tag{4}$$

B. DF cooperative transmission

Let $d_{s,d}$, $d_{s,r}$ and $d_{r,d}$ be the respective distances among the source, relay and destination node. During the first time slot, the destination and relay receive $y_{d,1}[n] = \frac{h_{s,d}}{d_{s,d}^{\alpha/2}} x_s[n] + n_d[n]$ from the source node, where $x_s[n]$ is the information transmitted by the source and $n_d[n]$ is white noise. During the second time slot, the destination node receives

$$y_{d,2}[n] = \begin{cases} \frac{h_{s,d}}{d_{s,d}^{\alpha/2}} x_s[n] + n_d[n], & \text{if } |\frac{h_{s,r}}{d_{s,r}^{\alpha/2}}|^2 < f(p) \\ \frac{h_{r,d}}{d_{r,d}^{\alpha/2}} x_r[n] + n_d[n], & \text{if } |\frac{h_{s,r}}{d_{s,r}^{\alpha/2}}|^2 \geq f(p) \end{cases} \tag{5}$$

where $f(p) = (2^{2b} - 1)/p$ can be derived from direct transmission and is analogous to (3). In this protocol, the relay transmits only if the SNR exceeds a threshold; otherwise, the source retransmits in the second time slot.

Assuming that the relay node can perform perfect decoding when the received SNR exceeds a threshold, the channel capacity of this cooperative link can be shown as

$$I_{s,d} = \begin{cases} \frac{1}{2}\log(1 + 2p|\mathrm{a}_{s,d}|^2), & |\mathrm{a}_{s,r}|^2 < f(p) \\ \frac{1}{2}\log(1 + p|\mathrm{a}_{s,d}|^2 + q|\mathrm{a}_{r,d}|^2), & |\mathrm{a}_{s,r}|^2 \geq f(p) \end{cases} \tag{6}$$

where p and q are the normalized source and relay power, respectively. Therefore, the outage event is given by $I_{s,d} < b$ and the outage probability becomes

$$\begin{aligned} &\epsilon^{out} = \Pr[I_{s,d} < b] \\ &= \Pr[|\mathrm{a}_{s,r}|^2 < f(p)]\Pr[2|\mathrm{a}_{s,d}|^2 < f(p)] \\ &+ \Pr[|\mathrm{a}_{s,r}|^2 \geq f(p)]\Pr[|\mathrm{a}_{s,d}|^2 + \left|\sqrt{\frac{q}{p}}\mathrm{a}_{r,d}\right|^2 < f(p)]. \end{aligned} \tag{7}$$

By computing the limit, we obtain from (7)

$$\begin{aligned} \frac{1}{f^2}\epsilon^{out} &= \underbrace{\frac{1}{f}\Pr[|\mathrm{a}_{s,r}|^2 < f]}_{\mathbf{T1}} \underbrace{\frac{1}{f}\Pr[2|\mathrm{a}_{s,d}|^2 < f]}_{\mathbf{T2}} \\ &+ \underbrace{\Pr[|\mathrm{a}_{s,r}|^2 \geq f]}_{\mathbf{T3}} \underbrace{\frac{1}{f^2}\Pr[|\mathrm{a}_{s,d}|^2 + \left|\sqrt{\frac{q}{p}}\mathrm{a}_{r,d}\right|^2 < f]}_{\mathbf{T4}} \end{aligned} \tag{8}$$

where $f = f(p)$, **T1** $\approx d_{s,r}^{\alpha}$, **T2** $\approx d_{s,d}^{\alpha}/2$, **T3** ≈ 1, which can be derived from direct transmission and are analogous to (3). Moreover, according to the results of Fact 1 and 2 of Appendix I in [11], we can derive the cumulative distribution function of the sum of two independent exponential random variables $|\mathrm{a}_{s,d}|^2$ and $|\mathrm{a}_{r,d}|^2$, and have the approximate value **T4** $\approx \frac{p}{q} d_{s,d}^{\alpha} d_{r,d}^{\alpha}/2$.

Since $f(p) = (2^{2b} - 1)/p$, we obtain a closed-form expression for the outage probability between the source and the destination using cooperative transmission

$$\epsilon_C^{out} = \frac{1}{2} d_{s,d}^{\alpha}(d_{s,r}^{\alpha} + \frac{p}{q} d_{r,d}^{\alpha}) \frac{(2^{2b} - 1)^2}{p^2}. \tag{9}$$

C. Optimal DF transmission power

A meaningful optimization problem is to minimize the total transmission power consumption of a cooperative link given that a target Quality-of-service (QoS) is satisfied and can be formulated as

$$\begin{aligned} \min \quad & p + q \\ s.t. \quad & \epsilon_C^{out}(p, q) \leq \eta \end{aligned} \tag{10}$$

- p and q denote the source and relay power, respectively, and $\epsilon_C^{out}(p, q)$ is the outage probability defined by (9),
- A QoS is decided by the target outage probability η and transmission data rate b, which is required by multimedia service applications.

Theorem 1: The optimal transmission power to minimize the total power consumption of DF cooperation given that a target QoS is satisfied, is given by

$$p^* = \sqrt{\frac{a + 2b}{2} + \frac{\sqrt{a^2 + 8ab}}{2}}, \quad q^* = \frac{ap^*}{p^{*2} - b} \tag{11}$$

where $a = \frac{\mu d_{s,d}^{\alpha} d_{r,d}^{\alpha}}{2\eta}$, $b = \frac{\mu d_{s,d}^{\alpha} d_{s,r}^{\alpha}}{2\eta}$, $\mu = (2^{2b} - 1)^2$ and η is the outage constraint.

Proof: See Appendix A. □

Property 2: The optimal relay power q^* is always smaller than the optimal source power p^* with

$$p^* > q^* \tag{12}$$

The result follows (11) and has $q* = \frac{2p^*}{[1+\sqrt{1+8d_{s,r}^{\alpha}/d_{r,d}^{\alpha}}]}$ which is always smaller than p^*.

In general, we find that the optimal DF cooperation saves the relay power as it moves closer to the destination. Moreover, the optimal cooperation can help reduce the total transmission power, which will be further analyzed in the following.

IV. Analysis of optimal DF cooperation

In this section, we provide a comprehensive analysis of the optimal DF cooperative transmission. First, we discuss the best relay location for optimal DF which can achieve the maximum energy saving compared with direct transmission. Then, we analyze its advantage in energy saving, by comparing it with a conventional cooperative scheme.

A. Power efficiency factor

We introduce a power efficiency factor β that represents the ratio of the total transmission power of cooperative transmission to that of direct transmission:

$$\beta = \frac{p+q}{p_D}\,. \tag{13}$$

Clearly, small values of β are always preferable.

According to (4) and (11), the power efficiency factor for optimal DF is defined by

$$\beta^* = \frac{p^*+q^*}{p_D} = \frac{\sqrt{\frac{m+1}{4}}(\sqrt{d_{s,r}^{\alpha}} + \frac{d_{r,d}^{\alpha}}{m\sqrt{d_{s,r}^{\alpha}}})}{K\sqrt{d_{s,d}^{\alpha}}}, \tag{14}$$

where $K = ((2^b+1)\sqrt{2\epsilon^{out}})^{-1}$ is the QoS factor, $\gamma = \frac{d_{r,d}^{\alpha}}{d_{s,r}^{\alpha}}$ and $m = \frac{\gamma+\sqrt{\gamma^2+8\gamma}}{2}$.

B. Best relay location for optimal DF

Result 3: For any relay r which is non-collinear with the source s and destination d, we can always find a mapping relay r' on $\overline{sd}$ which achieves a lower total power consumption, given the same target QoS.

Proof: As can be seen from Figure 2, given a relay r which is outside the line $\overline{sd}$, we can find a point r' on $\overline{sd}$ as the mapping relay where $\overline{rr'}$ is perpendicular to $\overline{sd}$. Clearly, we have $d'_{s,r} < d_{s,r}$, $d'_{r,d} < d_{r,d}$ and hence, $a' < a$, $b' < b$.

From (11), we define $f(a,b) = p^* + q^*$. Since $\frac{\partial f(a,b)}{\partial a} > 0$ and $\frac{\partial f(a,b)}{\partial b} > 0$, we can obtain $p^*+q^* = f(a,b) > f(a',b) > f(a',b') = p'^* + q'^*$, which completes the proof. □

Result 4: For path loss $\alpha = 2$, the best relay location that minimizes β^* for the optimal DF cooperation is at the destination.

Proof: From Result 3, we can find that the relay location which minimizes β^* for the optimal DF cooperation is surely

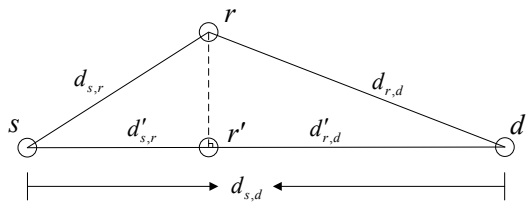


Fig. 2. The position of a mapping relay.

on the line $\overline{sd}$, namely $d_{s,r} + d_{r,d} = d_{s,d}$. Bring this result into (14), we can obtain the ratio for $\alpha = 2$:

$$\beta^* = \frac{1}{K}\sqrt{\frac{m+1}{4}}\left(1 + \left(\sqrt{\frac{\gamma}{m^2}} - 1\right)\frac{d_{r,d}}{d_{s,d}}\right)$$

where $\gamma = \frac{d_{r,d}^{\alpha}}{d_{s,r}^{\alpha}}, m = \frac{\gamma+\sqrt{\gamma^2+8\gamma}}{2}$. Since $\beta^* \geq 0$, it is easy to observe that the minimum value can be obtained as $\frac{1}{2K}$ when $\frac{d_{r,d}}{d_{s,d}} = 0$. □

Note that this result is different from that of cooperative schemes with identical power [26], [27], where for $\alpha > 1$ the best relay location for DF cooperation is proved to be the midway between source and destination.

C. Individual power behaviors

Most of recent literature on single relay selections are based on the identical power assumption for both source and relay, e.g., [25], [26], [28]. To better evaluate the performance of the optimal DF cooperation and compare its performance with existing solutions, we consider this equal power scenario as the conventional cooperative scheme where the source and relay nodes always use the identical transmission power, i.e., $p = q = p_{\text{con}}$. Hence the minimum total power consumption can be derived from (9) as follows:

$$2p_{\text{con}} = 2\sqrt{\frac{1}{2}d_{s,d}^{\alpha}(d_{s,r}^{\alpha} + d_{r,d}^{\alpha})\frac{(2^{2b}-1)^2}{\epsilon_C^{out}}}\,. \tag{15}$$

Then, the power efficiency factor is defined by:

$$\beta' = \frac{2p_{\text{con}}}{p_D} = \frac{\sqrt{d_{s,r}^{\alpha} + d_{r,d}^{\alpha}}(2^b+1)\sqrt{2\epsilon^{out}}}{\sqrt{d_{s,d}^{\alpha}}}. \tag{16}$$

Theorem 5: Given a relay r, the power efficiency of optimal DF (14) is always lower than that of conventional cooperative scheme (16), and we have the bound performance of optimal DF as:

$$\frac{\beta'}{2} < \beta^* < \beta'. \tag{17}$$

1) The lower bound is obtained when the relay approaches to the destination, where we have the optimal source power $p^* = p_{\text{con}}$ and the performance gain can reach to its maximum with the relay power q^* down to 0.
2) The upper bound is obtained when the relay closes to the source node, where we derive $p^* = q^* = p_{\text{con}}$, which means that the optimal cooperation uses the same amount of power as the conventional cooperation.

3) When the relay goes to infinite or stay in the middle of source and destination, we have $\frac{\beta^*}{\beta'} = \sqrt{\frac{27}{32}}$.

Proof: See Appendix B. □

Result 6: Compared with the transmission power of the conventional cooperative scheme, the optimal source power p^* is bounded by:

$$p_{\text{con}} < p^* < 1.23 p_{\text{con}}. \tag{18}$$

Proof: We first derive the upper bound of $\frac{p^*}{p_{\text{con}}}$. It is observed that if (32) can has the maximum value, then its inner term $\frac{1+\sqrt{\gamma^2+8\gamma}}{1+\gamma}$ should be maximum. Note that $h(\gamma) = \frac{1+\sqrt{\gamma^2+8\gamma}}{1+\gamma}$ is a convex function for $\gamma > 0$ since $\frac{\mathrm{d}^2 h(\gamma)}{\mathrm{d}^2 \gamma} \leq 0$. Hence there will be only one maximum for $\gamma > 0$. Taking the first order of $h(\gamma)$, we have the optimal γ^* to get the maximum $h(\gamma)$ as $\gamma^* = 2 - \sqrt{2}$. Replacing it in (32), we can obtain the upper bound.

From (32), the lower bound performance is achieved when the relay node closes to the source or the relay node closes to the destination, i.e., $\gamma = 0$ or $\gamma = \infty$. □

In general, Result 6 tells us that the optimal source actually spends more power than that in the conventional cooperation. However, from (31) and Theorem 5, a careful reader might notice that the optimal cooperation can help significantly reduce the relay power, especially when the relay approaches to the destination. In other words, slightly increasing the source power can help significantly reduce the relay power and thereafter saving the total energy.

D. Average Power Efficiency of DF

In this section, we further investigate how much transmission power can be saved by using cooperative transmission. We assume that relay candidates are randomly located in space according to a Poisson point process with density λ. A source-destination pair located at $(-\frac{d_{s,d}}{2}, 0)$ and $(\frac{d_{s,d}}{2}, 0)$, respectively, will choose the best relay node to achieve the minimum total transmission power among all available relay candidates, where the best relay is the one that results in the best efficiency factor defined in (13). A network with a higher density of relay nodes can provide better choices for relay selection.

We let R be a random variable of the selected relay distance to the destination and r denote the distance between the closest relay and the destination. The probability distribution function of r is given by

$$\begin{aligned} \Pr[R < r] &= 1 - \Pr[R \geq r] \\ &= 1 - \Pr[N_r = 0] = 1 - e^{-\lambda \pi r^2} \end{aligned} \tag{19}$$

where N_r is the number of relays within distance r from the destination. The probability density function (pdf) of the selected relay distance is Rayleigh distributed

$$f(r) = 2\lambda \pi r e^{-\lambda \pi r^2}, \quad r \geq 0\,. \tag{20}$$

We note that relays with the same distance r to the destination may not lead to the same β, since the source-to-relay distances may be different, and hence the optimal p^*. But we can use the probability distribution function (20) to bound $\mathrm{E}[\beta]$ as follows.

Theorem 7: The average power efficiency of the optimal DF cooperation relative to direct transmission for $\alpha = 2$ is lower bounded by

$$\mathrm{E}[\beta] > \frac{1 - e^{-\rho}}{2K} + \frac{\sqrt{2}}{K} \int_{\frac{d_{s,d}}{2}}^{\infty} \sqrt{\frac{1}{4} + \frac{(r - \frac{d_{s,d}}{2})^2}{d_{s,d}^2}} f(r) dr \tag{21}$$

where $K = ((2^b + 1)\sqrt{2\epsilon^{out}})^{-1}$, $\rho = \pi \lambda d_{s,d}^2 / 4$.

Proof: See Appendix C. □

It is worth noting that targeting a smaller outage probability can lead to better power efficiency. For any other path-loss exponent $\alpha > 2$, the best relay location can only be characterized numerically through (14) and the corresponding average power efficiency is shown by simulation results in Section VII.

Comparison with the conventional cooperative scheme: we consider a conventional cooperative scheme where the source and relay nodes always use the identical transmission power, i.e., $p = q$.

Theorem 8 [27]: The average power efficiency of the conventional cooperative scheme ($p = q$) relative to direct transmission is lower bounded by

$$\mathrm{E}[\beta'] > \frac{\sqrt{2}}{K} \left(\frac{1}{\rho}\right)^{\frac{\alpha}{4}} \Gamma\left(\frac{\alpha + 4}{4}\right) \tag{22}$$

where $\rho = \pi \lambda d_{s,d}^2 / 4$, α is the path-loss exponent and $\Gamma(x) = \int_0^\infty e^{-t} t^{x-1} dt$ is the gamma function.

From the above result, we can conclude that targeting a smaller outage probability, a longer distance or a larger path-loss exponent can lead to better power efficiency, which means that cooperative transmission can better cope with a harsh network environment. It is also worth noting that such conclusion is still valid for the optimal cooperation scheme (which does not assume $p = q$). Moreover, the optimal cooperative can achieve much better power efficiency as shown in Section VII-A.

V. Energy-efficient cooperative relaying for reliable communication

In this section, we consider a more general network setting where multiple nodes co-exist and cooperate with each other by acting as relays for the transmissions of each other. First, considering each node's cooperative state, we propose a weighted adaptive relay selection mechanism for single-hop transmission. Then, we apply the proposed relay selection mechanism into a practical M2M protocol [29], to facilitate the routing in delivering multimedia services.

A. System assumptions

Our interest is to find a strategy that determines which node to select as the relay for the maximal power efficiency of each node in this multi-node environment. It is worth noting

that relay selection affects the overall energy transmission, since the optimal DF power depends upon the location of the selected relay and the channel conditions. When multiple relays are available, we expect the overall energy consumption to decrease.

- Our setup consists of a set of nodes $N = \{1, ..., n\}$, where each node $i \in N$ transmits a number of packets over time, each time with some arbitrary destination node in the network. For simplicity, we assume all packets have the same constant length with the same QoS constraints, though it is straight-forward to derive relay selection rules in a more general setup. We also assume that time is divided into discrete time slots.
- TDMA is used to provide collision-free transmissions from the sources and the relays.
- We denote by $p_{i,j}(t)$ and $q_{i,j}(t)$ the transmit power of a source node i and a relay node j, respectively, when i would use cooperative transmission with j as the relay to some destination at time t. We assume that the source and the relay use the optimal transmission powers given by (11) for each packet transmission.
- When node i uses direct transmission at time t, we denote its transmit power as $p^D(t)$.
- Energy consumption of a node $E_i(t_1 : t_2)$ during a time interval $[t_1 : t_2]$ is the sum of node i's transmit power either as a source or a relay over all $t \in [t_1, t_2]$ (we assume a node consumes zero-power at t if it is neither a source or a relay at t).
- We use $\mathcal{R}_i(t)$ to denote the set of the nodes (except node i) which can achieve energy saving compared to direction ($\beta < 1$), for source node i's transmission to its destination at time t, i.e., $\mathcal{R}_i(t) = \{j \in N - \{i\} | p_{i,j}(t) + q_{i,j}(t) < p^D(t)\}$.

Result 9: For any time interval of $[t_1, t_2]$, the total energy consumption of the network $\sum_{i \in N} E_i(T)$ is minimized if each i is assigned a relay node at each time by the Min-Total-Energy-Selection rule, i.e., $r_i(t) = \arg\min_{j \in \mathcal{R}_i(t)} p_{i,j}(t) + q_{i,j}(t)$.

Proof: Since we are only interested in the total energy consumption, we can schedule the whole transmission into several rounds and each node can only transmit no more than one packet in each round. Since any assignment r is injective in each round, for any two nodes i and k, $S_i \cap S_k = \emptyset$, and $\cup_{i \in N} S_i \subseteq N$, where S_i is a set of source nodes whose relay is i. Therefore, the total energy consumption in each round $\sum_{i \in N} E_i = \sum_{i \in N}(p_{i,r_i} + \sum_{j \in S_i} q_{j,i})$ can be re-written as $\sum_{i \in N} p_{i,r_i} + \sum_{i \in N} \sum_{j \in S_i} q_{j,i} = \sum_{i \in N} p_{i,r_i} + \sum_{j \in N} q_{j,r_j} = \sum_{i \in N}(p_{i,r_i} + q_{i,r_i})$, which is minimized if each individual term $p_{i,r_i} + q_{i,r_i}$ is minimum. □

It is worth noting that this result is obtainable from the optimal power allocation method in (11). It is myopic in nature since the selection is based only on the projected power consumptions of itself and other potential relay nodes for the upcoming transmission at each t, but not on the past energy consumptions of itself or other nodes. However, it is easy to see that, though simple, the Min-Total-Energy-Selection rule is optimal in the sense that it minimizes the total energy consumption of the network. In other words, the relay assignments that yields the minimum total energy consumption can be simply obtained by having each source node select a relay node such that the combined transmission power for the source and the relay is minimum.

From the individual nodes' perspective, however, the relay selection can lead to the situation that some nodes end up with higher energy consumption than would be the case when all nodes employ direct transmission. This is especially true if some unfortunate nodes are heavily selected as relays and hence consume more energy in relaying than that saved from its own transmission as a source. We now consider how to handle such unfairness issue in CC.

B. Weighted adaptive relay selection

Our objective is to let each node act as a relay only when it has saved more energy than that it has lost from cooperative transmission in the past and meanwhile best achieve the energy efficiency due to cooperative transmissions.

1) Payoff function: To represent how much energy saving the cooperative transmission can yield in comparison to direct transmission, we begin by introducing the notion of the "payoffs" of the nodes.

The *payoff function*, $u_i(t)$, of node i at time t is defined as:

$$u_i(t) = \begin{cases} p_i^D(t) - p_{i,j}(t) & \text{if } \exists j \text{ s.t., } r_i(t) = j \\ -q_{j,i}(t) & \text{if } i = r_j(t) \text{ for some source } j \\ 0 & \text{otherwise.} \end{cases} \tag{23}$$

The above represents how much energy a node i *locally* saves (or loses) compared to direct transmission at time t, where $p_i^D(t) - p_{i,j}(t)$ denotes the power saved from i's cooperative transmission using some relay j at time t, and $-q_{j,i}(t)$ the power spent in i's transmission as a relay for some other node j at time t. In all other cases (if i does not transmit either as a source or a relay, or if i uses direct transmission), the payoff is 0. The initial $u_i(t)$ can be any arbitrary value, but for simplicity, we assume $u_i(t) = 0$ for all $i \in N$. Then the *cumulative payoff* over a time interval $[t_1 : t_2]$ is defined as $u_i(t_1 : t_2) = \sum_{\tau=t_1}^{t_2} u_i(\tau)$, which represents the overall energy savings of a node during the time interval.

2) Cooperation index: A binary cooperation index variable $C_i(t)$ is maintained for each node i and updated at each time t (hence the term "adaptive") such that

$$C_i(t) = \begin{cases} 1 & \text{if } u_i(0 : t-1) \geq 0 \\ (0 & \text{if } u_i(0 : t-1) = 0 \text{ for selfish node}^1) \\ 0 & \text{if } u_i(0 : t-1) < 0. \end{cases} \tag{24}$$

This $C_i(t)$ value[2] is used in the decision as to whether node i can act as a relay for other nodes (when $C_i(t) = 1$, i.e., in

[1]Details on the impact of selfish nature will be discussed in Section VII-B.

[2]We set $C_i(0) = 1$ in order to enable the initial cooperative condition when all nodes's payoffs are zero. If $C_i(0) = 0$ for all i, no node would cooperate to other nodes.

"cooperative" mode) or i should not be selected as relay for any other node (when $C_i(t) = 0$).

3) Fairness factor: Recognizing that some nodes may benefit more from the larger cooperative transmission opportunities than the others due to difference in the amount of data and to potentially unfair medium access protocol, we introduce the fairness factor to bring the balance (or "fairness") of the amount of payoffs that individual nodes collect. For example, two relay candidates with different positive payoffs may not be given the same priority to be selected as relay, since one relay candidate may have gain significant payoff from the past energy consumption, compared with another one with marginal positive payoff. In such a case, the node with higher payoff should give more opportunity to be selected as relay.

How much importance will be given to the fairness term reflecting the payoff and how much to the power consumption term depends on how fast the function $w(u)$ decays as the payoff value u increases. In our case, we employ a power-law function

$$w(u) = u^{-k} \tag{25}$$

where parameter k is a positive constant and can be used to tradeoff fairness for energy consumption. In our simulation study, we find that $w(u) = u^{-6}$ strikes a good balance.

Considering all above rules, we proposed a Weighted Adaptive Relay Selection approach to bring the balance (or fairness) of the amount of payoffs that individual nodes collect:

Weighted Adaptive Relay Selection: A relay is selected for source i at time t such that

$$r_i(t) = \arg \min_{j \in \mathcal{R}_i(t), C_j(t)=1} \{w\left(u_j(0:t-1)\right)\left(p_{i,j}(t)+q_{i,j}(t)\right)\}, \tag{26}$$

where $w(u) = u^{-6}$ is a non-increasing function of the payoff value u. The constraint $C_j(t) = 1$ guarantees that a node whose cumulative payoff is negative will cease to act as a relay, and will be potentially available as a relay when its payoff becomes positive. Here, along with the power consumption factor $(p_{i,j}(t) + q_{i,j}(t))$, the weight function $w(u_j(0 : t - 1))$ is introduced in the relay selection criteria, such that the nodes with larger payoffs (i.e., smaller weight) will have a higher chance to get selected as the relay for each packet transmission. More specifically, among relays which have the same total power consumption, preference will be given to the ones with higher cumulative payoff.

VI. Practical implementation of relay selection rule in supporting multimedia services

In low power and lossy networks (LLNs), mobile devices typically operate with constrained memory, processing power and energy, and their interconnections are typically characterized as unreliable links with high loss rates. RPL [29] is a routing protocol designed for LLNs, which is a de-facto M2M standard to support multimedia services provided by upper layer protocol, i.e., Constrained Application Protocol (CoAP). RPL is a distance vector routing protocol, in which nodes construct a destination oriented Acyclic Graph (DODAG) by exchanging distance vectors and root to a controller. Through broadcasting routing constraints, the root node (i.e., central control point) filters out the nodes that do not meet the constraints and select the optimum path according to the metrics (e.g., hop count, energy cost, latency). In the stable state, each node has identified a stable set of parents and forwarded packets along the path towards the "root" of the DODAG.

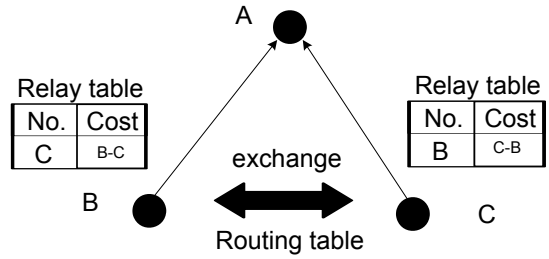


Fig. 3. An example of building up relay tables.

However, the current solution cannot well support multimedia services in wireless networks, for example transmitting images in a multi-hop fashion in a harsh outdoor environment to monitor emergency accidents may expect high packet loss. Moreover, because of the hierarchical transmission structure, the nodes closing to the root may experience more traffic and energy consumption, thus being vulnerable to the energy depletion. To address these issues and improve the reliability of wireless routing in low power and lossy networks, we incorporate CC into the RPL protocol and propose the cooperation-aided routing protocol for lossy networks. Specifically, in the stage of topology formation, each node should maintain two tables: the routing table, a list of parents toward the root; and the relay table, a set of candidate nodes that can be served as the relay between the node itself and its parents. Each node builds up its routing table through DIO message. Neighboring nodes periodically exchange routing tables to check if they have the same parent. If so, each of them will be selected as a candidate relay for the other and added to the corresponding relay table. In this way, the relay table constructs a relay link between both sides where cooperative transmission can be performed. An example of this process is shown in Fig. 3, where node B and C serve as the candidate relay for each other because they share a common parent node A.

Finally, when a node transmit its packet toward the root, the next hop is determined by the routing table. If its relay table is not empty, the node itself will select one relay from the candidates according to the weighted adaptive relay selection rule in V-B and perform the optimal DF cooperative transmission. Therefore, enhanced reception reliability and reduced energy consumption are expected during the transmission of each hop.

VII. Simulation results

In this section, we provide the numerical and simulation results obtained using MATLAB.

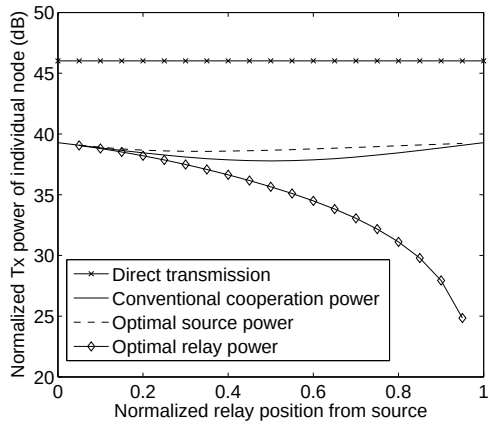


Fig. 4. Individual power behaviors for $\alpha = 2$: Normalize relay position from the source is the ratio of distance between source-relay to the distance between source-destination. 0 if relay is close to the source, 1 if relay is close to the destination.

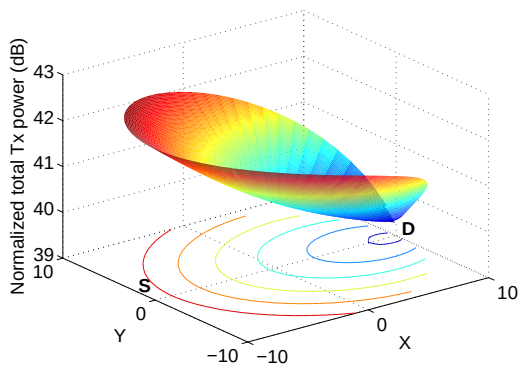


Fig. 5. Optimal total power behavior for $\alpha = 2$: The best relay location to achieve minimum total power consumption is at the destination.

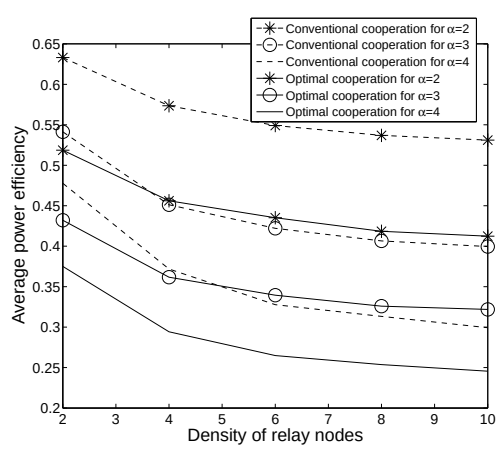


Fig. 6. Average power efficiency of the optimal CC and conventional CC.

A. Power consumption of optimal DF for single source-destination

We first evaluate the power consumption of CC for a single source-destination pair. Here we set the QoS constraints of the bit rate $b = 1$ bps/Hz, and the target outage probability $\epsilon^{\text{out}} = 0.01$, and the source and destination node are placed at the coordinates $(10m, 0)$ and $(-10m, 0)$ respectively in a 2-dimensional plane.

Fig. 4 shows the numerical results for the individual powers of the source and the relay in optimal CC as the location of the relay is varied along the line between the source and the destination. Here the x-axis represents the relative location of the relay w.r.t. those of the source and destination, and y axis is the transmit power in dB. It can be seen the source can reduce at least 7 dB of its power compared to the direct transmission. Moreover, the relay's power is always smaller than the source's, and monotonically decreases as its location gets closer to the destination. A careful reader might notice that the optimal source actually spends more power than that in the conventional cooperation. Therefore, slightly increasing the source power can help significantly reduce the relay power and thereafter saving the total energy. Fig. 5 shows the optimal total power consumption as the location of relay is varied in the 2-dimensional plane. The result also confirms Result 4 that the best relay location to achieve minimum total power consumption is at the destination.

In Fig. 6, we plot the power efficiency factor of optimal CC and conventional CC, for different path-loss exponent and density of the potential relays in the x-axis. We assume that relay candidates are randomly located in space according to a Poisson point process with density λ. The results are averaged over simulating 100 packet transmissions, and the relay with the smallest $p + q$ is used. The results are consistent with what our analysis predicts: the optimal cooperation consumes less energy than the conventional cooperation ($\beta^* < \beta'$) with an average improvement larger than 20%. It also shows that power efficiency improves as more relays are available. This is because it is easier to find a well-positioned relay in a dense network. Finally, we can observe that cooperative transmission achieves better power efficiency with larger path-loss exponents, thus being more helpful in a harsher radio environment.

B. Performance of relay selection for multi-node cooperation

In this scenario, we place N (varied between 5 and 25) nodes at uniformly random locations in a $100\text{m} \times 100\text{m}$ region (the edges of the region are wrapped (toroid) to eliminate edge effects). The transmission range of each node is 40m. Throughout the simulation, we set the path-loss exponent $\alpha = 3$, the data rate $b = 1$ bps/Hz and the targeted $\epsilon^{\text{out}} = 0.01$. A total of $50 \times N$ packets are transmitted, and at each time t, a packet is transmitted by a randomly selected source and a randomly selected destination. The initial payoff value of every node ($u_i(0)$) is set 0.

Fig. 7 shows the average energy consumption per node, normalized by the minimum value in the data set (i.e.,

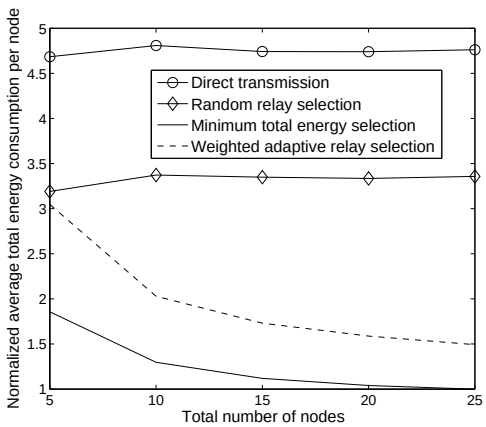


Fig. 7. Average total energy consumption per node

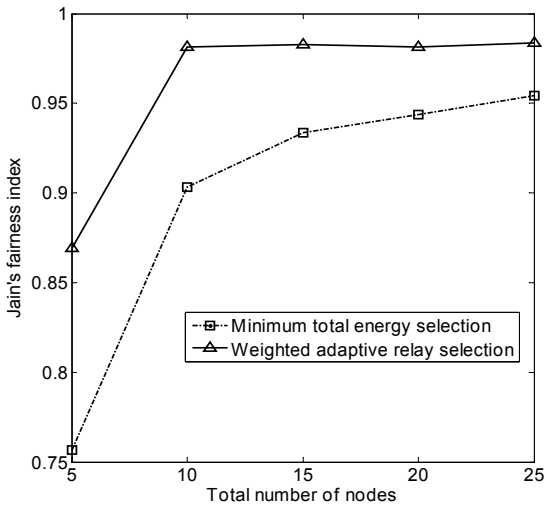


Fig. 8. Jain's fairness on payoff value.

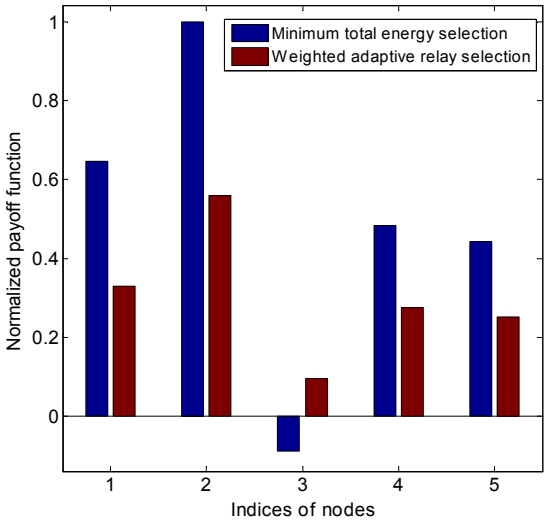


Fig. 9. Normalized payoff value per node.

Minimum total energy selection with 25 nodes) for different relay selection methods. The proposed relay selection scheme outperforms the direct transmission or the random relay selection. However, since the Minimum total energy selection is the optimal solution in this case, the weighted adaptive relay selection performs a bit worse (this is compensated by fairness results below). Furthermore, as the number of nodes increases, the average energy consumption of the proposed relay selection scheme decreases, this is because it is easier to find a well-positioned relay and thus save more power.

Fig. 8 shows the fairness in terms of how much energy is saved for individual nodes using each relay selection methods, where the y-axis represent Jain's fairness index of nodes' cumulative payoffs.[3] It is clear that the weighted adaptive relay selection scheme achieves the best fairness compared with the Minimum total energy selection. Moreover, the index curve shows a non-decreasing tendency toward increased total number of nodes, this is so because relay selection can be better balanced with an increasing number of relay choices in a dense network. As another example to highlight the fairness, we show in Fig. 9 the energy consumptions of individual nodes at the end of simulation in 5-node network. It is clear that the weighted adaptive relay selection achieves the best fairness in this example–it is the only scheme that ensures that all nodes have positive payoff–whereas Min-Total-Energy-Selection results in negative payoff for some node.

We additionally conduct a set of simulations to measure the impact of each node's "willingness" to cooperate when its payoff is zero when our adaptive relay selection rule is used. To see this, we slightly changed the rule (V-B) for a subset of nodes, and divide the nodes into two groups: $\mathcal{U} = \{i \mid C_i(t) = 1 \text{ if } u_i(t) = 0\}$ ('Unselfish group'), and $\mathcal{S} = \{i \mid C_i(t) = 0 \text{ if } u_i(t) = 0\}$ ('Selfish group'); the rule remains the same as (V-B) for both group when $u_i(t) \neq 0$, and run the simulations using adaptive [15] and weighted adaptive relay selection. We expect that the cooperative behaviors of the nodes tend to strengthen over time if more nodes are in the first group of "cooperative" nodes. In Fig. 10, we show the proportion of the nodes with $C_i(t) = 1$ in the y-axis as the time progresses in x-axis. Different curve represents different ratio of T_1:T_2, where $T_1 = |U|$ and $T_2 = |S|$ with 100 nodes in the network. The result is rather surprising: in all cases, the proportion of nodes in the cooperative states converges to 1, even when only one node cooperates initially to others out of 99. Also, convergence speed is faster with the weighted relay selection. What this result indicates is quite interesting: *the cooperative behavior of individuals is vital in cooperative communication*, and *the cooperation among the nodes can emerge even faster when combined with some policing mechanism for ensuring fair allocation of resources*. It will be an interesting future research topic to formally analyze the emergence of the cooperation in the cooperative

[3]Jain's fairness index is defined by $(\sum U_i)^2/(N\sum U_i^2)$. The result ranges from $\frac{1}{N}$ (worst case) to 1 (best case). The larger the index is, the better fairness that we can achieve.

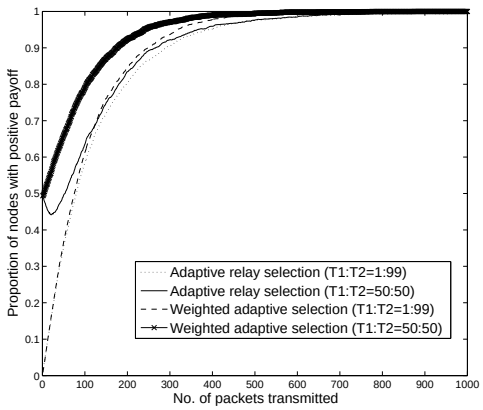


Fig. 10. Proportion of nodes with positive payoff

communication networks, possibly using the concepts and analytical tools in evolutionary game theories and population dynamics [30].

C. Performance of relay selection rule in M2M routing

In this scenario, we consider a grid network topology for multipoint-to-point simulation, where the designated root locates at the center of a $100\text{m} \times 100\text{m}$ region, with 12 surrounding nodes in the peripheral area. As shown in Fig. 11(a), according to the number of hops to the root, the surrounding nodes can be divided into two categories based on the RPL routing protocol, namely the rank 1 nodes 2∼5 and the rank 2 nodes 6∼13. Note that the solid lines are next-hop links and the dashed lines are relay links, as discussed in Section VI. Throughout the simulation, we set the path-loss exponent $\alpha = 3$, the data rate $b = 1$ bps/Hz and the targeted $\epsilon^{\text{out}} = 0.01$. The initial payoff value of every node ($u_i(0)$) is set 0. The transmission range is 45m. A total of 1000 packets are transmitted to the root from random selected source using RPL routing.

Fig. 11(b) shows the normalized total energy consumption of each node. Obviously, each node consumes less energy in the weighted adaptive relay approach compared to the direction transmission. Furthermore, it is worth noting that the performance of lower rank nodes (close to the root) with cooperation is closed to the performance of higher rank nodes without cooperation, which shows that the lower rank nodes with heavy traffic actually benefit more from cooperative transmission. Moreover, we can observe that the proposed relay selection scheme can fairly distribute the energy consumption among nodes with the same rank. This is so because our proposed scheme prioritize the selection of relays with larger payoff value, while in turn the relaying transmission reduces its cumulative payoff, thus balancing the opportunity of being selected among all nodes.

As a different example, we consider a random network topology as shown in Fig. 11(c), where the root stays at (40, 40) with 9 randomly located nodes. Without changing the parameters, the routing path is generated by RPL with next-hop links (solid lines) and relay links (dashed lines). To analyze the simulation result, we divide the 9 nodes into two groups: the cooperation group (node 2, 3, 4, 6, 7, 9, 10) and direct transmission group (node 5, 8).

Fig. 11(d) shows the comparison of normalized total energy consumption of cooperation-aided routing with that of using direction transmission. Overall, the nodes in cooperation group can significantly reduce their energy consumption because of the help from relaying; for node 5 and 8, because there is no potential relays nearby, the energy consumption is the same with direct transmission. Furthermore, it is worth noting that the nodes especially with heavy traffic load (e.g., node 2 and 7) successfully gain a satisfactory level of benefit from cooperation, which is consistent with our results in Fig. 11(b).

VIII. Conclusions

We have shown in this paper that it is advantageous to allocate non-uniform powers to various cooperative transmitters in wireless multimedia networks, which can significantly reduce the total power consumption while maintaining a given level of quality of service (QoS). Specifically, we have proposed an optimal power-allocation method for the decode-and-forward (DF) wireless cooperative networks and investigated its power efficiency. Our analysis shows how the proposed DF cooperation outperforms the conventional cooperation and direct transmission. We have also introduced the adaptive relay-selection rule that can serve as an effective tool to achieve a desirable tradeoff between fairness and energy consumption at each node, and demonstrated the advantages in practical routing protocols.

To develop further robust cooperative schemes to cope with new demands in future wireless multimedia networks, we plan to explore the performance gain of the cooperative relay-selection methods and propose additional robust relay-selection mechanisms. For example, the additional mechanisms must be able to consider network scenarios where nodes can have different traffic loads, while maintaining a satisfactory degree of fairness. We also plan to consider the life time or the remaining energy of each node as input parameters to the fairness measure.

Appendix A

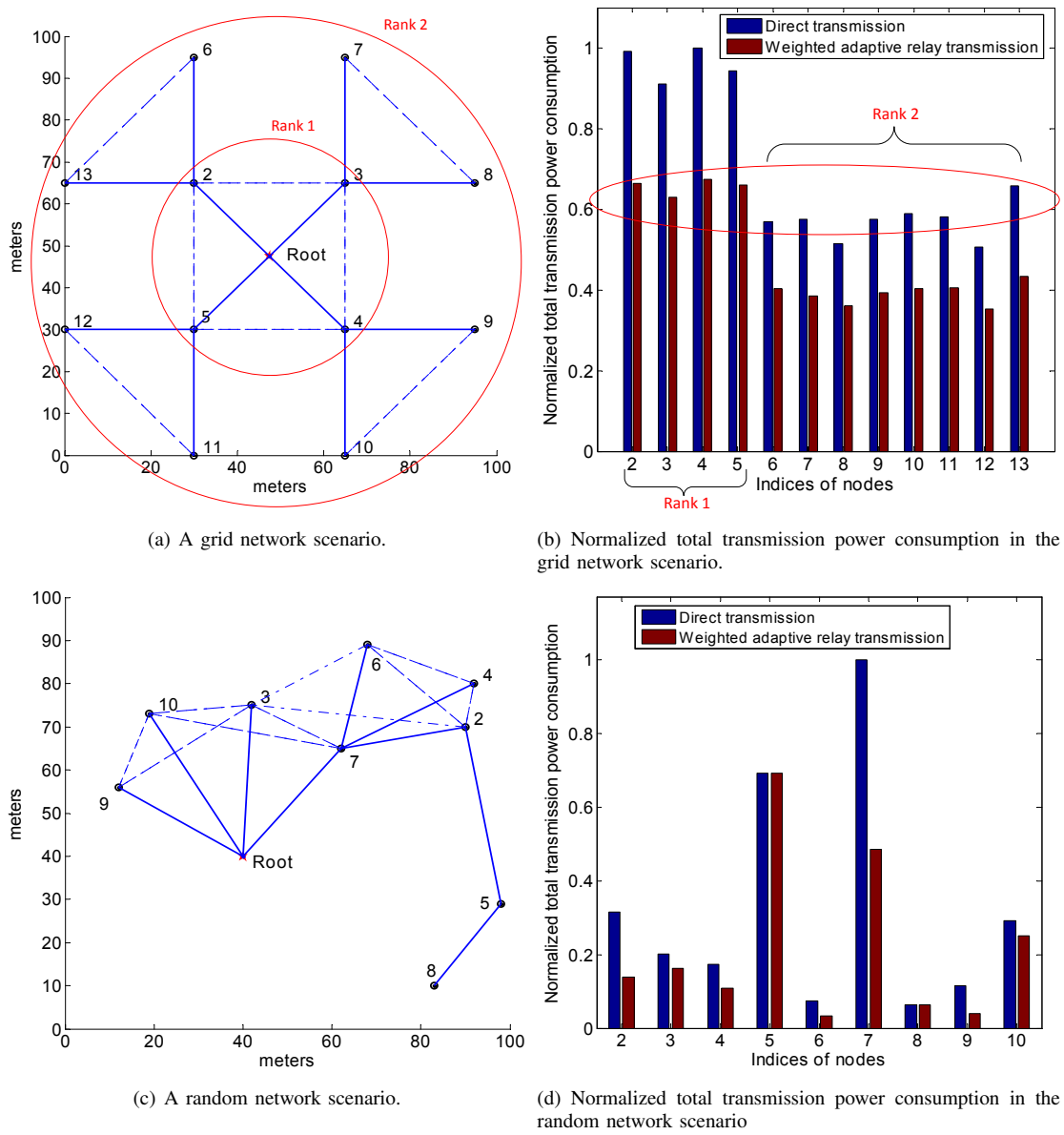
According to the Kuhn-Tucker condition (p.244: KKT conditions for convex problems [31]), the inequality constraint in (10) can be converted to the equality constraint and have the target outage probability

$$\frac{1}{2} d_{s,d}^{\alpha} (d_{s,r}^{\alpha} + \frac{p}{q} d_{r,d}^{\alpha}) \frac{(2^{2b}-1)^2}{p^2} = \eta \,. \tag{27}$$

Then we obtain

$$q = f(p) = \frac{ap}{p^2 - b} \tag{28}$$

where $a = \mu d_{s,d}^{\alpha} d_{r,d}^{\alpha}/2\eta$, $b = \mu d_{s,d}^{\alpha} d_{s,r}^{\alpha}/2\eta$, $\mu = (2^{2b}-1)^2$ and η is the outage constraint.



(a) A grid network scenario.

(b) Normalized total transmission power consumption in the grid network scenario.

(c) A random network scenario.

(d) Normalized total transmission power consumption in the random network scenario

Fig. 11. Simulation results

Substituting (28) into $p+q$, and minimizing wrt p, we have the solution

$$p^2 = \frac{a+2b}{2} \pm \frac{\sqrt{a^2+8ab}}{2}. \tag{29}$$

To be a valid solution for q, the solution must satisfy $p^2 > b$. So, we have a unique solution given by

$$p^* = \sqrt{\frac{a+2b}{2} + \frac{\sqrt{a^2+8ab}}{2}}. \tag{30}$$

Using this result in (28) leads to (11).

Appendix B

From (11), we can obtain the power ratio of the optimal source power to the optimal relay power as follows:

$$\frac{p^*}{q^*} = \frac{1}{2}\left(1+\sqrt{1+\frac{8}{\gamma}}\right) > 1. \tag{31}$$

From (11) and (15), we have the power ratio of the optimal source power to the conventional source power as follows:

$$\begin{aligned}\frac{p^*}{p_{\text{con}}} &= \sqrt{\frac{d_{r,d}^{\alpha} + \sqrt{d_{r,d}^{2\alpha} + 8d_{r,d}^{\alpha}d_{s,r}^{\alpha}} + 2d_{s,r}^{\alpha}}{2(d_{s,r}^{\alpha}+d_{r,d}^{\alpha})}} \\ &= \sqrt{\frac{1}{2}\left(1+\frac{1+\sqrt{\gamma^2+8\gamma}}{1+\gamma}\right)},\end{aligned} \tag{32}$$

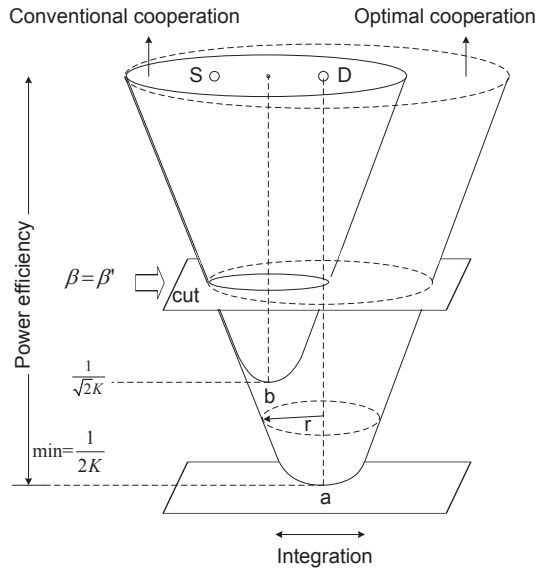


Fig. 12. Integration from geometric point of view

where $\gamma = \frac{d_{r,d}^{\alpha}}{d_{s,r}^{\alpha}}$. Bring (31) into (32), we can derive:

$$\frac{\beta^*}{\beta'} = \sqrt{1 + \frac{1+\sqrt{\gamma^2+8\gamma}}{1+\gamma}} \left(\frac{\sqrt{2}}{4} + \frac{\sqrt{2}}{2+2\sqrt{1+\frac{8}{\gamma}}} \right) \quad (33)$$

Note that (33) is a function of γ. Then, we have:

$$\frac{\beta^*}{\beta'} = g(\gamma), \ \forall \gamma > 0. \quad (34)$$

Since $\frac{\mathrm{d}g(\gamma)}{\mathrm{d}\gamma} > 0$, we can get the bound of $g(\gamma)$ as:

$$\begin{aligned} g_{\min}(\gamma) &= \lim_{\gamma \to 0} g(\gamma) = \frac{1}{2}, \\ g_{\max}(\gamma) &= \lim_{\gamma \to \infty} g(\gamma) = 1. \end{aligned} \quad (35)$$

Therefore, we have the result in (17). Additional comments to the bound performance are explained as follows:

1) Lower bound: This is obtained by putting $\gamma = 0$ in (31) and (32). It is worth noting that the optimal relay power highly depends on the relay location and has

$$q^* \to 0, \quad \text{if } d_{r,d} \to 0. \quad (36)$$

In that case, the whole receiver side can actually be treated as a MIMO antenna system with the relay and destination combined together.

2) Upper bound: This is obtained by putting $\gamma = \infty$ in (31) and (32).

3) The result $\frac{\beta^*}{\beta'} = \sqrt{\frac{27}{32}}$ is obtained by putting $\gamma = 1$ in (31) and (32).

□

APPENDIX C

Proof of Theorem 7: Fig. 12 illustrates the integration method of $\mathrm{E}[\beta]$, the integration is performed from the best relay location at the bottom with the minimum value $\frac{1}{2K}$ to infinity. r is the selected relay distance to the destination. Since the minimum β at point a is smaller than the minimum β' at point b, when β increases to point b, both β and β' have the same power efficiency on the same cut. It is worth noting that the two circles on the same cut are the set of relay locations that achieve the same power efficiency for the conventional cooperation and the optimal cooperation, respectively. Therefore, we have the expected power efficiency

$$\begin{aligned} \mathrm{E}[\beta] &= \int_0^{\infty} \beta f(r) dr \\ &> \int_0^{\frac{d_{s,d}}{2}} \beta f(r) dr + \int_{\frac{d_{s,d}}{2}}^{\infty} \beta' f(r) dr \\ &> \int_0^{\frac{d_{s,d}}{2}} \frac{1}{2K} f(r) dr + \frac{\sqrt{2}}{K} \int_{\frac{d_{s,d}}{2}}^{\infty} \sqrt{\frac{1}{4} + \frac{(r-\frac{d_{s,d}}{2})^2}{d_{s,d}^2}} f(r) dr \\ &= \frac{1-e^{-\rho}}{2K} + \frac{\sqrt{2}}{K} \int_{\frac{d_{s,d}}{2}}^{\infty} \sqrt{\frac{1}{4} + \frac{(r-\frac{d_{s,d}}{2})^2}{d_{s,d}^2}} f(r) dr \,. \end{aligned} \quad (37)$$

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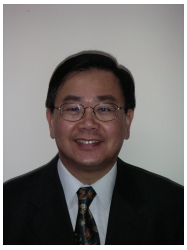

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