Energy-Aware Cooperation Strategy with Uncoordinated Group Relays for Delay-Sensitive Services

A-Long Jin, Wei Song, Peijian Ju, and Dizhi Zhou

***Abstract*—Due to channel fading and user mobility in wireless networks, quality-of-service (QoS) provisioning for multimedia services requires great efforts. It is even more challenging to support the fast-growing multimedia services in a green manner. As a promising technique, cooperative communications make use of the broadcasting nature of the wireless medium to facilitate data transmission, and can achieve energy saving. To support the delay-sensitive multimedia services in an energy-efficient manner, we consider a new framework in this paper where multiple source-destination pairs share a group of relays with energy constraint. We also propose an effective uncoordinated cooperation strategy, which is based on the backoff timer. The theoretical performance bounds of the proposed strategy are derived with respect to the collision probability and the transmission success probability. As shown in the numerical and simulation results, the proposed strategy outperforms a probability-based uncoordinated strategy in terms of average packet delay, delay outage probability, and energy consumption. Further, we investigate the scalability of our proposed strategy and find it can be deployed in a large-scale network.**

***Index Terms*—Cooperative wireless networks, delay-sensitive services, quality-of-service, uncoordinated cooperation strategy, performance analysis, energy efficiency, scalability.**

I. INTRODUCTION

With rising energy costs and rigid environmental standards, green communications have attracted considerable research attention in recent years, especially for the fast-growing multimedia services in wireless networks [1,2], since mobile devices are usually energy constrained. Due to the challenging issues imposed in wireless networks [3], such as channel fading and user mobility, quality-of-service (QoS) provisioning for the delay-sensitive multimedia services is much more difficult than in wired networks. To deal with these challenges, attractive techniques, such as multiple input and multiple output (MIMO) [4,5] and cooperative communications [6]–[8], have been developed by exploiting spatial diversity [9]. Nonetheless, due to the size, cost and energy limitations of mobile devices, it can be infeasible to deploy multiple antennas in some wireless terminals.

To meet the ever-increasing demands for multimedia services in future wireless networks, user cooperation [10] is studied as a promising low-cost and energy-efficient technique to provide spatial diversity. Taking advantage of the inherent broadcasting nature of the wireless medium, the nodes with good channel conditions can forward the overheard data to facilitate the transmission of one S-D pair, which includes a single source (S) and a single destination (D). As shown in Fig. 1, the relay(s) that correctly overhear the packet from S can forward the data to D. Different relaying strategies can be used by the relays, such as amplify-and-forward (AF), decode-and-forward (DF), and coded-cooperation (CC) [6,7]. Based on this model, the number of relays that participate in each cooperation depends on the channel conditions and the cooperation strategy. It is often assumed that a collision occurs when two or more relays happen to transmit the packet at the same time. Hence, the cooperation gain [11,12] can vary considerably with the relay selection strategy and the medium access control (MAC) protocol. It is vital to design an effective and efficient cooperation strategy to identify and coordinate the optimal cooperating nodes.

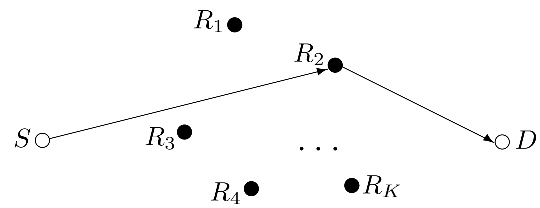

Fig. 1. A widely studied network model for cooperative communications.

In the centralized solutions such as [13,14], a central controller (e.g., the source node) needs to acquire the knowledge of the potential relays via additional handshaking messages, and then chooses the optimal relay. The message exchanging may induce unacceptable delay for multimedia services as well as high energy consumption. In contrast, a distributed solution usually does not require such *a priori* information and carries out relay selection in an uncoordinated fashion. For example, the relays that correctly receive the data from the source can contend to forward the packet to the destination.

For the probability-based uncoordinated cooperation strategies [15]–[17], each relay that successfully overhears the data independently determines a forwarding probability. Although such strategies involve little signalling overhead, the collision probability can be potentially high when the number of available relays is large. As a consequence, retransmissions will incur high energy consumption as well as long delay. Hence, such cooperation strategies may not be able

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to accommodate green multimedia services. There is another class of uncoordinated strategies that make use of the relay's local information to tune a backoff timer [18,19]. A relay of higher transmission capability is prioritized with shorter backoff time. Such backoff-based uncoordinated strategies can greatly reduce collisions and offer a good match to support green multimedia communications.

Extending the simple cooperation scenario in Fig. 1, we consider a new framework where multiple S-D pairs share a group of relays with energy constraint. To satisfy the QoS requirements of multimedia services in a green manner, we propose an energy-aware uncoordinated cooperation strategy based on the backoff timer. Also, its performance is evaluated analytically with respect to the theoretical bounds of the collision probability and the transmission success probability. Extensive simulations are conducted to compare the performance of different uncoordinated strategies and the analytical bounds. The numerical and simulation results demonstrate that our proposed strategy is preferable for the delay-sensitive multimedia services and achieves significant energy saving.

The remainder of this paper is structured as follows. The related work is reviewed in Section II. Section III gives the system model and the problem formulation. In Section IV, we propose a novel uncoordinated cooperation strategy and then analyze its performance bounds in Section V. Numerical and simulation results are presented in Section VI, which validates the analysis accuracy and demonstrates the performance improvement with the proposed strategy. Section VII concludes the paper.

II. Related Work

In the literature, many studies on cooperative communications focus on the network model shown in Fig. 1, where a group of relays can overhear the transmission from S, and one or more relays can help forward the overheard data to D. The selection and coordination of the relays is essential to the achievable performance. The centralized approaches usually require a global knowledge of the relays, and it is often infeasible to acquire such information timely and accurately. Hence, there has been substantial research on distributed cooperation strategies to effectively identify and organize the optimal relay(s).

For the probability-based strategies in [15,16], each potential relay independently decides a forwarding probability by considering a variety of factors, such as the distance, direction, local signal-to-noise ratio (SNR) [15], or the statistical information of the local environment [16]. As a collision occurs when more than one relay happens to forward the overheard data at the same time, the probabilistic cooperation strategies need to minimize the collision probability and maximize the transmission success probability. However, when the number of relays builds up, it becomes challenging to determine the optimal forwarding probability for each relay. If the forwarding probability is underestimated, the transmission success probability can be low since the relays are overconservative. On the other hand, if the forwarding probability is overvalued, the transmission success probability can be low as well, because of high collisions. As a result, the transmission success probability is usually upper bounded at a low level. Frequent retransmissions not only result in high energy consumption but also fail to guarantee the stringent QoS requirements of the delay-sensitive multimedia services.

From this point of view, another class of distributed cooperation strategies based on the backoff timer seems more promising, because of their low collision probability and high transmission success probability. In [18], a cross-layer distributed strategy is proposed by extending the conventional ready-to-send/clear-to-send (RTS/CTS) handshaking with a ready-to-help (RTH) message from the optimal relay. The relay selection is based on the composite cooperative transmission rate (CCTR), which involves the broadcast rate from the source and the data rate from the relay to the destination. In order to reduce collisions in relaying, the contention process is divided into inter-group contention and intra-group contention. The relays are grouped according to CCTR and send out indication signals after different backoff time. The optimal relay of the highest CCTR waits for the shortest time and wins the contention. In [19], the authors propose a simple cooperative diversity method based on the local measurements of the instantaneous conditions of the source-to-relay and relay-to-destination channels. Two policies are proposed to map the estimated channel conditions into a backoff timer value. The theoretical analysis of the collision probability also demonstrates the advantage of the two backoff policies.

Nevertheless, many existing cooperation strategies neglect the energy consumption of relays, which may lead to unacceptable performance in the energy constrained scenario, especially for the QoS-demanding multimedia services. Besides, many studies focus on a single S-D pair served by a number of dedicated relays. It becomes more complicated to consider multiple S-D pairs that share a group of relays, which is a more realistic scenario in practice. The energy concern together with the new cooperation scenario pose new challenges in the cooperation strategy design. In addition, the scalability of the cooperation strategies is another key issue that requires further investigation.

III. System Model and Problem Formulation

A. System Model

Consider a wireless network with M S-D pairs and K relay nodes as illustrated in Fig. 2. We assume that the relays are uniformly distributed in a given region and the relay distribution is time-stationary. This assumption is generally valid for a variety of scenarios, e.g., under random direction mobility [20,21]. The sources refer to the nodes that generate data traffic, while the destinations refer to the nodes that receive data traffic. Relay nodes have no intrinsic traffic demands. Since the relays are shared by multiple S-D pairs, we consider that the relays are energy constrained. When a relay runs out of energy, it is not eligible for future relaying. The sources can communicate with their destinations only through these shared relays using a two-hop DF [6] protocol; other cooperative communication protocols can also be considered in a similar way.

We assume that each node knows its own location, which can be obtained either from a positioning technique based

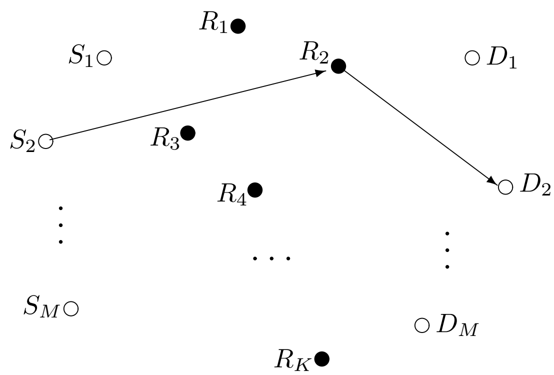


Fig. 2. An illustration of the system model for cooperative transmission.

on signal strength, time-of-arrival or angle-of-arrival measurements with nearby nodes [22,23], or through a GPS receiver that is becoming increasingly ubiquitous in mobile devices. Further, the relay nodes can obtain the locations of the sources and destinations from the piggybacked information within the overheard packets. It should be noted that the sources do not have the knowledge of the locations of the relays, and one relay does not have the location information of other relays either. Besides, we assume that the locations of all the nodes in the network do not change significantly during the short cooperative transmission period, which is a typical assumption that generally holds.

For the data transmission between a transmitter located at x and a receiver located at y, the SNR of the received signal can be written as

$$\gamma_{xy} = \frac{P_0}{N_0} h_{xy} g_{xy} \tag{1}$$

where P_0 is the transmit power, N_0 is the power of additive white Gaussian noise (AWGN), and h_{xy} denotes the small-scale channel fading which is exponentially distributed with unit mean. The path-loss effect is captured by $g_{xy} = \|x - y\|^{-\alpha}$, where $\|x - y\|$ is the Euclidean distance, and α is the path-loss exponent. We assume that the receiver is able to correctly decode the received signal only when the instantaneous SNR is no less than a threshold T_0 [15]. Therefore, the probability that a packet is successfully received is given by

$$P_{xy} = \Pr\{\gamma_{xy} \geq T_0\} = \exp\Big(- \frac{T_0}{P_0/N_0} \|x - y\|^{\alpha} \Big). \tag{2}$$

Since the location information of the sources and destinations is available to the relays, the distances between them can be calculated. Thus, we can estimate the transmission success probabilities from the M sources to the relay R_i by

$$P_{S,R_i} = \big[P_{S_1 R_i}, P_{S_2 R_i}, \ldots, P_{S_M R_i}\big], \qquad i = 1, 2, \ldots, K.$$

Similarly, the transmission success probabilities from the relay R_i to the M destinations are given by

$$P_{R_i,D} = \big[P_{R_i D_1}, P_{R_i D_2}, \ldots, P_{R_i D_M}\big], \qquad i = 1, 2, \ldots, K.$$

B. Problem Formulation

To achieve a high transmission success probability, a centralized relay selection protocol generally identifies the best relay(s) by exploiting the global view of the network. However, additional overhead is usually incurred to exchange the channel state information and results in a large delay. On the other hand, the distributed solutions often require an effective approach to mitigate collisions among multiple potential relays. The probability-based uncoordinated strategies use a forwarding probability that is independently determined for each relay. Nonetheless, when the network scales up, it becomes more difficult to figure out the optimal forwarding probability. Unfortunately, the transmission success probability of these probability-based strategies is upper bounded by $1/e \approx 0.368$ [16,24] due to high collisions, which also lead to a large delay. In contrast, the backoff-based distributed strategies can handle collisions more effectively and present better performance in terms of the transmission success probability and delay.

In this work, we propose a novel backoff-based uncoordinated cooperation strategy, in which each potential relay sets a backoff timer based on a variety of factors. Considering the group cooperation model in Section III-A, we need to effectively address the energy constraint of the relays, which are shared by multiple S-D pairs. The proposed cooperation strategy should not only provide QoS guarantee to the delay-sensitive multimedia services but also perform well in a large-scale network. It is known that the real-time multimedia services are sensitive to delay and delay jitter. In view of the time-varying nature of wireless networks, we consider a statistical QoS guarantee for the delay. That is, the delay outage probability defined in (3) is ensured bounded within an acceptable range:

$$P_{out} = \Pr\{\mathcal{D} \geq \mathcal{D}_{max}\} < \varepsilon \tag{3}$$

where $\mathcal{D}$ is the packet delay, $\mathcal{D}_{max}$ is the acceptable upper bound, and ε is a small probability that is allowed for QoS violation.

IV. Energy-Aware Cooperation Strategy

A. Cooperation Criteria

For a backoff-based cooperation strategy, the determination of the backoff timer is critical to reduce collisions, because a collision may occur when the backoff timers of the first two or more relays expire within an indistinguishable small interval. To improve the achievable performance, the backoff timer is often based on the cooperation capability of the relay. Hence, we need to properly choose the metrics that characterize the cooperation capability, so that the backoff timers of the group of relays can be appropriately scattered to decrease the collision probability.

First, we consider the distance between a relay and a destination, which can be estimated from the location information without incurring extra cost. This distance can capture the transmission success probability of the relay-to-destination channel according to (2). This is because we are interested in the potential relays that have correctly overheard the packet from the source and thus only focus on the relay-to-destination channel condition. Denoting the distance between the relay R_i and the destination D_j by d_{ij}, we define the cooperation

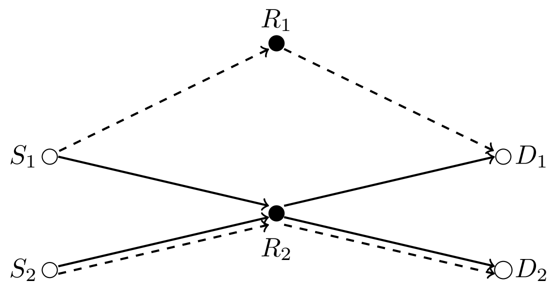


Fig. 3. An illustration showing how the energy constraint of the relays affects relay selection. The solid lines indicate the cooperative transmissions without considering the energy status; and the dashed lines indicate the cooperative transmissions with the energy status taken into account.

capability of R_i for D_j with respect to the distance as

$$W_{ij}^d = \begin{cases} 1 - \left(\dfrac{d_{ij}}{L}\right)^2, & \text{if} \quad d_{ij} \le L \\ 0, & \text{if} \quad d_{ij} > L \end{cases} \tag{4}$$

where L is the largest distance to the destination for a node to be considered as a potential relay. As such, a relay with a smaller distance to the destination is characterized with a greater cooperation capability, because of a higher transmission success probability over the relay-to-destination channel.

Second, the energy status of the relay is also accounted into the estimation of the cooperation capability, since the shared relays are energy constrained. The example in Fig. 3 illustrates the importance of incorporating the energy status into the characterization of the cooperation capability. As seen, the relay R_2 is the best relay for both S_1-D_1 and S_2-D_2 pairs, if only the distance to the destination is concerned. Consequently, R_2 will run out of energy quickly. The S_1-D_1 and S_2-D_2 pairs will need to switch to the relay R_1. The performance of the S_1-D_1 pair will remain almost the same, whereas the S_2-D_2 pair will suffer from a performance degradation since R_1 is far from S_2 and D_2. On the other hand, if both the distance and the energy status are taken into account, R_1 and R_2 should serve S_1-D_1 and S_2-D_2, respectively. Thus, the relaying capacities are utilized in a more balanced manner. Therefore, we further consider the energy status of R_i to characterize its cooperation capability by

$$W_i^e = E_i / E_c \tag{5}$$

where E_i is the energy level of R_i with an energy upper limit of E_c. Here, we assume that all the relays have the same energy upper limit and their energy levels are uniformly distributed. Therefore, W^e follows a uniform distribution between 0 and 1, denoted by $U(0,\ 1)$. As seen, a relay of a higher energy level thus has a greater cooperation capability.

Based on the two metrics in (4) and (5), the overall cooperation capability of the relay R_i for the destination D_j is defined as

$$W_{ij} = \theta \cdot W_i^e + (1-\theta) \cdot W_{ij}^d \tag{6}$$

where $\theta \in [0,1]$ is a weighting parameter to trade-off between the importance of the energy status and that of the distance metric. As seen, $W_{ij} \in [0,\ 1]$.

TABLE I
ENERGY-AWARE COOPERATION STRATEGY.

Initialize cooperation capabilities W of relays according to (6)
while a new transmission occurs between any S_j-D_j pair **do**
  for all the relays **do**
    if relay R_i overhears the packet correctly **then**
      Set the backoff timer of R_i to $1 - W_{ij}$
    end if
  end for
  for all the relays correctly received the packet **do**
    if backoff timer expires and no relaying sensed **then**
      Forward the packet to D_j
    end if
  end for
  if only one relay R_i transmits within time interval c **then**
    if D_j decodes the packet correctly **then**
      Transmission succeeds
    else
      Transmission fails
    end if
    // *Update W concerning energy consumption*
    $W_{ir} \leftarrow W_{ir} - \theta \cdot \eta$, for $r = 1, 2, \ldots, M$
  else
    Collision happens and transmission fails
    for every relay R_c that transmitted **do**
      // *Update W concerning energy consumption*
      $W_{cr} \leftarrow W_{cr} - \theta \cdot \eta$, for $r = 1, 2, \ldots, M$
      // *Update W concerning collision*
      $W_{cj} \leftarrow W_{cj} - (1-\theta) \cdot W_{cj}^d \cdot \eta$
    end for
  end if
end while

B. Distributed Cooperation Strategy

Table I presents the proposed energy-aware cooperation strategy in detail. Based on the cooperation capabilities of the relays, the optimal relay for the S_j-D_j pair is defined as

$$R_i = \arg \max_{i \in \{1,\ldots,K\}} \{\mathbf{1}_{A_j}(i) \cdot W_{ij}\}$$

where A_j is the set of relays that correctly overhear the data packet from S_j, and

$$\mathbf{1}_{A_j}(i) = \begin{cases} 1, & \text{if} \quad R_i \in A_j \\ 0, & \text{if} \quad R_i \notin A_j. \end{cases}$$

To ensure that the optimal relay has the fastest access to the channel, the relay R_i sets an initial backoff time inversely proportional to its cooperation capability for the S_j-D_j pair as

$$T_{ij} = 1 - W_{ij} \tag{7}$$

in which the maximum backoff time is taken to be one unit time. As such, the optimal relay of the highest cooperation capability sets the smallest backoff time. If the first two or more relays time out within an indistinguishable small interval c, a collision happens [19].

To account for the energy consumption of packet forwarding of R_i for any S-D pair, we update the cooperation capability of R_i for all S-D pairs as follows

$$W_{ir} = W_{ir} - \theta \cdot \eta, \qquad r = 1, 2, \ldots, M \tag{8}$$

where η is the update step length. This is to yield the forwarding opportunities to other relays and thus balance the energy consumption.

Here comes a problem when a collision happens among the relays. If all the relays involved in the collision update their cooperation capabilities according to (8), a collision will happen again in the next transmission. Therefore, we need to penalize these relays by updating their cooperation capabilities to

$$W_{ij} = W_{ij} - (1-\theta) \cdot W_{ij}^d \cdot \eta, \qquad i = c_1, c_2, \ldots, c_n \tag{9}$$

where $c_1, c_2, \ldots, c_n$ are the indices of the relays $R_{c_1}, \ldots, R_{c_n}$ that collide when forwarding the packet for the S_j-D_j pair. As a higher W_{ij}^d implies a lower energy level when a collision happens, the corresponding relay is punished more to achieve the energy balance and avoid further collisions.

V. Performance Analysis

To satisfy the delay requirements of multimedia services, it is essential to minimize the collision probability so as to maximize the transmission success probability. In this section, we analyze the performance bounds of the proposed cooperation strategy in terms of the collision probability and the transmission success probability. Here, we focus on one S-D pair, since the achievable performance of all S-D pairs is the same, given the homogeneous setting of S-D pairs in the system model.

A. Upper Bound of Collision Probability

Lemma 1. *If the relays are uniformly distributed, the probability density function (PDF) of their distance d to the destination D within L is given by*

$$f(d) = \begin{cases} \dfrac{2d}{L^2}, & \text{if} \quad d \le L \\ 0, & \text{otherwise}. \end{cases} \tag{10}$$

Proof: Consider the polar coordinate system where D is the origin and an arbitrary relay is located at $(d,\ \varphi)$. The corresponding location of the relay in the Cartesian coordinate system is then $(x,\ y)$, where $x = d \cdot \cos(\varphi)$, and $y = d \cdot \sin(\varphi)$. For the relays uniformly distributed within the circle of a radius L and centered at D, the joint PDF of their locations $(x,\ y)$ is given by

$$f_{X,Y}(x,y) = \begin{cases} \dfrac{1}{\pi L^2}, & \text{if} \quad \sqrt{x^2+y^2} \le L \\ 0, & \text{otherwise}. \end{cases}$$

Since $d = \sqrt{x^2+y^2}$, according to the Jacobian matrix, we can obtain the PDF of d as shown in (10). ■

Lemma 2. *If the PDF of the distance of a relay to the destination follows (10), the general cooperation capability concerning the distance, W^d defined in (4), follows a uniform distribution between 0 and 1.*

Proof: The cumulative distribution function (CDF) of W^d is given by

$$\begin{aligned} \Pr\{W^d \le w\} &\overset{\text{Eq. (4)}}{=} \Pr\{1-(d/L)^2 \le w\} \\ &= 1 - \Pr\{d \le L\sqrt{1-w}\} \\ &\overset{\text{Lemma 1}}{=} 1 - \int_0^{L\sqrt{1-w}} f(x)\mathrm{d}x \\ &= 1 - \frac{d^2}{L^2}\bigg|_0^{L\sqrt{1-w}} = w. \end{aligned}$$

Therefore, $W^d \sim U(0,\ 1)$. ■

Theorem 1. *Since $W^e \sim U(0,\ 1)$ and $W^d \sim U(0,\ 1)$, the overall cooperation capability defined in (6) with $\theta \in (0, 0.2]$ concerning both the distance and the energy status follows a distribution with a PDF*

$$f_W(w) = \begin{cases} \dfrac{w}{\theta(1-\theta)}, & \text{if} \quad 0 \le w \le \theta \\ \dfrac{1}{1-\theta}, & \text{if} \quad \theta < w \le 1-\theta \\ \dfrac{1-w}{\theta(1-\theta)}, & \text{if} \quad 1-\theta < w \le 1 \\ 0, & \text{otherwise}. \end{cases} \tag{11}$$

Proof: Given two continuous random variables U and V, if $V = aU$, the PDFs of U and V are related according to

$$f_V(x) = \left(\frac{1}{a}\right) f_U\left(\frac{x}{a}\right).$$

where $f_U(\cdot)$ and $f_V(\cdot)$ are the PDFs of U and V, respectively. Since $W^e \sim U(0,\ 1)$ and $W^d \sim U(0,\ 1)$ (Lemma 2), we have

$$X = \theta \cdot W^e \sim U(0,\ \theta)\ ,\ Y = (1-\theta) \cdot W^d \sim U(0,\ 1-\theta)\ .$$

Then, for $W = \theta \cdot W^e + (1-\theta) \cdot W^d = X + Y$, we have

$$\begin{aligned} f_W(w) &= \int_{-\infty}^{\infty} f_X(w-y) f_Y(y)\mathrm{d}y \\ &= \frac{1}{1-\theta}\int_0^{1-\theta} f_X(w-y)\mathrm{d}y \end{aligned}$$

Only when $0 \le w-y \le \theta$, i.e., $w-\theta \le y \le w$, $f_X(w-y) = 1/\theta$ and the above integral is not zero. Therefore, we have

$$\begin{aligned} f_W(w) &= \frac{1}{1-\theta}\int_0^w \frac{1}{\theta}\,\mathrm{d}y = \frac{w}{\theta(1-\theta)}, \quad \text{if } 0 \le w \le \theta \\ f_W(w) &= \frac{1}{1-\theta}\int_{w-\theta}^w \frac{1}{\theta}\,\mathrm{d}y = \frac{1}{1-\theta}, \quad \text{if } \theta < w \le 1-\theta \\ f_W(w) &= \frac{1}{1-\theta}\int_{w-\theta}^{1-\theta} \frac{1}{\theta}\,\mathrm{d}y = \frac{1-w}{\theta(1-\theta)}, \text{if } 1-\theta < w \le 1 \end{aligned}$$

which conclude the proof. ■

According to Theorem 1 for $\theta \in (0,\ 0.2]$, it can be easily shown that the backoff time as defined by (7) follows a distribution with a PDF, given by

$$f_T(t) = \begin{cases} \dfrac{t}{\theta(1-\theta)}, & \text{if } \ 0 \le t \le \theta \\ \dfrac{1}{1-\theta}, & \text{if } \ \theta < t \le 1-\theta \\ \dfrac{1-t}{\theta(1-\theta)}, & \text{if } \ 1-\theta < t \le 1 \\ 0, & \text{otherwise.} \end{cases} \tag{12}$$

Assume that N relays $(R_{i_1}, \ldots, R_{i_N})$ correctly overhear the transmitted packet from one particular source. Let $T_1 < T_2 < \cdots < T_N$ denote the order statistics of the backoff time of the N relays. According to [19], the collision probability P_c is given by

$$P_c = \Pr\{T_2 < T_1 + c\} = 1 - I_c \tag{13}$$

$$I_c = N(N-1)\int_c^1 f_T(t)\Big[1 - F_T(t)\Big]^{N-2} F_T(t-c)\mathrm{d}t \tag{14}$$

where $f_T(t)$ is the PDF of the backoff time and $F_T(t)$ is the corresponding CDF. Here, c is an indistinguishable small interval and a collision happens when the backoff timers of the first two or more relays time out within c. As one example, the distributed coordination function (DCF) of IEEE 802.11 can choose a maximum backoff time of 1024 time slots [25]. Then, the interval c can be considered as one time slot. Provided that the maximum backoff time is taken to be one unit time, the interval c can be in the order of 10^{-3}.

When $\theta = 0$, we have $W = W^d$ according to (6). Based on Lemma 2, this means that the cooperation capability W follows a uniform distribution between 0 and 1. Thus, the backoff time defined in (7) is also uniformly distributed with $f_T(t) = 1$ and $F_T(t) = t$ for $0 \le t \le 1$. From (14), we can easily obtain

$$I_c = (1-c)^N. \tag{15}$$

For $0 < \theta \le c$, we have

$$I_c = \frac{N(N-1)}{(1-\theta)^N}\Bigg\{\Big(1-\frac{3}{2}\theta\Big)^{N-1}\Big(\frac{1-\theta-c}{N-1} - \frac{1-3\theta/2}{N}\Big) + \Big(\frac{\theta}{2}\Big)^{N-1}\Big(\frac{2c - c^2/\theta}{2N-2} - \frac{2c}{2N-1}\Big)\Bigg\}. \tag{16}$$

For $\theta > c$, because a closed-form I_c is not tractable, we derive the following lower bound in Appendix A

$$I_c > \frac{N(N-1)}{(1-\theta)^N}\Bigg\{\Big(1-\frac{3}{2}\theta\Big)^{N-2}\Big(\theta - c\Big)^3\Big(\frac{1}{8\theta} + \frac{c}{24\theta^2}\Big) + \Big(1-\frac{3}{2}\theta\Big)^{N-1}\Big(\frac{1-\theta-c}{N-1} - \frac{1-3\theta/2}{N}\Big) + \Big(\frac{\theta}{2}\Big)^{N-1}\Big(\frac{2c - c^2/\theta}{2N-2} - \frac{2c}{2N-1}\Big)\Bigg\}. \tag{17}$$

Defining the righthand-side terms in (15)-(17) as I_c^L, we have $I_c \ge I_c^L$ and

$$P_c = 1 - I_c \le 1 - I_c^L \triangleq P_c^U \tag{18}$$

where P_c^U denotes an upper bound of the collision probability.

B. Lower Bound of Transmission Success Probability

When the traffic load is high, most of the relays will run out of energy quickly, and the distribution of their cooperation capabilities will no longer follow (11). Thus, it is hard to theoretically derive a lower or upper bound for the transmission success probability. Therefore, we focus on a normal traffic load when analyzing the lower bound of the transmission success probability in this section and its upper bound in the next section. In this circumstance, the energy constraint can be relaxed by setting $\theta = 0$. Then, the cooperation capability is only determined by the distance metric and follows a uniform distribution between 0 and 1.

A relay R_i participates in the cooperative relaying for the S_j-D_j pair only if R_i correctly receives the packet from S_j and its cooperation capability W_{ij} is the maximum among the N relays $(R_i, R_{i_1}, \ldots, R_{i_{N-1}})$ that overhear this packet successfully. With the largest W_{ij}, R_i sets the shortest backoff time and becomes the first to forward the packet. We have the corresponding occurrence probability

$$\begin{aligned} P_{ij} &= P_{S_jR_i} \cdot \prod_{r=1}^{N-1} \Pr\{W_{ij} > W_{i_rj}\} \\ &= P_{S_jR_i} \cdot (W_{ij})^{N-1}. \end{aligned} \tag{19}$$

Besides, the probability that at least one relay successfully overhears and forwards the packet for S_j is given by

$$Q_j = 1 - \prod_{r=1}^{K}(1 - P_{S_jR_r}). \tag{20}$$

Hence, the probability that R_i transmits the packet for S_j in the long term is given by

$$\overline{P_{ij}} = Q_j \cdot \frac{P_{ij}}{\sum_{r=1}^{K} P_{rj}}. \tag{21}$$

Finally, we have the transmission success probability for the S_j-D_j pair

$$\begin{aligned} P_{suc}^{(j)} &= \sum_{r=1}^{K} \overline{P_{rj}} \cdot P_{R_rD_j} \cdot (1 - P_c) \\ &\ge (1 - P_c^U) \cdot \sum_{r=1}^{K} \overline{P_{rj}} \cdot P_{R_rD_j} \triangleq P_{suc}^L \end{aligned} \tag{22}$$

where P_{suc}^L denotes the lower bound of the transmission success probability.

C. Upper Bound of Transmission Success Probability

In Section V-B, the energy constraint is relaxed to derive the lower bound of the transmission success probability. To obtain the upper bound, we assume no collisions among the relays in data forwarding. The upper bound of the transmission success probability for an arbitrary S_j-D_j pair is then given by

$$P_{suc}^U = P_{S_jR_{(1)}} \cdot P_{R_{(1)}D_j} + (1 - P_{S_jR_{(1)}}) \cdot P_{S_jR_{(2)}} \cdot P_{R_{(2)}D_j} + \cdots + \prod_{r=1}^{K-1} (1 - P_{S_jR_{(r)}}) \cdot P_{S_jR_{(K)}} \cdot P_{R_{(K)}D_j} \quad (23)$$

where $P_{R_{(1)}D_j} > P_{R_{(2)}D_j} > \cdots > P_{R_{(K)}D_j}$. The first term in (23) represents the case that the best relay $R_{(1)}$ has correctly received the packet from S_j with a probability $P_{S_jR_{(1)}}$, and its forwarding over the relay-to-destination channel to D_j succeeds with a probability $P_{R_{(1)}D_j}$. The second term in (23) indicates that the best relay $R_{(1)}$ fails to receive the packet from S_j with a probability $(1 - P_{S_jR_{(1)}})$, while the second best relay $R_{(2)}$ successfully receives and forwards the packet to D_j with a probability $P_{S_jR_{(2)}} \cdot P_{R_{(2)}D_j}$. The other terms in (23) can be interpreted in a similar way.

In addition, a relaxed upper bound of the transmission success probability can be obtained as

$$\widetilde{P_{suc}^U} = Q_j \cdot \max_{r \in \{1,2,\ldots,K\}} \{P_{R_rD_j}\} > P_{suc}^U \quad (24)$$

where Q_j is given by (20). Here, $\widetilde{P_{suc}^U}$ is derived by considering the maximum success probability over the relay-to-destination channel when at least one relay forwards the packet.

VI. Numerical Evaluation

In this section, numerical and simulation results are presented to demonstrate the effectiveness of our proposed cooperation strategy and the analytical bounds. For comparison purposes, we consider an uncoordinated probability-based algorithm, in which each potential relay R_i chooses its forwarding probability according to

$$P_{\tau_i} = \left[1 + \frac{P_0}{N_0T_0L^2} \cdot \ln\left(P_{R_iD}\right)\right]^{N-1} \quad (25)$$

where N is the number of relays that correctly overhear the packet from the source. Here, P_{τ_i} is actually the probability that R_i is the relay with the maximum transmission success probability over the relay-to-destination channel (with $\alpha = 2$). The derivation of (25) is given in Appendix B. In the simulation, we further minimize collisions by normalizing P_{τ_i} to

$$P_\tau^{(i)} = \frac{P_{\tau_i}}{\sum_{r=1}^{N} P_{\tau_r}}. \quad (26)$$

In practice, it is not appropriate for a distributed approach to allow a relay to obtain the forwarding probabilities of other relays. Thus, the real performance of the probability-based algorithm can be worse.

In the following experiments, we assume that the nodes are uniformly distributed in a 40m × 200m area, as illustrated by the example in Fig. 4. The maximum distance of potential relays to a destination is $L = 55$ m, since the transmission success probability over the relay-to-destination channel is lower than 0.25 when $L > 55$ m. Assume that all the relays are fully charged at the beginning, and each relay can transmit up to 10^4 packets. More system parameters are given in Table II.

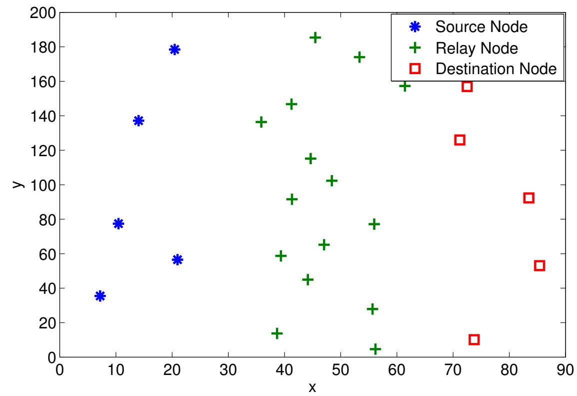


Fig. 4. Nodes topology for analysis and simulation.

TABLE II
System Parameters.

Symbol	Value	Definition
P_0/N_0	40 dB	Transmit SNR
T_0	5	SNR threshold of signal decoding
α	2	Path-loss exponent
L	55 m	Maximum distance of potential relays to a destination
θ	$0 \sim 0.2$	Weighting parameter for distance and energy
η	0.0001	Update step length
c	$0.001 \sim 0.01$	Indistinguishable backoff time interval for collision

A. Collision Probability

Fig. 5 shows the analytical bounds and simulation results of the collision probability. As seen, when the collision interval c increases, the collision probability increases accordingly. Further, when the number of relays K increases, the collision probability increases as well. We also find that the analytical upper bound of the collision probability works well for the proposed strategy. Besides, it is observed that the collision probability of the proposed strategy is smaller than 10%, even when the collision interval and the number of relays are large. In contrast, the probability-based algorithm has a collision probability greater than 18%, which is much higher than that of the proposed strategy. It should be noted that the collision probability of the probability-based algorithm has been minimized by normalizing the forwarding probability of each relay, which makes the approach not purely distributed.

B. Transmission Success Probability

Fig. 6 compares the transmission success probability of different strategies with the analytical bounds. We can see that the transmission success probability of the probability-based algorithm is bounded by $1/e \approx 0.368$, which verifies the conclusions in [16,24]. In contrast, our proposed backoff-based strategy can easily achieve a transmission success probability higher than 0.6, because of the reduced collision probability. Moreover, we find that the upper bound and the lower bound

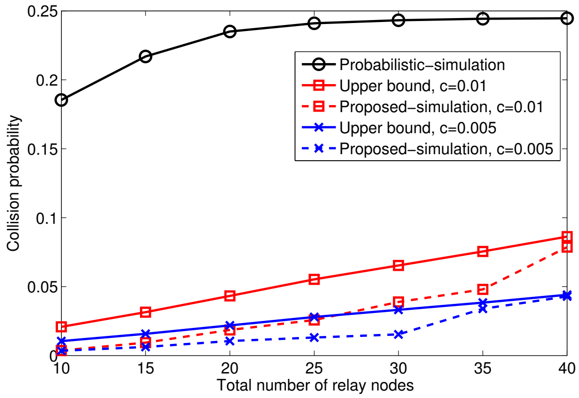


Fig. 5. Collision probability P_c vs. total number of relay nodes.

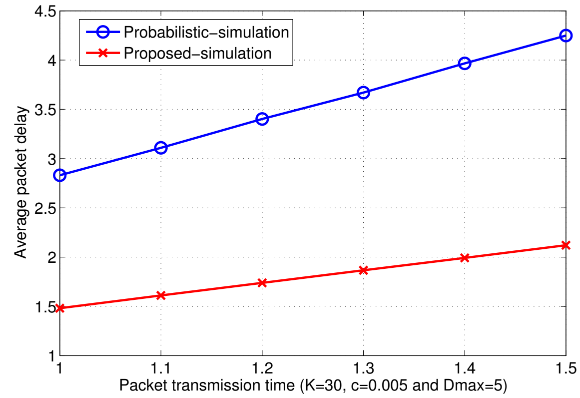


Fig. 7. Average packet delay $\overline{\mathcal{D}}$ vs. the packet transmission time.

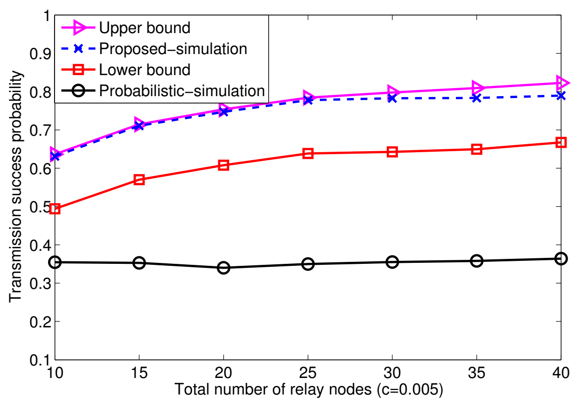


Fig. 6. Transmission success probability vs. total number of relay nodes.

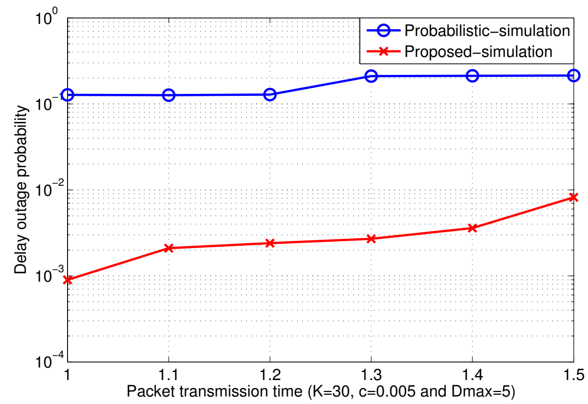


Fig. 8. Delay outage probability P_{out} vs. packet transmission time.

of the transmission success probability both work well. The proposed strategy approaches the upper bound in a normal traffic load.

Furthermore, it is seen in Fig. 6 that the transmission success probability of the proposed strategy increases with a greater number of relays, whereas that of the probability-based algorithm remains almost the same. This seems counter-intuitive since Fig. 5 shows the collision probability of both algorithms increases with the number of relays. This is because the opportunity of finding a good relay increases with more potential relays. Thus, packet loss caused by poor channel conditions can be reduced.

C. Average Delay and Delay Outage Probability

Fig. 7 shows the average packet transfer delay of the two algorithms against the packet transmission time. The packet transfer delay represents the time duration from a packet generation to successful transmission, while the packet transmission time is given by the packet length over the transmission rate. Here, the maximum backoff time is taken to be one unit time. As seen, the average packet delay of the proposed algorithm is much smaller than that of the probability-based algorithm, even though the proposed algorithm requires extra backoff time. This is because the collision probability of the proposed backoff-based algorithm is much lower than that of the probability-based algorithm, as shown in Fig. 5. As a result, the transmission success probability is improved significantly, as seen in Fig. 6. Thus, the average packet transfer delay is reduced accordingly. In addition, we find that the average packet delay of the backoff-based algorithm increases slower than that of the probability-based algorithm, which implies that our proposed algorithm can achieve more gain for a larger packet length.

Fig. 8 compares the delay outage probability (in log scale) of the two algorithms with respect to the packet transmission time. It can be seen that the backoff-based algorithm has a delay outage probability smaller than 0.01. On the other hand, the delay outage probability of the probability-based algorithm increases faster from 0.12 to 0.21, when the packet transmission time increases from 1 to 1.5. Therefore, our proposed algorithm is preferable for the real-time delay-sensitive services.

D. Energy Saving and Energy Balance

To further investigate the energy consumption of the two algorithms, Fig. 9 shows the average energy cost of the relays for a packet with respect to the total number of relays K. Here, the unit of energy cost is the energy consumption of one transmission attempt for a packet with a transmission time of one time unit. As seen in Fig. 9, our proposed backoff-based algorithm can save around 50% of energy on average, compared to the probability-based algorithm. This

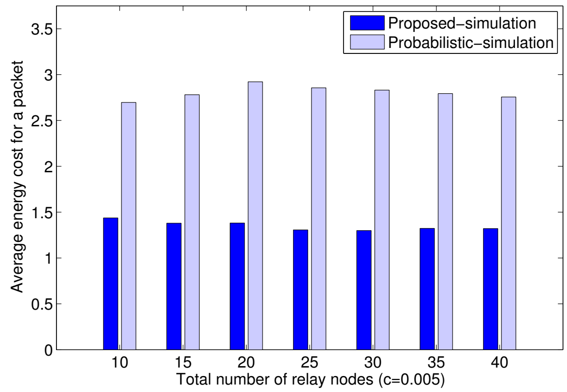
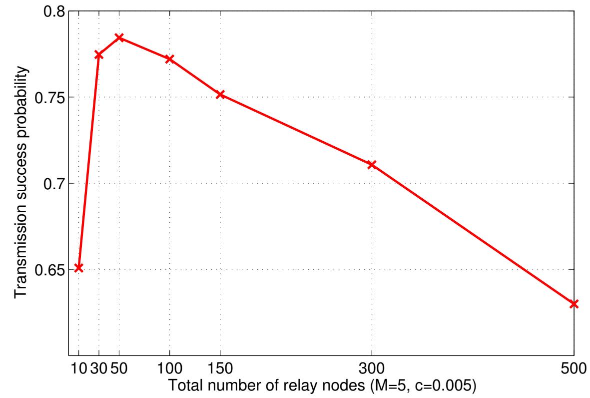


Fig. 9. Average energy cost for a packet vs. total number of relay nodes.



(a) P_{suc} vs. K

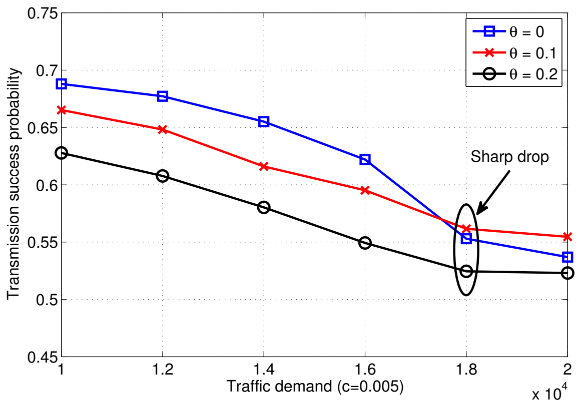
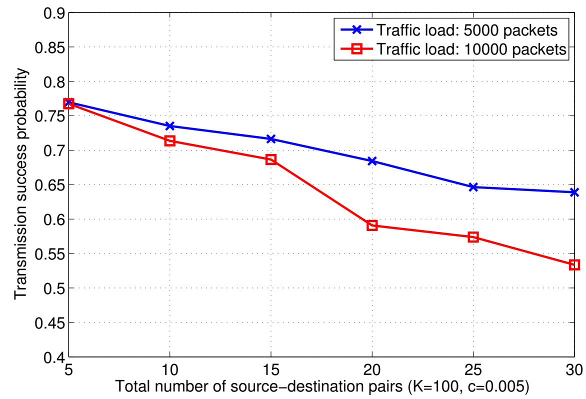


Fig. 10. Transmission success probability P_{suc} vs. traffic demand.



(b) P_{suc} vs. M

Fig. 11. Scalability of the proposed cooperation strategy.

energy saving is due to the low collision probability and high transmission success probability of the backoff-based algorithm.

In Fig. 10, we show the variations of the transmission success probability with the traffic demand of an S-D pair. Here, the traffic demand is the number of packets transmitted for an S-D pair, excluding the retransmitted packets. It is assumed in the simulation that all M S-D pairs have the same traffic demand. As seen, when the traffic demand is low, the highest transmission success probability is achieved at $\theta = 0$. Given a low traffic demand, no relay runs out of energy to satisfy the demand and the relays with the best channel conditions are always available to forward the packets. Hence, the energy constraint does not take effect and it is not necessary to consider energy balance in relay selection.

On the other hand, the situation becomes different with a high traffic demand. As seen in Fig. 10, when the traffic demand is greater than 1.8×10^4, the transmission success probability with $\theta = 0$ is no longer higher than that of $\theta = 0.1$. This is because the energy constraint is not addressed with $\theta = 0$ and consequently the best relay candidates may run out of energy very quickly. In contrast, we can take advantage of energy balance by setting $\theta = 0.1$ for relay selection and thus extend the survival time of the relays. As a result, the average transmission success probability can be improved. Moreover, it is observed in Fig. 10 that the transmission success probability with $\theta = 0.2$ is always worse than that of $\theta = 0$ and $\theta = 0.1$. This implies that the weight $\theta = 0.2$ overvalues the importance of energy status but underestimates that of the relay's distance to the destination. Consequently, the relay selection becomes kind of "blind" to the transmission success probability over the relay-to-destination channel. Therefore, it is usually assumed that $\theta \leq 0.2$.

E. Scalability

To study the scalability of the proposed algorithm, we vary the total number of relays K and the total number of S-D pairs M in the simulation. Given a fixed number of S-D pairs, $M = 5$, Fig. 11(a) shows that the transmission success probability first increases with the number of relays and then decreases when $K \geq 50$. On one hand, more good relays become available for an S-D pair when the total number of relays is larger. On the other hand, the collision probability also increases correspondingly. At the beginning, the advantage of having more good relays dominates the side effect of collisions. On the contrary, when the number of relays further grows, the collision probability becomes very high and the transmission success probability decreases. For example, the collision probability with $K = 300$ is 20.86%, which is much higher than 10.34% with $K = 100$. For the relaying area considered in the simulation, $K = 500$ is an extremely high and rare density in practice. Even so, we still find that the transmission success probability is above 60% and much larger than that of the probability-based algorithm.

Fig. 11(b) shows the transmission success probability vs. the number of S-D pairs M given a fixed number of relays $K = 100$. The two scenarios in comparison have different traffic loads, which are the total number of packets transmitted for each S-D pair, including the retransmitted packets. It is observed that the transmission success probability is above 50% with a reasonable number of S-D pairs ($M \leq 30$) when the traffic load is normal. This verifies that our proposed algorithm can be deployed in a large-scale network. Moreover, it is seen that the transmission success probability decreases with a larger number of S-D pairs. When more S-D pairs share a group of common relays, the relays with better channel conditions to the destinations will run out of energy quickly. As a result, the transmission success probability goes down, but decreases slower with a lower traffic load. Hence, in order to guarantee the QoS requirements, the amount of traffic that enters the network should be regulated by controlling the number of S-D pairs and/or their admissible traffic loads. In addition, we find that the Jain's fairness index of the transmission success probability among the M S-D pairs is almost 1, which implies that the group of relays are evenly shared by all S-D pairs with the proposed backoff-based algorithm.

VII. Concluding Remarks

In this paper, we study the uncoordinated cooperative communications between multiple S-D pairs that share a group of energy-constrained relays. A novel cooperation strategy is proposed based on backoff timers. It makes use of the cooperative capability, which is characterized by the distance information and the energy status of the relay. Thus, the relay of a higher cooperative capability ends up with a shorter backoff time. The best relay times out first and wins the contention. However, a collision still happens if the backoff timers of the first two or more relays expire within an indistinguishable time interval. Hence, we also derive the theoretical performance bounds for the proposed strategy with respect to the collision probability and the transmission success probability.

As shown in the numerical results, our proposed strategy can achieve a much lower collision probability and thus a higher transmission success probability, compared to a probability-based reference strategy. We find that the transmission success probability can approach the upper bound in a normal traffic load, which verifies that our algorithm can effectively and efficiently identify the optimal relay in an uncoordinated manner. Besides, our algorithm also outperforms the probability-based strategy in terms of average packet delay, delay outage probability, as well as the energy consumption. By adjusting the weighting parameter θ, we can achieve good performance in the high traffic load condition through energy balance. Therefore, it is safe to conclude that our proposed algorithm can serve as an energy-efficient cooperation strategy for delay-sensitive multimedia services and it is a scalable solution for a large-scale network.

Appendix A
Proof of (17)

According to (14), when $\theta > c$, we have

$$I_c = N(N-1)(I_{c_1} + I_{c_2} + I_{c_3}) \tag{27}$$

where I_{c_1}, I_{c_2} and I_{c_3} are given by

$$I_{c_1} = \int_c^\theta \frac{t}{\theta(1-\theta)}\left[1 - \frac{t^2/2}{\theta(1-\theta)}\right]^{N-2} \frac{(t-c)^2/2}{\theta(1-\theta)}\mathrm{d}t \tag{28}$$

$$I_{c_2} = \int_\theta^{1-\theta} \frac{1}{1-\theta}\left[1 - \frac{t-\theta/2}{1-\theta}\right]^{N-2} \frac{t-c-\theta/2}{1-\theta}\mathrm{d}t \tag{29}$$

$$I_{c_3} = \int_{1-\theta}^1 \frac{1-t}{\theta(1-\theta)}\left[\frac{(1-t)^2}{2\theta(1-\theta)}\right]^{N-2}\left[1 - \frac{(1-t+c)^2}{2\theta(1-\theta)}\right]\mathrm{d}t. \tag{30}$$

As a closed-form expression is not tractable for I_{c_1}, we take $t \leq \theta$ and have

$$\begin{aligned} I_{c_1} &\geq \int_c^\theta \frac{t}{\theta(1-\theta)}\left[1 - \frac{\theta^2/2}{\theta(1-\theta)}\right]^{N-2} \frac{(t-c)^2/2}{\theta(1-\theta)}\mathrm{d}t \\ &= \Big(\frac{1}{1-\theta}\Big)^N\Big(1 - \frac{3}{2}\theta\Big)^{N-2}\Big(\theta - c\Big)^3\Big(\frac{1}{8\theta} + \frac{c}{24\theta^2}\Big). \end{aligned} \tag{31}$$

The closed-form expressions of I_{c_2} and I_{c_3} can be obtained as

$$\begin{aligned} I_{c_2} = \Big(\frac{1}{1-\theta}\Big)^N &\bigg\{\frac{1-\theta-c}{N-1}\bigg[\Big(1-\frac{3}{2}\theta\Big)^{N-1} - \Big(\frac{\theta}{2}\Big)^{N-1}\bigg] \\ &- \frac{1}{N}\bigg[\Big(1-\frac{3}{2}\theta\Big)^N - \Big(\frac{\theta}{2}\Big)^N\bigg]\bigg\} \end{aligned} \tag{32}$$

$$I_{c_3} = \Big(\frac{\theta/2}{1-\theta}\Big)^N\Big(\frac{2}{\theta}\Big)\bigg[\frac{2(1-\theta) - c^2/\theta}{2N-2} - \frac{2c}{2N-1} - \frac{\theta}{2N}\bigg]. \tag{33}$$

The last three equations conclude the proof to (17).

Appendix B
Proof of (25)

According to (2), we obtain the transmission success probability over the relay-to-destination channel with $\alpha = 2$ as

$$P_{RD} = e^{-\phi d^2} \tag{34}$$

where $\phi = T_0 N_0 / P_0$. Given the PDF of d in (10), we derive the CDF of P_{RD} by

$$\begin{aligned} \Pr\{P_{RD} \leq p\} &= \Pr\{e^{-\phi d^2} \leq p\} = 1 - \Pr\left\{d \leq \sqrt{-\frac{\ln p}{\phi}}\right\} \\ &= 1 - \int_0^{\sqrt{-\frac{1}{\phi}\ln p}} f(x)\mathrm{d}x = 1 - \frac{d^2}{L^2}\bigg|_0^{\sqrt{-\frac{1}{\phi}\ln p}} \\ &= 1 + \frac{P_0}{N_0 T_0 L^2}\ln p. \end{aligned}$$

Thus, it is easy to show that the probability that a relay has the maximum transmission success probability over the relay-to-destination channel among N candidates is given by (25).

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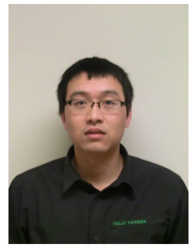

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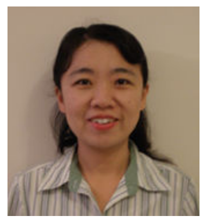

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