Distributed Opportunistic Two-Hop Relaying With Backoff-Based Contention Among Spatially Random Relays

Wei Song, *Member, IEEE*, Peijian Ju, A-Long Jin, and Yu Cheng, *Senior Member, IEEE*

***Abstract*—Cooperative transmission can exploit the broadcast nature of a wireless medium and leverage relay nodes to forward overheard data from the source to the destination. To optimize the performance gain, effective cooperation strategies are essential to identify the best relay(s) with a minimum overhead and enable forwarding with high success probability. In this paper, we focus on an opportunistic relaying scenario and develop two distributed cooperation strategies. Both adopt a backoff-based intergroup coordination, whereas the intragroup contention is based on either the forwarding probability or backoff timer. In particular, we employ stochastic geometry to address the impact of spatial distribution of relays. Considering a Poisson point process for random relays, we derive the probability distributions of the average received signal-to-noise ratio (SNR) and transmission success probability of potential relays. Making use of such statistics and location information, each relay can independently determine its contention parameters such as backoff time and/or a forwarding probability. We analytically evaluate the relaying performance and validate the accuracy with simulations. The results demonstrate the improvement over a pure probabilistic scheme and the gap to the upper bound of a centralized scheme with the preselected best relay.**

***Index Terms*—Cooperative communications, opportunistic relaying, random relays, relay selection, uncoordinated strategies.**

I. Introduction

GIVEN the broadcast nature of a wireless medium, data transmission from a source can be overheard by some nodes other than the destination. The nodes that experience better channel conditions to the destination can act as relays and forward the overheard data to the destination. Such user cooperation offers the benefits of spatial diversity and throughput improvement. Relay selection and medium access control (MAC) is an essential problem to identify the best relay(s) and optimize cooperation gain [1]–[3].

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W. Song, P. Ju, and A.-L. Jin are with the Faculty of Computer Science, University of New Brunswick, Fredericton, NB E3B 5A3, Canada (e-mail: wsong@unb.ca; i1689@unb.ca; along.jin@unb.ca).

Y. Cheng is with the Department of Electrical and Computer Engineering, Illinois Institute of Technology, Chicago, IL 60616 USA (e-mail: cheng@iit.edu).

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Centralized solutions such as those proposed in [4]–[6] need to acquire knowledge of potential relays usually via additional handshaking messages. Thus, the relays can be shortlisted, and the best relay is chosen in a centralized manner, at the source node for example. On the other hand, distributed solutions such as those in [7]–[9] do not require *a priori* information of the relays. The relays that correctly overhear a packet from the source contend in a distributed fashion to forward the packet to the destination. A collision may occur if two or more relays happen to transmit at the same time. Hence, the contention policies should take into account a variety of factors to reduce collisions and improve the relay success probability.

The probabilistic uncoordinated cooperation strategies in [7] and [8] have each relay that correctly overhears a packet independently determine a forwarding probability, depending on the distance, direction, local signal-to-noise ratio (SNR) [7], or statistical information of the local environment [8]. It is found in [8] that the transmission success probability of the probabilistic strategy is upper bounded by $1/e \approx 0.368$. Although the probabilistic strategies require little signaling overhead, the collision probability can be high, and the determination of forwarding probability is critical for the performance.

There is another class of distributed solutions that make use of local information of relays to tune the backoff timer [10]–[12]. Such solutions are also distributed since the backoff time is determined by each individual relay itself based on local information. The relays of better transmission capability are prioritized with a smaller backoff time. The relay capability can be characterized by the distance to the destination [10], channel estimates for the source-to-relay channel and the relay-to-destination channel [11], or a composite cooperative transmission rate [12], which involves the broadcast rate from the source and the data rate from the relay to the destination. As such, the backoff-based solutions naturally rank the relays for access contention according to their transmission capabilities. Collisions are thus greatly reduced but still possible when two or more relays are similar in terms of the defined transmission capabilities and end up with indistinguishable backoff time.

It can be seen that the distributed solutions offer a good match to the opportunistic relaying scenario, where the communication peers do not need *a priori* global knowledge of the relays. Nonetheless, it is challenging but vital to appropriately coordinate the cooperative contributions of the relays so as to reduce collisions and improve the relay success probability. The existing work usually assumes a certain number of relays that are randomly deployed in a given area. The impact of the spatial distribution of relays has yet to be well understood. In fact, the spatial distribution can be exploited in the cooperation strategy to enhance the relaying performance. Specifically, this work focuses on the following key aspects.

- Considering an opportunistic relaying scenario, we take into account the spatial distribution of random relays and derive the probability distributions of the average received SNR and the transmission success probability of the potential relays that successfully overhear a packet from the source.
- Based on knowledge of such statistics and location information, we develop two distributed cooperative relaying schemes, in which each potential relay independently determines a backoff time and/or a forwarding probability.
- We compare the proposed schemes with a centralized scheme with the preselected best relay as an upper bound and a pure probabilistic distributed scheme as a lower bound. We also analytically evaluate the performance of the proposed schemes and the reference schemes in terms of the relay success probability and backoff delay. The analysis accuracy is validated by simulations.

The remainder of this paper is organized as follows. Section II reviews the related work, and Section III gives the system model. In Section IV, we propose two novel cooperative relaying schemes with backoff-based intergroup coordination and different intragroup contention strategies. Section V introduces our analytical approaches to evaluate the relaying performance. Simulation and analysis results are provided in Section VI, which validate the analysis accuracy, compare the proposed schemes with the upper and lower bounds, and demonstrate the variation of performance with different system settings. The conclusion and future work are discussed in Section VII.

II. Related Work

In the literature, the distributed relay selection and MAC has attracted considerable research attention. The distributed solutions usually do not require global knowledge of the relays and rely on the contention among the relays to naturally select the best relay. The contention mainly depends on local information of the relays, such as the instantaneous SNR, available transmission rate, and location-aware parameters including distance and direction. In [7] and [8], each relay independently decides a forwarding probability that it will forward an overheard packet. If more than one relay happens to simultaneously transmit, a collision occurs. Different probabilistic cooperation strategies have been proposed to reduce collisions while maximizing the chance that an optimal relay wins the contention. However, the relay success probability is not ideal [8], although it can be augmented by advanced techniques such as maximal ratio combining [7].

The local information of relays can also be exploited in a distributed fashion from another perspective. That is, the backoff timer can be tuned so that the relays of higher transmission capability are prioritized with a smaller backoff timer. The GeRaF method proposed in [10] uses the local geographical information and distance to the destination to decide the order that the relays issue a clear-to-send (CTS) message in response to a ready-to-send (RTS) message. Based on partitions of the coverage area, the relays in the region closest to the destination can respond with a CTS in the first slot after an RTS, whereas the relays in the second closest region can send a CTS in the second slot if all the relays in the closest region are silent, and so on. The cross-layer solution in [12] extends the conventional RTS-CTS handshaking with a ready-to-help message from the optimal helper, which wins the contention among the relays. The two-level intergroup and intragroup contention is based on a composite cooperative transmission rate (CCTR), which involves the broadcast rate from the source and the data rate from the helper to the destination. The relays are grouped according to CCTR and send out indication signals after a different number of backoff slots. The optimal helper of the highest CCTR waits for the shortest time and wins the contention. The opportunistic relaying method in [11] is based on the channel estimates of each relay for the source-to-relay channel and the relay-to-destination channel. Two policies are proposed to map the channel estimates into a backoff timer value. Nonetheless, the analysis of the collision probability assumes a fixed number of relay candidates with independent and identically distributed channel statistics. The spatial distribution of relays will result in a nonidentical but still independent case, which requires further investigation.

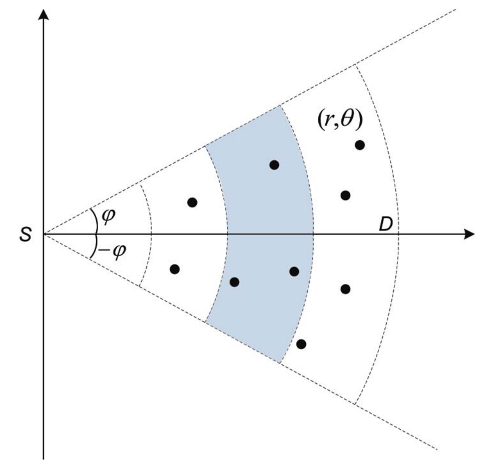

Fig. 1. Coordinate system for source S, destination D, and the relays that are distributed as a PPP.

III. System Model

Consider a wireless network with a source node S and a destination node D, where the distance between them is fixed at R. The relay nodes are randomly distributed in a given region, following a homogeneous Poisson point process (PPP) with an intensity function λ. We assume that the PPP is time stationary, which is generally valid under broad assumptions, e.g., the random direction mobility model [13]. Consider a polar coordinate system shown in Fig. 1, in which S is at the origin, and D is at $(R, 0)$. To achieve a higher relay success probability, the packet from S should be directed toward the relays closer to D. Hence, the relays should lie within a symmetric angle interval of $(-\pi/2, \pi/2)$ with respect to the source–destination axis [7]. To reduce collisions, the relays within a smaller sector of $(-\phi, \phi)$, $\phi \leq \pi/2$, can be focused on. This sector region is denoted by $\Omega_{\rm SD}$.

We assume that each node knows its own location, which can be obtained either from a locating technique based on signal strength, time-of-arrival, or angle-of-arrival measurements with nearby nodes [14], [15], or through a Global Positioning System receiver that is becoming increasingly ubiquitous in mobile devices. Furthermore, S can obtain the location of D in advance via a prior handshaking process and piggyback the locations of S and D within the transmitted packet. The relay nodes can thus acquire such information from the overheard packet. It should be noted that S does not know the locations of relays, and the relays do not have the location information of each other.

For the data transmission between a certain transmitter located at x and a certain receiver located at y, considering log-distance path loss and Rayleigh fading, we have the SNR of the received signal, which is given by

$$\gamma_{xy} = \frac{P_0}{N_0} \|x - y\|^{-\alpha} h_{xy} \tag{1}$$

where P_0 is the transmit power, N_0 is the power of the additive white Gaussian noise, $\|x - y\|$ is the Euclidean distance, α is the path-loss exponent, and h_{xy} denotes the small-scale channel fading, which is exponentially distributed with unit mean. The receiver is able to successfully decode the received signal only when the local SNR is no less than a threshold T_0 [7]. The transmit SNR P_0/N_0 and decoding threshold T_0 are assumed to be the same for all nodes. Therefore, the probability that a packet is received successfully is given by

$$p_{xy} = \Pr[\gamma_{xy} \geq T_0] = e^{-K_0 \|x-y\|^\alpha}, \quad K_0 = \frac{T_0 N_0}{P_0}. \tag{2}$$

When S broadcasts a data packet to D, it is possible that an intermediate relay correctly overhears it with a probability given by (2). We refer to the relays that correctly receive the packet as *potential relays*. Then, the potential relays can follow a distributed cooperation strategy and use decode-and-forward to transmit the overheard packet to D. The distributed strategy does not require global knowledge of the relays. Nonetheless, it is assumed that each relay is aware of the spatial distribution parameters of the random relays such as λ and ϕ. Moreover, since the locations of S and D are piggybacked in the transmitted packet and, thus, available to the relays, each relay can estimate its transmission success probability to D according to (2). Together with the location information and other local estimates, each relay can independently determine a backoff timer and/or a forwarding probability to participate in the relaying.

IV. Cooperative Relaying Strategies

Based on the system model in Section III, the relays that correctly overhear the packet from the source can forward the data to the destination opportunistically. On one hand, the more relays that participate in the cooperative transmission, the higher chance that some promising relays of good channel conditions to the destination can be selected. On the other hand, if two or more relays happen to simultaneously transmit, a collision occurs. In this paper, we develop effective cooperation strategies to select good relays and coordinate their opportunistic forwarding in a distributed fashion. Focusing on the MAC perspective, we assume that a collision causes a transmission failure and aim to minimize collisions in the first place. Nonetheless, if the signal received from one relay is sufficiently stronger than the interference from the collided signals of other relays, it is still possible for the receiver to successfully recover the data from the collided signals. This capture effect has been analyzed in many previous studies [16]–[18] on random access MAC protocols for wireless networks. The given assumption on collision-caused packet loss is actually a worst case scenario. Due to the capture effect, the achievable relay success probability of the proposed cooperation strategies can be even higher in practice.

Section II discusses two types of distributed cooperation solutions. For the probabilistic uncoordinated strategies, each potential relay independently determines a forwarding probability that it will transmit the overheard packet. While the probabilistic strategies offer the benefit of light signaling overhead, the high collision probability often upper bounds the success probability by $1/e \approx 0.368$ [8], [19]. For the backoff-based strategies, each potential relay sets a backoff timer depending on its location information and other local estimates. When the backoff timer expires, a potential relay starts to transmit the packet if no forwarding signal is heard from any other relay. The backoff-based strategies can significantly reduce collisions by properly characterizing the transmission capability of relays and mapping that to a backoff time. Nonetheless, a time synchronization overhead is also involved. Based on the given observations, we propose two novel distributed cooperation schemes that take advantage of the spatial distribution of random relays to combine the strengths of the probabilistic and backoff-based solutions.

A. Intergroup Backoff-Based Contention

To reduce collisions, we consider two-level intergroup and intragroup contentions similar to [12]. As there may exist a large number of potential relays in the entire sector (denoted by $\Omega_{\rm SD}$) in Fig. 1, a backoff-based scheme works better for the intergroup contention. Since the potential relays closer to D generally have a higher transmission success probability, a natural idea for grouping is to partition the sector into L strips. The radius boundaries are denoted by a vector $\vec{\mathbf{r}} = [r_0, r_1, r_2, \ldots, r_L]$, where $r_0 = 0$, $r_i < r_j$ for $i < j$ and $0 \leq i,\ j \leq L$. To prioritize the relays in a strip closer to D, the potential relays in region L (denoted by Ω_l) set a minimum backoff time

$$t_{l,\min} = (L - l + 1) \cdot \Delta, \quad 1 \leq l \leq L \tag{3}$$

where Δ is a time constant.

B. Intragroup Contention

When the intensity of relay nodes is very high, the collision probability within a group may still be intolerable. Effective intragroup contention strategies are important to further reduce collisions. First, the relays in region Ω_l can choose their backoff time on the basis of the group minimum time $t_{l,\min}$. That is, a relay in group L sets its backoff time in the range of $[t_{l,\min}, t_{l,\min} + \Delta)$. Second, a probabilistic strategy can be used since the number of contending relays in each group is expected to be much smaller. That is, each relay in a certain contention group independently determines a forwarding probability for the cooperative relaying. Although the basic rationale behind these two strategies is that a better relay ends up with a smaller backoff time and/or a higher forwarding probability, the specific algorithms deriving such parameters are critical for the achievable performance.

1) Backoff-Based Strategy: In the first intragroup contention strategy, a potential relay $R_{l,i}$ in region Ω_l first estimates its transmission success probability to D, i.e., $p_{l,i}$, according to the location information. Then, on the basis of the group minimum given in (3), $R_{l,i}$ can set its backoff time to

$$t_{l,i} = t_{l,\min} + (1 - p_{l,i}) \cdot \Delta. \tag{4}$$

As such, $R_{l,i}$ forwards the packet after a backoff time $t_{l,i}$ if there is no forwarding signal overheard, which means that the region of $R_{l,i}$ is the closest to D among all potential relays and that its transmission success probability is the highest among the potential relays in the same region.

2) Probabilistic Strategy: Another probabilistic strategy for the intragroup contention is to have each potential relay $R_{l,i}$ in region Ω_l estimate its transmission success probability $p_{l,i}$ and use $p_{l,i}$ to determine a forwarding probability, denoted by $\tau_{l,i}$. That is, after a backoff time $t_{l,\min}$, $R_{l,i}$ forwards the packet with probability $\tau_{l,i}$, only if no forwarding signal is overheard from the potential relays in regions closer to D $(\Omega_{l+1}, \ldots, \Omega_L)$, which are supposed to time out earlier. As a result, there is no collision if only one relay in region Ω_l transmits, while none relay in regions $(\Omega_{l+1}, \ldots, \Omega_L)$ correctly overhears the packet or all potential relays therein are silent.

Intuitively, a potential relay with a higher transmission success probability should end up with a larger forwarding probability. Provided that the statistics of the transmission success probability of potential relays are known, the potential relay $R_{l,i}$ in region Ω_l can set its forwarding probability to

$$\tau_{l,i} = \left[G_{P,l}(p_{l,i})\right]^{\lceil \Lambda_l \rceil - 1} \tag{5}$$

where Λ_l is the average number of potential relays in region Ω_l, and $G_{P,l}(\cdot)$ is the cumulative distribution function (cdf) of the transmission success probability of the potential relays in region Ω_l. We will derive Λ_l and $G_{P,l}(\cdot)$ in Section V-A.

The physical meaning of (5) can be interpreted as follows. Supposing that there are M relays $(M \geq 1)$ in region Ω_l that correctly overhear the packet, we have $P_{l,(1)} < P_{l,(2)} < \cdots < P_{l,(M)}$ denote the M-order statistics of the transmission success probability of these potential relays in the group. Then, a given potential relay $R_{l,i}$ has the highest transmission success probability among the M candidates with probability $[G_{P,l}(p_{l,i})]^{M-1}$. This also means that the transmission success probabilities of $(M-1)$ potential relays are all no greater than that of $R_{l,i}$, $p_{l,i}$. Since the relays are not aware of the status of others, the average number of potential relays is used here for approximation.

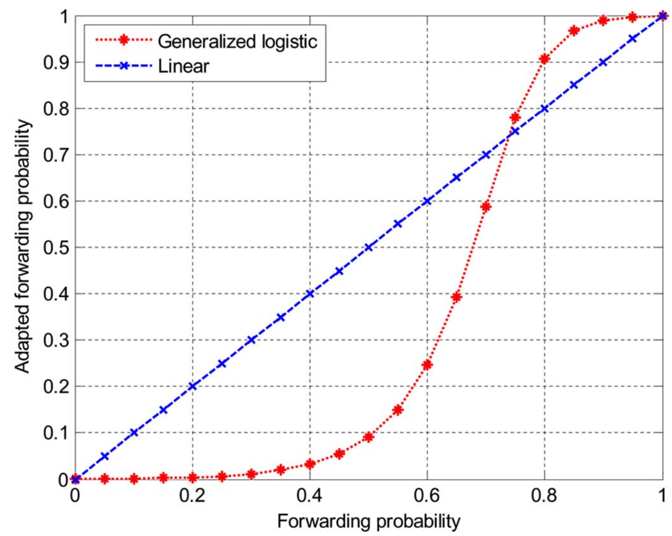

Fig. 2. Adaptation of forwarding probability with a generalized logistic function.

To further reduce intragroup collisions and augment the forwarding probability of best relays, we can use the generalized logistic function [20] (a.k.a Richards' curve) to adapt $\tau_{l,i}$ in (5) as follows:

$$\widetilde{\tau}_{l,i} = \frac{1}{\left[1 + \nu e^{-\mu(\tau_{l,i} - q)}\right]^{1/\nu}} \tag{6}$$

where μ and ν can be determined so that $\widetilde{\tau}_{l,i}$ is bounded within (0, 1). The parameter q indicates the point at which the growth rate is maximum. It is tricky to find the best setting for q, and we have referred to the average transmission success probability to adjust this parameter. Fig. 2 shows one example of the logistic function in comparison with the linear case without adaptation. It is expected that, after the forwarding probability is adapted by the logistic function, the bad relays of small transmission success probability are suppressed, while the forwarding probabilities are boosted for good relays of high transmission success probability.

V. Performance Analysis

As shown in Section IV, the intragroup contention parameters highly depend on the location information as well as the transmission success probability of the potential relays and its statistics. The spatial distribution of the relays thus has an essential impact on the determination of the contention parameters and the achievable performance. Here, we first derive the statistic distributions of the transmission success probability of the potential relays in a region. Then, we develop effective analytical approaches to evaluate the relay performance of the proposed cooperation strategies.

A. Probability Distributions of Spatial Random Relays

Given the system model in Section III, the relays are deployed in the given sector Ω_{SD} between S and D as a homogeneous PPP, which is denoted by $\mathbf{\Phi}_{\rm SD}$. According to (2), a relay at location (r, θ) successfully receives the packet from S and becomes a *potential relay* with probability

$$p(r) = e^{-K_0 r^\alpha}. \quad (7)$$

Considering the intergroup contention strategy in Section IV-A, we divide all the potential relays into L groups. The potential relays in each region Ω_l $(1 \le l \le L)$ form a new point process, which is denoted by $\mathbf{\Phi}_l$, from the original PPP $\mathbf{\Phi}_{\rm SD}$ by retaining a point at (r, θ) with probability $p(r)$ and deleting the point with probability $1 - p(r)$. This is referred to as a $p(x)$-thinning operation in stochastic geometry [21]. In this $p(x)$-thinning operation, the retention probability that determines a potential relay is independent of the locations and possible retentions of any other points. According to Prekopa's theorem [21], the distribution of these potential relays in region Ω_l also follows a Poisson distribution with a mean

$$\Lambda_l = \int_{r_{l-1}}^{r_l} \int_{-\phi}^{\phi} p(r)\lambda r \, dr \, d\theta, \quad 1 \le l \le L. \quad (8)$$

According to (7), we can easily obtain

$$\Lambda_l = \frac{\lambda\phi}{K_0}\left[\exp\left(-K_0 r_{l-1}^\alpha\right) - \exp\left(-K_0 r_l^\alpha\right)\right]. \quad (9)$$

The distribution of the number of *potential relays* in Ω_l is then given by

$$\Pr\left[\mathbf{\Phi}_l = k\right] = \frac{\Lambda_l^k}{k!}\exp(-\Lambda_l), \quad k = 0, 1, 2, \ldots. \quad (10)$$

Let $P_{RD,l}$ denote the probability that an arbitrary potential relay $R_{l,i}$ in Ω_l forwards the overheard packet to D successfully. Based on (2), we write the cdf of $P_{RD,l}$ as

$$\begin{aligned} G_{P,l}(y) &= \Pr\left[P_{RD,l} \le y\right] \\ &= \Pr\left[\exp\left(\frac{-T_0}{P_0/N_0\|R_{l,i} - D\|^{-\alpha}}\right) \le y\right]. \end{aligned} \quad (11)$$

Letting $\Gamma_{RD,l}$ denote the average received SNR at D for the forwarded signal from a potential relay, that is, $\Gamma_{RD,l} = (P_0/N_0)\|R_{l,i} - D\|^{-\alpha}$, we rewrite (11) as

$$\begin{aligned} G_{P,l}(y) &= \Pr\left[\exp\left(\frac{-T_0}{\Gamma_{RD,l}}\right) \le y\right] \\ &= \Pr\left[\Gamma_{RD,l} \le \frac{-T_0}{\ln(y)}\right] \triangleq F_{\Gamma,l}\left(\frac{-T_0}{\ln(y)}\right) \end{aligned} \quad (12)$$

where $F_{\Gamma,l}(x)$ denotes the cdf of $\Gamma_{RD,l}$.

Here, $F_{\Gamma,l}(x)$ depends on the spatial distribution of the potential relays as follows:

$$\begin{aligned} F_{\Gamma,l}(x) &= \Pr\left[\frac{P_0}{N_0}\|R_{l,i} - D\|^{-\alpha} \le x\right] \\ &= \Pr\left[\|R_{l,i} - D\|^{\alpha} \ge \frac{P_0/N_0}{x}\right]. \end{aligned} \quad (13)$$

When $\alpha = 2$, we can further express (13) as

$$\begin{aligned} F_{\Gamma,l}(x) = &\iint_{\Omega_l} \exp(-K_0 r^2)\lambda r \\ &\times \mathbf{1}_{\mathbb{R}^+}\left(r^2 + R^2 - 2rR\cos\theta - \frac{P_0/N_0}{x}\right) dr\, d\theta \\ &\Big/ \iint_{\Omega_l} \exp(-K_0 r^2)\lambda r \, dr\, d\theta \end{aligned} \quad (14)$$

where $\mathbf{1}_{\mathbb{R}^+}(\cdot)$ is the indicator function [22] with the set of positive real numbers, i.e., $\mathbb{R}^+$, given by

$$\mathbf{1}_{\mathbb{R}^+}(y) = \begin{cases} 1, & \text{if } y \in \mathbb{R}^+ \\ 0, & \text{if } y \notin \mathbb{R}^+. \end{cases}$$

The denominator in (14) is actually Λ_l derived by (9). The ratio in (14) defines the fraction of the potential relays in region Ω_l that satisfy the condition $\|R_{l,i} - D\|^\alpha \ge (P_0/N_0)/x$, for a given average received SNR x. Although there is not a complete closed-form expression to (14), it can be more efficiently calculated by the algorithm given in the Appendix.

Based on the cdf $G_{P,l}(y)$ of the transmission success probability of potential relays in region Ω_l, we can easily evaluate the average success probability by

$$\overline{P}_{RD,l} = \int_0^1 \left[1 - G_{P,l}(y)\right] dy. \quad (15)$$

The average success probability can be interpreted as the ratio of the average number of potential relays that successfully transmit to D to the overall average number of potential relays. Therefore, when $\alpha = 2$, $\overline{P}_{RD,l}$ can also be computed by (16), shown at the bottom of the next page.

B. Performance of Two-Level Backoff-Based Strategy

Combining the backoff-based strategies for both the intergroup and intragroup contentions, we have a two-level backoff-based relaying scheme. That is, a potential relay $R_{l,i}$ in region Ω_l first determines a minimum backoff time based on the location information according to (3). Then, $R_{l,i}$ estimates its transmission success probability to destination D and sets its backoff time according to (4).

As seen, the group of potential relays in region Ω_l will have an opportunity to win the intergroup contention and proceed with intragroup contention only if none of the relays in the regions closer to D has correctly received the packet. Similar to (8) and (9), we see that the number of all potential relays in regions $(\Omega_{l+1}, \ldots, \Omega_L)$ is Poisson distributed with a mean

$$\Lambda_{l+} = \frac{\lambda\phi}{K_0}\left[\exp\left(-K_0 r_l^\alpha\right) - \exp(-K_0 R^\alpha)\right], \quad 1 \le l \le L-1.$$

According to the Poisson distribution, there is no potential relay in these regions with probability

$$W_l = \begin{cases} \exp(-\Lambda_{l+}), & \text{if } 1 \le l \le L-1 \\ 1, & \text{if } l = L. \end{cases} \quad (17)$$

This is the probability that the potential relays in region Ω_l win the intergroup contention and are eligible for further intragroup contention.

A potential relay in the winning region Ω_l can estimate the transmission success probability and set its backoff time according to (4). Based on the spatial distribution of random relays, the cdf of the transmission success probability of potential relays in region Ω_l, i.e., $G_{P,l}(\cdot)$, is analyzed in Section V-A. Accordingly, the cdf of the backoff time of potential relays in Ω_l (denoted by T_l) can be obtained as

$$\begin{aligned} H_{T,l}(t) &= \Pr[T_l \le t] = \Pr\left[t_{l,\min} + (1 - P_{RD,l}) \cdot \Delta \le t\right] \\ &= \Pr\left[P_{RD,l} \ge 1 - \frac{t - t_{l,\min}}{\Delta}\right] \\ &= 1 - G_{P,l}\left(1 - \frac{t - t_{l,\min}}{\Delta}\right). \end{aligned} \tag{18}$$

The corresponding probability density function (pdf) of T_l can be easily derived by

$$\begin{aligned} h_{T,l}(t) &= \left[1 - G_{P,l}\left(1 - \frac{t - t_{l,\min}}{\Delta}\right)\right]' \\ &= \frac{1}{\Delta} g_{P,l}\left(1 - \frac{t - t_{l,\min}}{\Delta}\right) \end{aligned} \tag{19}$$

where $g_{P,l}(y) = G'_{P,l}(y)$ is the pdf of the transmission success probability for region Ω_l.

Supposing that there are M relays $(M \ge 1)$ that correctly overhear the packet in region Ω_l, we have the M-order statistics of their backoff time, which is denoted by $T_{l,(1)} < T_{l,(2)} < \cdots < T_{l,(M)}$. In [11], Bletsas *et al.* derived the joint pdf of the minimum and second minimum of M-order statistics and the probability that the difference of the minimum and second minimum is greater than a constant. Based on their conclusion, if the difference of the minimum and second minimum backoff time is greater than a constant c, the probability of no collision is given by

$$\begin{aligned} I_{l|M} &= \Pr\left[T_{l,(2)} \ge T_{l,(1)} + c\right] = M(M-1) \\ &\quad \int_{t_{l,\min}+c}^{t_{l,\min}+\Delta} h_{T,l}(t)\left[1 - H_{T,l}(t)\right]^{M-2} H_{T,l}(t-c)\, dt. \end{aligned} \tag{20}$$

Recall that $P_{l,(1)} < P_{l,(2)} < \cdots < P_{l,(M)}$ denote the M-order statistics of the transmission success probability of the potential relays in the group. Since the backoff time is chosen to be inversely proportional to the transmission success probability, the best relay corresponds to the maximum of the order statistics of the transmission success probability, i.e., $P_{l,(M)}$. The cdf of $P_{l,(M)}$ can be written as

$$\widetilde{G}_{P,l}(y|M) = \Pr\left[P_{l,(M)} \le y|M\right] = \left[G_{P,l}(y)\right]^M, \; 0 \le y \le 1$$

which is actually the probability that all of the M-order statistics, i.e., $P_{l,(1)}, \ldots, P_{l,(M)}$, are no greater than y, since $P_{l,(M)}$ is the maximum. The average transmission success probability of the best relay within the group is then given by

$$\widetilde{P}_{RD,l}(M) = \int_0^1 \left[1 - \widetilde{G}_{P,l}(y|M)\right] dy. \tag{21}$$

Thus, the relay success probability of the two-level backoff-based scheme can be expressed as

$$P_{\text{suc}}^{\text{bk}} = \sum_{l=1}^{L} \sum_{M=1}^{\infty} \frac{\Lambda_l^M}{M!} e^{-\Lambda_l} \cdot W_l \cdot I_{l|M} \cdot \widetilde{P}_{RD,l}(M). \tag{22}$$

The terms inside the double summations of (22) give the probability that a potential relay in region Ω_l successfully forwards the packet to destination D without collisions when there are totally M $(M \ge 1)$ potential relays in the same group. First, there are M potential relays in region Ω_l with probability $({\Lambda_l}^M/M!)e^{-\Lambda_l}$. Then, W_l is the probability that no relay is available in the regions $(\Omega_{l+1}, \ldots, \Omega_L)$ closer to D than Ω_l, which is given in (17); $I_{l|M}$ is the probability of no collision to the best relay in Ω_l with the shortest backoff time, which is given in (20); and $\widetilde{P}_{RD,l}(M)$ is the average transmission success probability of the best relay in Ω_l, which is given in (21).

As a potential relay determines its backoff time according to (3) and (4), intuitively, the collision probability is lower with a larger Δ, whereas a longer backoff delay is involved with the relay selection. To quantify the tradeoff between the collision probability and backoff delay, we evaluate the average backoff delay of the two-level backoff-based scheme by

$$\begin{aligned} D_{\text{sel}}^{\text{bk}} &= \sum_{l=1}^{L} W_l \cdot Q_l^{1+}\left[(L-l+1) + (1 - \overline{P}_{RD,l})\right]\Delta \\ &\quad + e^{-\Lambda_R} \cdot (F+1)\Delta \\ &= \sum_{l=1}^{L} W_l \cdot (1 - e^{-\Lambda_l})\left[(L-l+1) + (1 - \overline{P}_{RD,l})\right]\Delta \\ &\quad + e^{-\Lambda_R} \cdot (F+1)\Delta \end{aligned} \tag{23}$$

$$\begin{aligned} \overline{P}_{RD,l} &= \frac{\int_0^\phi d\theta \int_{r_{l-1}}^{r_l} \exp\left(-K_0 r^2\right) \cdot \exp\left(-K_0(r^2 + R^2 - 2rR\cos\theta)\right) \lambda r\, dr}{\int_0^\phi d\theta \int_{r_{l-1}}^{r_l} \exp\left(-K_0 r^2\right) \lambda r\, dr} \\ &= \frac{2K_0 \exp\left(-K_0 R^2\right)}{\phi\left[\exp\left(-K_0 r_{l-1}^2\right) - \exp\left(-K_0 r_l^2\right)\right]} \int_0^\phi \int_{r_{l-1}}^{r_l} \exp\left(-K_0(2r^2 - 2rR\cos\theta)\right) r\, dr\, d\theta \end{aligned} \tag{16}$$

where W_l is the probability that there is no potential relay in the regions closer to D than Ω_l, which is given in (17), and Q_l^{1+} is the probability that there is at least one potential relay in Ω_l, which can be easily obtained according to (9). Thus, $W_l \cdot Q_l^{1+}$ is the probability that the potential relays in region Ω_l are selected, whereas $[(L-l+1)+(1-\overline{P}_{RD,l})]\Delta$ is the average backoff time taken by these relays. Here, $\overline{P}_{RD,l}$ is the average transmission success probability of potential relays in region Ω_l, given in (15). The last term in (23) addresses the situation that there is no relay in the entire sector Ω_{SD} that correctly receives the packet from S. In this case, the source does not hear any forwarding signal from the relays and has to retransmit the packet by itself after a maximum backoff time $(F+1)\Delta$. The corresponding occurrence probability is $e^{-\Lambda_R}$, where Λ_R is the intensity measure of potential relays in Ω_{SD}, given by

$$\Lambda_R = \frac{\lambda\phi}{K_0}\left[1-\exp(-K_0 R^\alpha)\right]. \quad (24)$$

C. Performance of Hybrid Backoff and Probabilistic Strategy

When the backoff-based intergroup contention is considered with the probabilistic intragroup contention, we have a hybrid cooperation scheme. A potential relay $R_{l,i}$ in region Ω_l first determines a backoff time based on the location information according to (3). When the backoff timer expires and no transmission signal is overheard, $R_{l,i}$ forwards the packet to D with the probability defined in (5). According to the hybrid scheme, a relay $R_{l,i}$ in region Ω_l forwards to D successfully, only if the relays in regions $(\Omega_{l+1},\ldots,\Omega_L)$ closer to D are all silent, and $R_{l,i}$ is the only relay in Ω_l that transmits and the transmission succeeds.

Let Q_l^0 denote the probability that there is no potential relay in region Ω_l or all potential relays in Ω_l if any remain silent. Then, the probability that there is no forwarding from the relays in $(\Omega_{l+1},\ldots,\Omega_L)$ is given by $\sum_{j=l+1}^{L} Q_j^0$. Provided that all except one relay in Ω_l are silent, with the occurrence probability denoted by $\widetilde{Q}_l^0$, we represent the probability that one potential relay exists in Ω_l and transmits successfully to D by P_l^1. Thus, the relay success probability of the hybrid scheme can be expressed as

$$P_{\text{suc}}^{\text{hyb}} = \sum_{l=1}^{L}\left(\sum_{j=l+1}^{L} Q_j^0\right)\cdot \widetilde{Q}_l^0 \cdot P_l^1. \quad (25)$$

In the following, we derive Q_l^0, $\widetilde{Q}_l^0$, and P_l^1, using an approach similar to that in [7].

Consider a sufficiently small arc region centered at (r,θ) in Ω_l of an area $\delta A = r\delta r\delta\theta$. The probability that a potential relay exists in this small region and that it forwards the overheard packet is given by

$$q(r,\theta) = \lambda p(r)\tau_l(r,\theta)\delta A = \lambda e^{-K_0 r^\alpha}\left[G_{P,l}\left(e^{-K_0 r_d^\alpha}\right)\right]^{\lceil\Lambda_l\rceil-1}\delta A$$

where $p(r)$ is given by (7), and $\tau_l(r,\theta)$ refers to the forwarding probability in (5). Here, we revise the notation of $\tau_{l,i}$ to highlight its dependance on the location of the potential relay (r,θ). According to (5), we have $\tau_l(r,\theta) = [G_{P,l}(e^{-K_0 r_d^\alpha})]^{\lceil\Lambda_l\rceil-1}$, where r_d is the distance of the potential relay at (r,θ) to D, given by $r_d = \sqrt{r^2+R^2-2rR\cos\theta}$. Then, we obtain

$$\begin{aligned} Q_l^0 &= \lim_{\delta A\to 0}\prod_{(r,\theta)}\left[1-\lambda p(r)\tau_l(r,\theta)\delta A\right] \\ &= \lim_{\delta A\to 0}\exp\left\{\sum_{(r,\theta)}\log\left[1-\lambda p(r)\tau_l(r,\theta)\delta A\right]\right\} \\ &= \lim_{\delta A\to 0}\exp\left[\sum_{(r,\theta)} -\lambda p(r)\tau_l(r,\theta)\delta A\right] \\ &= \exp\left\{-\iint_{\Omega_l}\lambda p(r)\tau_l(r,\theta) r\,dr\,d\theta\right\}. \end{aligned} \quad (26)$$

Comparing the definitions of Q_l^0 and $\widetilde{Q}_l^0$, we see that Q_l^0 assumes no forwarding from any potential relay in region Ω_l, whereas $\widetilde{Q}_l^0$ assumes that all but one potential relay are silent. Considering the infinitesimal impact of excluding a single point from continuous space [7], we have $\widetilde{Q}_l^0 = Q_l^0$.

Given that no relay in $(\Omega_{l+1},\ldots,\Omega_L)$ is forwarding and that all except one relay in Ω_l are silent, we can derive the probability that one relay in Ω_l transmits to D successfully by

$$P_l^1 = \iint_{\Omega_l}\lambda p(r)\tau_l(r,\theta)e^{-K_0 r_d^\alpha} r\,dr\,d\theta. \quad (27)$$

Applying (26) and (27) to (25), we can obtain the relay success probability of the hybrid scheme. Likewise, the backoff delay of the hybrid scheme can be evaluated by

$$\begin{aligned} D_{\text{sel}}^{\text{hyb}} = \sum_{l=1}^{L}\left(\sum_{j=l+1}^{L} Q_j^0\right)\cdot\left(1-\widetilde{Q}_l^0\right)\cdot[(L-l+1)\Delta] \\ + e^{-\Lambda_R}\cdot(F+1)\Delta. \end{aligned} \quad (28)$$

Here, the potential relays in region Ω_l win the contention for forwarding only if the relays in the closer regions are all silent and at least one potential relay in region Ω_l transmits after a backoff time $(L-l+1)\Delta$. The first condition happens with probability $\sum_{j=l+1}^{L} Q_j^0$, whereas the occurrence probability of the second condition is $(1-\widetilde{Q}_l^0)$. The last term in (28) is the same as the last term in (23), which addresses the case that there is no potential relay in the entire sector Ω_{SD}.

VI. Numerical Results and Discussions

Here, we first introduce two reference cooperation schemes, including a centralized scheme with the preselected best relay and a pure probabilistic scheme. The performance achieved by the two reference schemes is considered as an upper bound and a lower bound for comparison purposes. Then, we present analysis and simulation results to validate the analytical approaches in Section V. After that, the cooperation strategies proposed in Section IV are evaluated and compared with the two reference schemes in various system settings. Finally, we investigate the impact of the contention parameters, such as L, Δ, and the region segmentation, on the relay success probability, as well as the backoff delay of relay selection.

A. Performance Upper and Lower Bounds

While the distributed solutions can reduce the coordination overhead for cooperative transmission, it is also vital to ensure a high success probability. In the following, we consider a performance upper bound, which is achieved by the preselected best relay given the global knowledge of potential relays. That is, among all potential relays in the entire sector $\Omega_{\rm SD}$, only the relay with the highest transmission success probability to D forwards the overheard packet. The relay success probability of this centralized scheme can be similarly evaluated as the approach in Section V-B. In this case, $L = 1$ with $r_0 = 0$ and $r_L = R$.

The cdf of the transmission success probability P_{RD} of all potential relays, which is denoted by $Y_P(y)$, can be calculated in the same manner as in Section V-A. With the preselection of the best relay, there is no collision, and the relay success probability only depends on the transmission success probability of the best relay. The cdf of the transmission success probability of the best relay among M potential candidates is $[Y_P(y)]^M$. Thus, we obtain the relay success probability as

$$P_{\rm suc}^{\max} = \sum_{M=1}^{\infty} \frac{\Lambda_R^M}{M!} e^{-\Lambda_R} \int_0^1 \left[1 - (Y_P(y))^M\right] dy \tag{29}$$

where the integral term gives the average transmission success probability of the preselected best relay, and Λ_R is the intensity measure of the potential relays in the entire sector $\Omega_{\rm SD}$, which is given in (24).

In addition, we consider a pure probabilistic scheme without partitioning the sector for grouping. Similar to (5), a potential relay R_i in the sector $\Omega_{\rm SD}$ independently sets its forwarding probability to

$$\tau_i = [Y_P(p_i)]^{\lceil \Lambda_R \rceil - 1} \tag{30}$$

where Λ_R is given by (24), and p_i is the local estimate of R_i for its transmission success probability to D. A collision happens if more than one relay forwards the packet. Obviously, the collision probability can be much higher since all potential relays in the entire sector contend for forwarding. Hence, we consider the performance of this pure probabilistic scheme as a lower bound.

Following the analytical approach in Section V-C, we can evaluate the relay success probability of the pure probabilistic scheme by

$$P_{\rm suc}^{\rm prob} = \widetilde{Q}_R^0 \cdot P_R^1 \tag{31}$$

where $\widetilde{Q}_R^0$ is the probability that all but one potential relay in sector $\Omega_{\rm SD}$ remain silent, and P_R^1 is the transmission success probability of the only potential relay in $\Omega_{\rm SD}$. Similar to (26), we derive $\widetilde{Q}_R^0$ by

$$\begin{aligned}\widetilde{Q}_R^0 = Q_R^0 &= \exp\left\{\iint_{\Omega_{\rm SD}} -\lambda p(r)\tau(r,\theta) r\, dr\, d\theta\right\}\\ &= \exp\left\{\iint_{\Omega_{\rm SD}} -\lambda e^{-K_0 r^\alpha}\left[Y_P(e^{-K_0 r_d^\alpha})\right]^{\lceil \Lambda_R \rceil - 1} r\, dr\, d\theta\right\}.\end{aligned}$$

TABLE I
SYSTEM PARAMETERS

Symbol	Value	Definition
λ	$0.001 \sim 0.025$	Intensity function of relay distribution
P_0/N_0	40 dB	Transmit SNR
T_0	4	Decoding SNR threshold
R	$50 \sim 90$ m	Source-destination distance
ϕ	$30^\circ \sim 90^\circ$	Directional angle toward destination
L	$1 \sim 16$	Number of region partitions of the sector between S and D
Δ	$4 \sim 22$	Backoff time unit for inter-group contention
c	1	Collision threshold for backoff time of intra-group contention
q	0.7	Point of maximum growth rate of generalized logistic function
μ	22.2326	Parameter of generalized logistic function
ν	2.1780	Parameter of generalized logistic function

Likewise, P_R^1 is obtained from (27) as

$$\begin{aligned}P_R^1 &= \iint_{\Omega_{\rm SD}} \lambda p(r)\tau(r,\theta) e^{-K_0 r_d^\alpha} r\, dr\, d\theta\\ &= \iint_{\Omega_{\rm SD}} \lambda e^{-K_0 r^\alpha}\left[Y_P(e^{-K_0 r_d^\alpha})\right]^{\lceil \Lambda_R \rceil - 1} e^{-K_0 r_d^\alpha} r\, dr\, d\theta.\end{aligned}$$

B. CDF of Transmission Success Probability

In Section V-A, we introduce an analytical approach to evaluate the cdf of the transmission success probability of potential relays in a region. This cdf can be efficiently calculated by the algorithm in the Appendix. As the forwarding probability and the performance analysis depend on this cdf, we need to validate the accuracy of the calculation algorithm. Considering the system parameters in Table I, we conduct extensive numerical analysis and computer simulations by MATLAB 8.1.0 (R2013a) [23].

Taking the entire sector between S and D, i.e., $\Omega_{\rm SD}$, as an example, we can get the cdf $Y_P(y)$, $0 \le y \le 1$. Fig. 3 shows the distribution that the transmission success probability of potential relays, i.e., P_{RD}, falls into small intervals within $[10^{-3}, 1]$. For example, the probability that $y_1 \le P_{RD} \le y_2$ is given by $Y_P(y_2) - Y_P(y_1)$. As such, we can clearly compare the analysis results with the simulation results. As shown in Fig. 3, they match quite well. The average difference is around 4.5%. Since we run the simulations for 100 rounds to remove the randomness effect, the minor difference is mainly due to the errors with the numerical evaluation of the integrals in (38) and (40) without closed-form expressions.

Similarly, we can evaluate the cdf $G_{P,l}(y)$ of transmission success probability $P_{RD,l}$ for each strip region Ω_l. Based on $G_{P,l}(y)$, the average transmission success probability $\overline{P}_{RD,l}$ of potential relays in Ω_l can be computed by (15). Fig. 4 shows $\overline{P}_{RD,l}$ of each contention region. As shown, the analysis results are validated by the simulation results. The small calculation error is bounded within the range (0.27%, 1.88%). It is worth mentioning that Fig. 4 is based on segmentations that partition the entire sector into concentric arcs of an equal area. The equal-area segmentation is also used in Figs. 5–8.

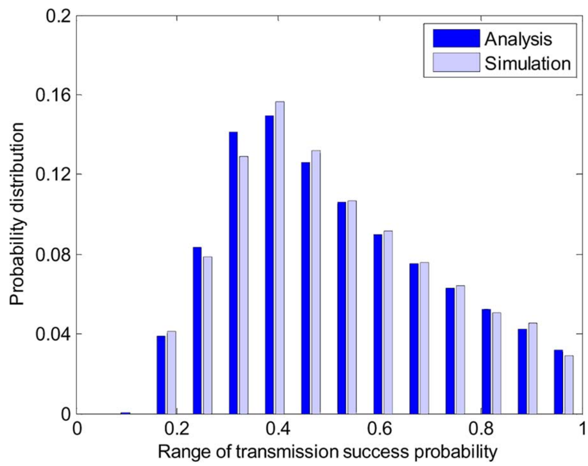

Fig. 3. Distribution of transmission success probability of potential relays in $\Omega_{\rm SD}$ ($\lambda = 10^{-2}$, $R = 70$, and $\phi = 45^\circ$).

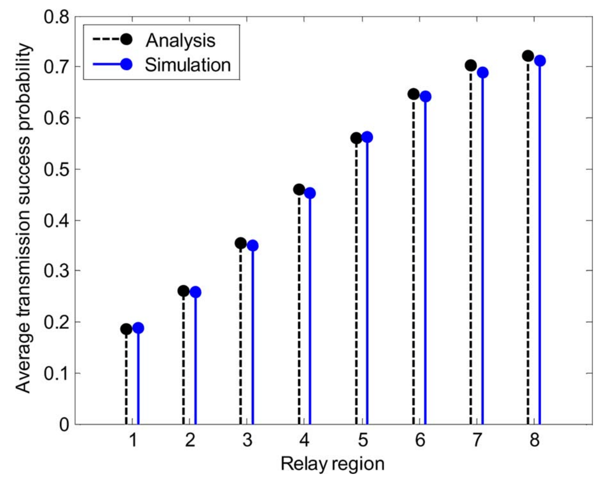

Fig. 4. Average transmission success probability of potential relays in each region Ω_l ($\lambda = 10^{-2}$, $R = 70$, $\phi = 45^\circ$, and $L = 8$).

C. Analytical Accuracy of Relay Success Probability

Jointly considering the intergroup and intragroup contentions, we propose two distributed cooperation strategies in Section IV, which exploit both the location information and local estimate of transmission success probability. The first strategy is a two-level backoff-based scheme, whose relay success probability can be analytically evaluated by (22). The second strategy is a hybrid scheme with backoff-based intergroup contention and probabilistic intragroup contention. The relay success probability of the hybrid scheme is analyzed by (25). For the two reference schemes introduced in Section VI-A, the scheme with the preselected best relay can achieve a performance upper bound, whereas the performance of the pure probabilistic scheme without grouping is considered as a lower bound due to more collisions. Fig. 5 shows the analysis results and simulation results of the two proposed schemes and the two reference schemes. Note that the relay success probability in Fig. 5 only accounts for the forwarding success via potential relays. The overall packet success probability can be even higher, considering the successful direct transmission from S to D. Since the cooperative relaying strategies only differ in the forwarding phase via the relays, we focus on the relay success probability to highlight the difference of these relaying strategies. As shown, the analysis and simulation results match well, and our analytical approaches are quite accurate.

D. Relay Success Probability Versus λ, R, and ϕ

In addition, Fig. 5 compares the performance of the proposed schemes with the upper and lower bounds of the reference schemes with respect to the relay intensity. As shown, the proposed cooperation schemes greatly outperform the pure probabilistic scheme, whose maximum relay success probability is limited to 0.3496. On average, the relay success probability of the two-level backoff-based scheme is 1.07 times higher than that of the pure probabilistic scheme, whereas the average performance gain of the hybrid scheme with adaptation is 85.3%.

Moreover, it is observed in Fig. 5 that the two-level backoff-based scheme achieves a stable relay success probability and well outperforms the hybrid scheme when the relay intensity is relatively low. In particular, the relay success probability of the two-level backoff-based scheme first increases fast with the relay intensity and then decreases slightly. When the relay intensity is larger, there are more contending potential relays in each group. On one hand, more relays of good channel conditions to the destination likely exist. On the other hand, the contention among more relays can lead to a higher collision probability. Hence, when the relay intensity is sufficiently high, the gain of locating good relays is offset by the increased collisions, and the relay success probability even decreases slightly with λ.

It is also noticed in Fig. 5 that the performance of the hybrid scheme does not vary with the relay intensity as smoothly as the other schemes. This is not due to the randomness effect since we run the simulations for 100 rounds and the simulation results match well the validated analysis results. This fluctuation is mainly because each relay determines its forwarding probability based on the average number of contending potential relays in a region (Λ_l). The forwarding probability $\tau_{l,i}$ in (5) uses the ceiling function to Λ_l and causes the truncation effect. The performance can be improved if each relay knows the exact number of relays in contention. However, extra overhead will be introduced to acquire such information, which also harms the distributed nature of the cooperation strategy.

In addition, Fig. 5 clearly shows the difference between the two cases of the hybrid scheme with and without using the logistic function in (6) to adapt the forwarding probability. As shown, the relay success probability of both cases is much lower than that of the two-level backoff-based scheme when the relay intensity is relatively low. This implies that the relays are overconservative with a small forwarding probability in such scenarios. By using the logistic function to adapt the forwarding probability, the hybrid scheme approaches and even slightly exceeds the high performance of the two-level backoff-based scheme when $\lambda > 0.0134$. As shown in Fig. 2, the logistic function can suppress the forwarding probability of poor relays of low transmission success probability and promote the forwarding probability of good relays. Consequently, the adaptation can ensure a high forwarding probability for very

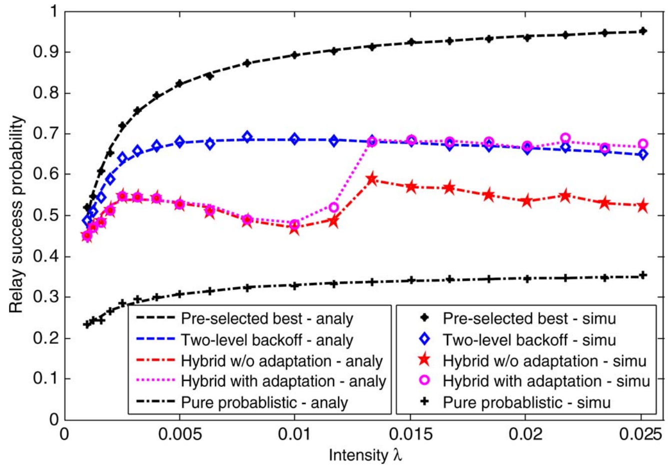

Fig. 5. Relay success probability of different schemes versus relay intensity λ ($R = 70$, $\phi = 45^\circ$, $L = 8$, and $\Delta = 16$).

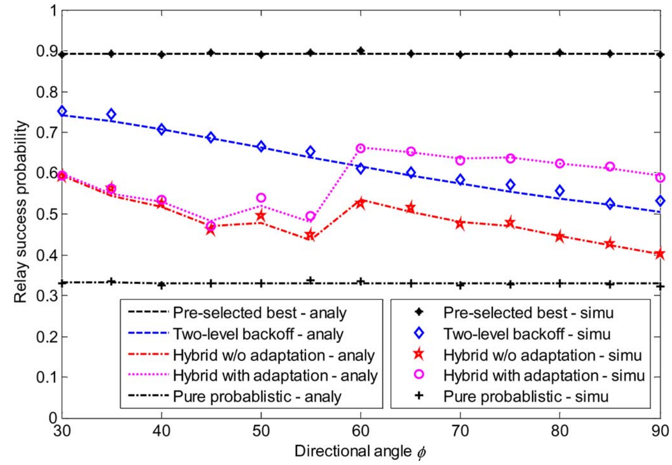

Fig. 7. Relay success probability of different schemes versus directional angle ϕ ($\lambda = 10^{-2}$, $R = 70$, $L = 8$, and $\Delta = 16$).

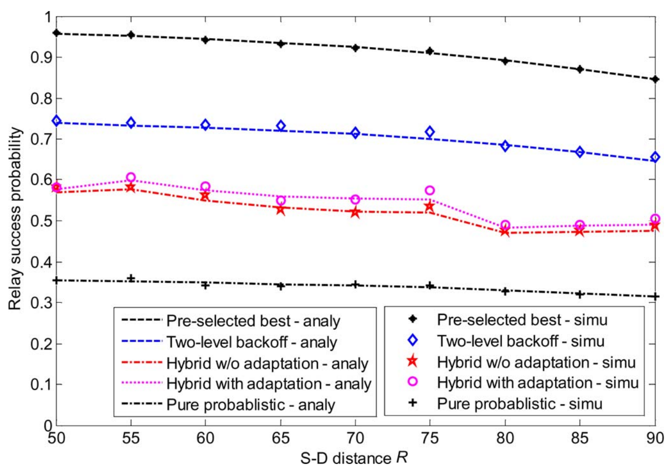

Fig. 6. Relay success probability of different schemes versus $S{-}D$ distance R ($\lambda = 10^{-2}$, $\phi = 45^\circ$, $L = 8$, and $\Delta = 16$).

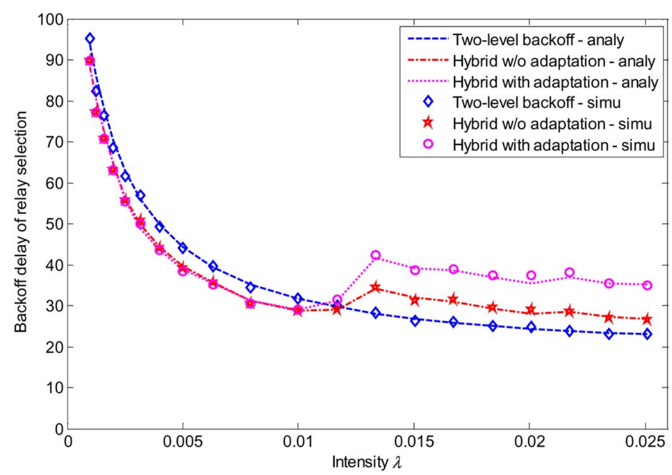

Fig. 8. Average backoff delay of relay selection of different schemes versus relay intensity λ ($R = 70$, $\phi = 45^\circ$, $L = 8$, and $\Delta = 16$).

selective good relays and, thus, mitigate the collisions among a large number of contending relays.

Fig. 6 shows the variation of the four relaying schemes with respect to the $S{-}D$ distance R. As shown, the relay success probability of all schemes slowly degrades with the increase of R. This is intuitive since a larger $S{-}D$ distance results in a higher path loss.

Fig. 7 shows the variation of the four schemes with directional angle ϕ for sector $\Omega_{\rm SD}$. As expected, the preselected best relay scheme and the pure probabilistic scheme are insensitive to ϕ, given the relay spatial distribution as a homogenous PPP. The two-level backoff-based scheme has a higher relay success probability with a smaller ϕ. This is because, when the relay region is more narrowly tuned toward the destination, the potential relays are closer to D, and there are less collisions with fewer relays in the smaller arc region. Nonetheless, Fig. 7 considers a relatively high relay intensity, and it is not always true that the smaller ϕ the better. When the relay intensity is low, there may not be sufficient good relays in the small region, which can degrade the relay success probability. The hybrid scheme without adaptation using the logistic function also shows a decreasing trend with ϕ in the long run. Meanwhile, there is slight fluctuation due to the truncation effect of the ceiling function for the forwarding probability. When the logistic function is used to adapt the forwarding probability, the relay success probability first decreases with ϕ, then increases fast to the highest at $\phi = 60^\circ$, and finally decreases slowly beyond that. This is because the logistic function takes a better effect when there are more relay candidates in a larger relay region with a larger ϕ. The analytical approaches in Section V can characterize the impact of various system parameters on the achievable performance and be used to adjust the setting of ϕ.

E. Backoff Delay of Proposed Cooperation Schemes

As shown in Section VI-D, the relay success probability varies with the system parameters λ, R, and ϕ in different manners. In Section V, we also analyze another aspect of the relay performance in terms of the average backoff delay of relay selection. Fig. 8 shows the analysis and simulation results for the backoff delay of the proposed cooperation schemes. As shown, the analysis results match well the simulation results, which validates the accuracy of our analytical approaches.

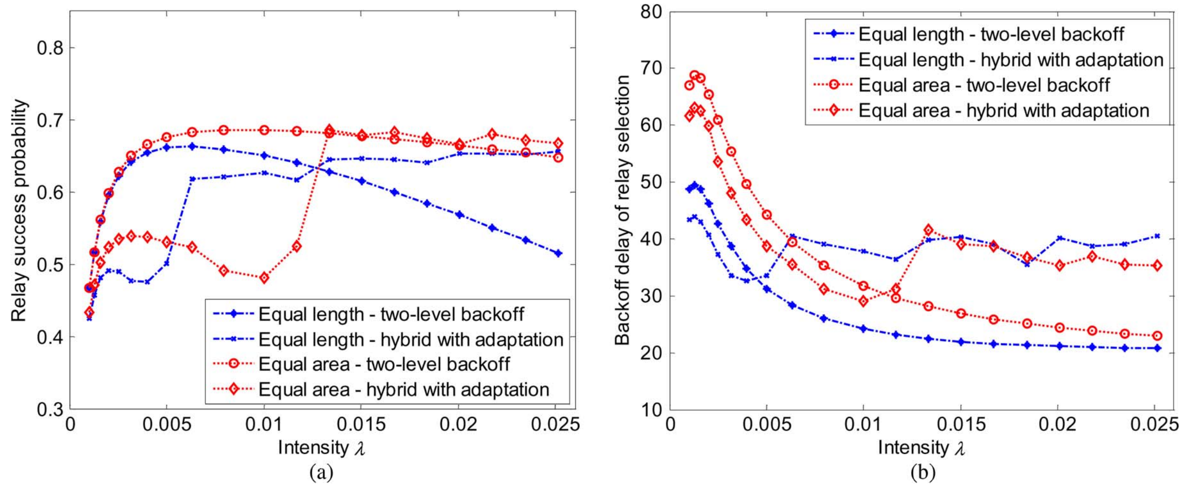

Fig. 9. Relay performance of the proposed cooperation schemes with different region segmentations. (a) Relay success probability. (b) Average backoff delay.

Moreover, it is found in Fig. 8 that, when the relay intensity is low, the hybrid scheme takes a shorter backoff time before any potential relay, or the source starts the retransmission. This is because the backoff delay is mainly attributed to the backoff-based intergroup contention since the hybrid scheme uses the probabilistic strategy for the intragroup contention. Nonetheless, it is observed in Fig. 5 that the hybrid scheme achieves a smaller relay success probability when the relay intensity is low. Hence, we can see the tradeoff between the relay success probability and the backoff delay. On the other hand, when there is a high relay intensity, the hybrid scheme involves a backoff delay longer than that of the two-level backoff-based scheme, whereas the relay success probability of the hybrid scheme with adaptation is very close to that of the two-level backoff-based scheme. This implies that the hybrid scheme does not guarantee that the winning relay is located in a region closer to the destination with a shorter backoff time. Even so, the logistic function can adapt the forwarding probability of the relays so that only few best relays can maintain high forwarding probabilities, which ensures fewer collisions and more successful transmissions.

F. Relay Success Probability and Backoff Delay With Different Configurations

The performance of the proposed cooperation schemes not only varies with system parameters λ, R, and ϕ but depends on the configurations such as the region segmentation $\vec{\mathbf{r}} = [r_0, r_1, r_2, \ldots, r_L]$, the number of groups L, and the backoff time unit for intergroup contention Δ as well. In the following, we examine the impact of different configurations on the relay performance.

As given in Section IV, we partition the entire sector Ω_{SD} into L groups, whose radius boundaries are defined by vector $\vec{\mathbf{r}}$. In addition to the equal-area segmentation considered in Figs. 4–8, another natural idea for grouping is to divide the source–destination distance R into L equal-length segments. Fig. 9 compares the relay performance of the two different configurations. As shown in Fig. 9(a), for the two-level backoff-based scheme, the equal-area segmentation achieves a higher relay success probability than the equal-length segmentation. Intuitively, the number of potential relays in each region should be comparable since the contention interval Δ for each region is the same. As the relays are deployed in sector Ω_{SD} as a homogeneous PPP of intensity λ, the number of relays in a region is proportional to the region area. Hence, the equal-area segmentation is preferable for the two-level backoff-based scheme. Nonetheless, it is observed in Fig. 9(b) that the equal-area segmentation results in a larger backoff delay. Compared with the equal-length segmentation, the equal-area segmentation allocates more relays to the groups farther away from the destination, which take a longer backoff time. As a result, the backoff delay of equal-area segmentation is larger on average.

On the other hand, for the hybrid scheme, the equal-area segmentation achieves a relay success probability higher than that of the equal-length segmentation when the relay intensity is very low and very high. The equal-length segmentation only outperforms the equal-area segmentation when the relay intensity is in the middle range of (0.005, 0.0117). Similar to the two-level backoff-based scheme, equal-length and equal-area segmentations for the hybrid scheme also exhibit opposite trends regarding relay success probability and backoff delay.

Fig. 10 shows the dependence of performance on the configurations of L and Δ when the relay intensity is relatively low and high. As shown in Fig. 10(a) and (b) for $\lambda = 0.001$, both the relay success probability and backoff delay increases with the number of groups L. This is intuitive since the number of contending relays decreases with more groups, which results in a lower collision probability but a longer backoff time with a constant intragroup contention interval Δ. Moreover, it is observed in Fig. 10(a) and (b) that the two-level backoff-based scheme has a higher relay success probability and backoff delay with a larger Δ. However, the increase becomes minor when L and Δ are sufficiently large. In contrast, the relay success probability of the hybrid scheme is insensitive to Δ. Given sufficient time separation among the groups, there is no intergroup collision, whereas the probabilistic intragroup contention of the hybrid scheme is obviously irrelevant to Δ. Nevertheless, because the same backoff-based intergroup

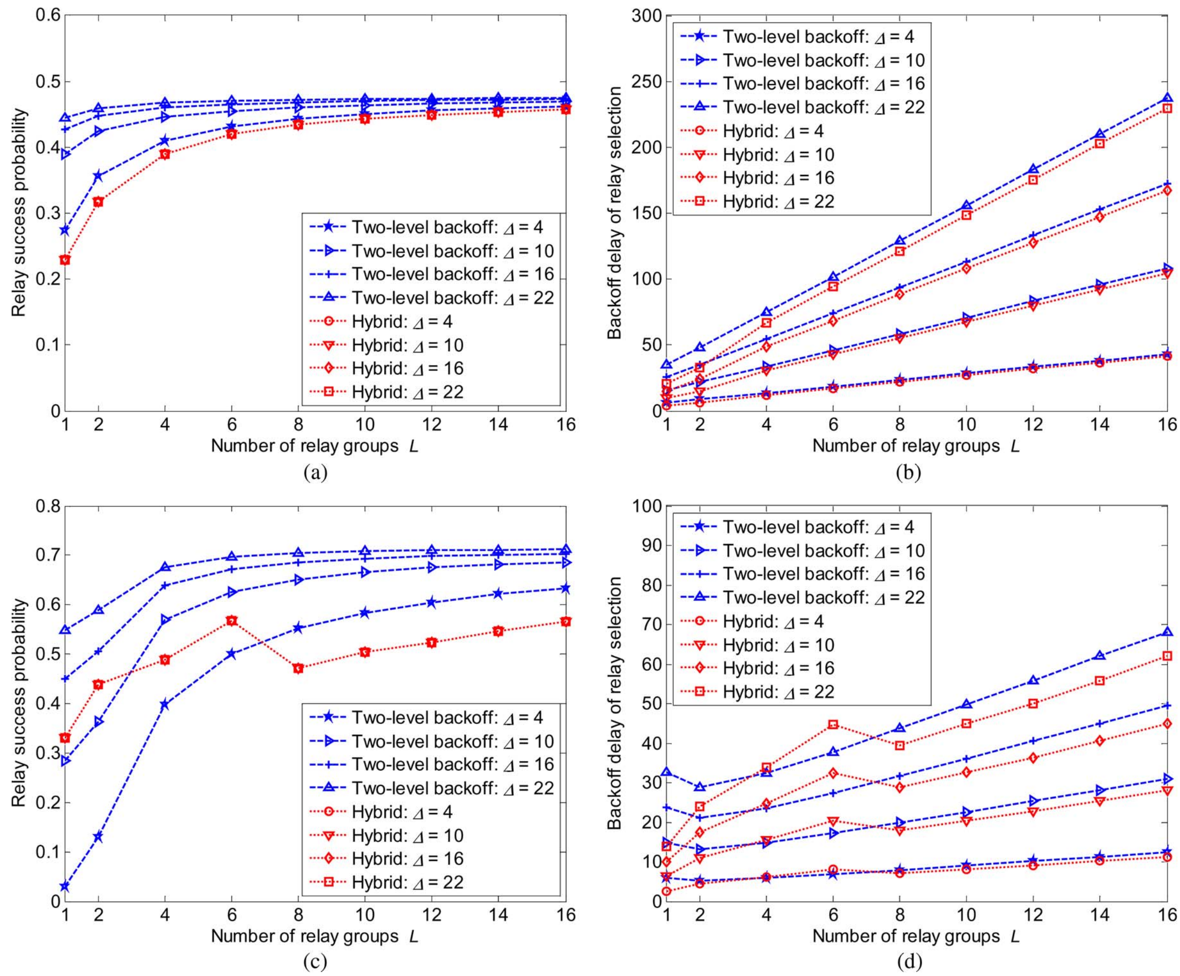

Fig. 10. Relay performance of the proposed cooperation schemes with different L and Δ ($\lambda = 0.001$, 0.01). (a) Relay success probability ($\lambda = 0.001$). (b) Average backoff delay ($\lambda = 0.001$). (c) Relay success probability ($\lambda = 0.01$). (d) Average backoff delay ($\lambda = 0.01$).

contention is used, the backoff time of the hybrid scheme also increases with Δ in the long run.

Fig. 10(c) and (d) shows the variation of the relay success probability and backoff delay with L and Δ for $\lambda = 0.01$. We can see that the two-level backoff-based scheme presents increasing trends with L and Δ similar to Fig. 10(a) and (b). In contrast, the hybrid scheme shows more fluctuations. While the relay success probability increases with L in the long run, there is some temporary dropping. This implies that the truncation effect of the forwarding probability can be exacerbated when the relay intensity is relatively high. Although the relay success probability of the hybrid scheme in Fig. 10(c) is the highest at $L = 6$, the corresponding backoff time is also at peak among the adjacent cases of L.

VII. Conclusion and Future Work

In this paper, we have studied opportunistic cooperative relaying with spatially random relays. In particular, we have derived the probability distributions of the transmission success probability of spatially distributed relays and proposed two distributed relaying strategies that exploit such statistics. In the two-level backoff-based scheme, each relay independently sets a backoff time according to the location information and its transmission success probability to D. In the other hybrid backoff and probabilistic scheme, each relay first determines a backoff time according to the location information and then a forwarding probability based on its transmission success probability to D. The forwarding probability can be further adapted with a generalized logistic function to suppress poor relays and promote good relays.

In addition, we have analytically evaluated the performance of the proposed schemes in terms of the relay success probability and average backoff delay of relay selection. The analysis accuracy is well validated by simulations. We also considered a centralized scheme with the preselected best relay as an upper bound and a pure probabilistic scheme as a lower bound. The proposed schemes were compared with the two reference schemes in a variety of system settings, and significant performance gain is observed over the pure probabilistic scheme. Furthermore, we examined the impact of the configurations of $\vec{\mathbf{r}}$, L, and Δ on the relay performance. The proposed analytical approaches can be used to determine appropriate configurations that balance the tradeoff between relay success probability and backoff delay.

In the future, we are interested in further addressing energy efficiency for this opportunistic cooperative scenario. Specifically, given the spatial distribution of random relays, an

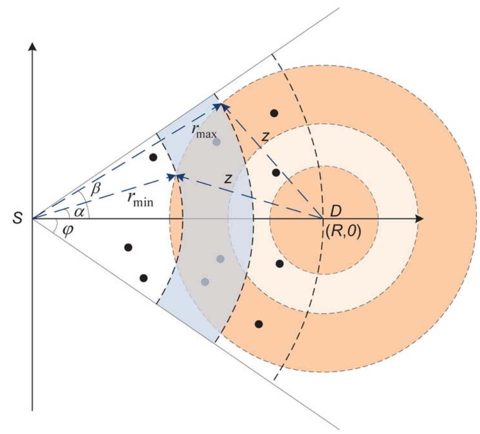

Fig. 11. Calculation of $F_{\Gamma,l}(x)$.

intelligent thinning process can be put in place to deactivate certain relays in advance. The thinning process needs to minimize the number of active relays to save energy, while it should ensure that a sufficient number of good relays are available and properly distributed. Moreover, we are also studying an extended scenario, in which multiple pairs of sources and destinations share a group of relays in an opportunistic manner. The energy constraints of the shared relays then become another critical factor to be considered in coordinating the packet forwarding.

Appendix
Calculation of the CDF $F_{\Gamma,l}(x)$ of $\Gamma_{RD,l}$

The cdf of the average received SNR at D for the forwarded signal from a potential relay in region Ω_l is defined in (14), which can be rewritten as

$$F_{\Gamma,l}(x) = \frac{1}{\Lambda_l} \iint_{\Omega_l} \exp(-K_0 r^2)\lambda r \times \mathbf{1}\left(r^2 + R^2 - 2rR\cos\theta \geq \frac{P_0/N_0}{x}\right) dr\, d\theta. \tag{32}$$

Since region Ω_l is symmetric to the x-axis, we can focus on the half strip above the x-axis for $0 \leq \theta \leq \phi$ and define the above double integral as $2A_\Gamma(x)$.

As shown in Fig. 11, we refer to a circle centered at D of radius $z = \sqrt{(P_0/N_0)/x}$ as D_z and define $r_{\min} = r_{l-1}$ and $r_{\max} = r_l$. According to the indicator function in (32), $A_\Gamma(x)$ depends on the area of region Ω_l outside the circle D_z. The shaded blue strip in Fig. 11 represents a specific region Ω_l under consideration. There are three cases of this region Ω_l with respect to $r_{\min}$, $r_{\max}$, and $R - z$. They are illustrated by the three dashed circles centered at D, from the smallest to the largest, respectively. First, when $R - z \geq r_{\max}$, obviously, $F_{\Gamma,l}(x) = 1$, since the entire circle D_z is outside Ω_l. Second, when $r_{\min} \leq R - z \leq r_{\max}$, the circle D_z overlaps with the right arc of region Ω_l, and its angle to the origin falls within $[\alpha, \beta]$, where $\alpha = 0$, and

$$\beta = \arccos\left(\frac{R^2 + r_{\max}^2 - z^2}{2Rr_{\max}}\right). \tag{33}$$

Third, when $R - z \leq r_{\min}$, the dashed arrow lines illustrate the corresponding situation with $r_{\min}$, $r_{\max}$, and z. Different from the second case, D_z overlaps with both arcs of Ω_l, and the overlapped arc of D_z has an angle to the origin within $[\alpha, \beta]$, where β is defined in (33), and α is given by

$$\alpha = \arccos\left(\frac{R^2 + r_{\min}^2 - z^2}{2Rr_{\min}}\right). \tag{34}$$

In the following, we derive $A_\Gamma(x)$ for $r_{\min} \leq R - z \leq r_{\max}$ and $R - z \leq r_{\min}$, assuming $\phi \geq \max(\alpha, \beta)$. The same approach can be easily used to analyze other cases of ϕ. On one hand, when $\alpha \leq \beta$, e.g., $\alpha = 0 \leq \beta$ if $r_{\min} \leq R - z \leq r_{\max}$, we have

$$A_\Gamma(x) = \int_\beta^\phi d\theta \int_{r_{\min}}^{r_{\max}} \exp(-K_0 r^2)\lambda r\, dr + \int_\alpha^\beta d\theta \int_{r_{\min}}^{r(\theta)} \exp(-K_0 r^2)\lambda r\, dr \tag{35}$$

where $r(\theta)$ depicts the arc of D_z inside Ω_l, and it satisfies

$$z^2 = R^2 + r^2 - 2Rr\cos\theta. \tag{36}$$

Solving this quadratic equation, we have

$$r(\theta) = \begin{cases} R\cos\theta - \sqrt{z^2 - R^2\sin^2\theta}, & \text{if } \alpha \leq \beta \\ R\cos\theta + \sqrt{z^2 - R^2\sin^2\theta}, & \text{if } \alpha > \beta. \end{cases} \tag{37}$$

Then, (35) can be expressed as

$$\begin{aligned} A_\Gamma(x) &= \frac{\lambda(\phi-\beta)}{2K_0}\left[\exp\left(-K_0 r_{\min}^2\right) - \exp\left(-K_0 r_{\max}^2\right)\right] \\ &\quad + \int_\alpha^\beta \frac{\lambda}{2K_0}\exp\left(-K_0 r_{\min}^2\right) d\theta \\ &\quad - \int_\alpha^\beta \frac{\lambda}{2K_0}\exp\left(-K_0 r^2(\theta)\right) d\theta \\ &= \frac{\lambda(\phi-\alpha)}{2K_0}\exp\left(-K_0 r_{\min}^2\right) \\ &\quad - \frac{\lambda(\phi-\beta)}{2K_0}\exp\left(-K_0 r_{\max}^2\right) \\ &\quad - \int_\alpha^\beta \frac{\lambda}{2K_0}\exp\left(-K_0\left(z^2 + R^2\cos(2\theta)\right)\right) \\ &\qquad \times \exp\left(K_0\left(2R\cos\theta\sqrt{z^2 - R^2\sin^2\theta}\right)\right) d\theta. \end{aligned} \tag{38}$$

On the other hand, when $R - z \leq r_{\min}$ it is possible that $\alpha > \beta$. Similarly, we can write $A_\Gamma(x)$ as

$$A_\Gamma(x) = \int_\alpha^\phi d\theta \int_{r_{\min}}^{r_{\max}} \exp(-K_0 r^2)\lambda r\, dr + \int_\beta^\alpha d\theta \int_{r(\theta)}^{r_{\max}} \exp(-K_0 r^2)\lambda r\, dr. \tag{39}$$

Referring to (37) for $r(\theta)$ when $\alpha > \beta$, we simplify (39) to

$$\begin{aligned} A_\Gamma(x) =& \frac{\lambda(\phi-\alpha)}{2K_0}\left[\exp\left(-K_0 r_{\min}^2\right) - \exp\left(-K_0 r_{\max}^2\right)\right] \\ & - \int_\beta^\alpha \frac{\lambda}{2K_0}\exp\left(-K_0 r_{\max}^2\right) d\theta \\ & + \int_\beta^\alpha \frac{\lambda}{2K_0}\exp\left(-K_0 r^2(\theta)\right) d\theta \\ =& \frac{\lambda(\phi-\alpha)}{2K_0}\exp(-K_0 r_{\min}^2) \\ & - \frac{\lambda(\phi-\beta)}{2K_0}\exp(-K_0 r_{\max}^2) \\ & + \int_\beta^\alpha \frac{\lambda}{2K_0}\exp\left(-K_0\left(z^2+R^2\cos(2\theta)\right)\right) \\ & \times \exp\left(-K_0\left(2R\cos\theta\sqrt{z^2-R^2\sin^2\theta}\right)\right) d\theta. \quad (40) \end{aligned}$$

As (39) and (40) can efficiently evaluate $A_\Gamma(x)$, we have the cdf of the average received SNR of potential relays given by $F_{\Gamma,l}(x) = 2A_\Gamma(x)$. Then, according to (12), we can obtain the cdf of the transmission success probability of potential relays in region Ω_l, i.e., $G_{P,l}(y)$.

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Wei Song (M'09) received the Ph.D. degree in electrical and computer engineering from the University of Waterloo, Waterloo, ON, Canada, in 2007.

From 2008 to 2009, she was a Postdoctoral Research Fellow with the Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA, USA. In 2009, she joined the Faculty of Computer Science, University of New Brunswick, Fredericton, NB, Canada, where she is currently an Associate Professor. Her current research interests include the heterogeneous interworking of wireless networks, cooperative wireless networking, mobile hotspots, and cross-layer design for multimedia service provisioning.

Peijian Ju received the B.Eng. and M.Eng. degrees from Huazhong University of Science and Technology, Wuhan, China, in 2009 and 2011, respectively. He is currently working toward the Ph.D. degree with the University of New Brunswick, Fredericton, NB, Canada.

His research interests include the physical and medium access control layers of cooperative wireless networks and game theory for cooperative networks.

A-Long Jin received the B.Eng. degree in communications engineering from Nanjing University of Posts and Telecommunications, Nanjing, China, in 2012. He is currently working toward the M.S. degree with the University of New Brunswick, Fredericton, NB, Canada.

His primary research interests include cooperative wireless networks, machine learning, and optimization.

Yu Cheng (S'01–M'04–SM'09) received the B.E. and M.E. degrees in electronic engineering from Tsinghua University, Beijing, China, in 1995 and 1998, respectively, and the Ph.D. degree in electrical and computer engineering from the University of Waterloo, Waterloo, ON, Canada, in 2003.

From 2004 to 2006, he was a Postdoctoral Research Fellow with the Department of Electrical and Computer Engineering, University of Toronto, Toronto, ON, Canada. Since 2006, he has been with the Department of Electrical and Computer Engineering, Illinois Institute of Technology, Chicago, IL, USA, where he is currently an Associate Professor. His research interests include next-generation Internet architectures and management, wireless network performance analysis, network security, and wireless/wireline interworking.