Uncoordinated Cooperative Communications with Spatially Random Relays

Chao Zhai, *Student Member, IEEE,* Wei Zhang, *Senior Member, IEEE,* and Guoqiang Mao, *Senior Member, IEEE*

***Abstract*—In the traditional cooperative communication scenario, coordination is required among relay nodes to help data transmission through distributed signal transmission or coding techniques. For large cooperative networks, the overhead for coordination is huge and the synchronization among relays is very difficult. In this paper, we propose uncoordinated cooperative communication strategies in a large wireless network that do not need the coordination among relays while realizing cooperative diversity for the source-destination link. Without a central controller, all relays that are spatially randomly placed contend for the channel to relay the packet from source to destination in a distributed fashion. The competition for the channel access is governed by the retransmission probability that is independently calculated by the relays according to the location or channel quality information. Three schemes of uncoordinated cooperative communications are proposed to determine the retransmission probabilities of the potential relays based on the local distance, direction, and channel quality, referred to as distance based, sectorized, and local SNR based scheme, respectively. Success probabilities for the proposed uncoordinated schemes are analyzed. Numerical and simulation results show that the local SNR based scheme has the best performance, and the distance based scheme outperforms the sectorized scheme.**

***Index Terms*—Cooperative communications, diversity technique, relay, stochastic geometry, truncated ARQ.**

I. Introduction

COOPERATIVE automatic repeat request (ARQ) with best relay selection [1]–[5] is an attractive technique that can significantly improve the link throughput by forwarding the data using the best available relay node when the original transmission between source and destination fails. Moreover, space diversity can be achieved by allowing relays to do the retransmission, because the probability of relay-destination and source-destination channels undergoing deep fading simultaneously is very small. However, for the explicit relay selection [6], a global knowledge of all relay metrics is needed for the source to determine which relay is the best. The overhead of exchanging the metric values, resource allocation results, and source decisions, etc. is usually very heavy, that is contrary to the goal of improving the spectral efficiency. Furthermore, if the channel coherence time is short, it is suboptimal to choose the best relay based on the outdated channel information obtained in the previous time slot. In the opportunistic relaying scheme [7], every relay node should monitor the instantaneous channel state towards the source and the destination, and determines whether it is the best or not via executing a back-off mechanism. However, the high overhead of coordination or synchronization becomes prohibitive when the network size is large, as the frequent coordination may negate any potential performance gains.

The coordinated cooperative ARQ schemes are widely studied and they are briefly reviewed here. In the hybrid-ARQ-based intra-cluster geographic relaying (HARBINGER) scheme, the relays maintain and combine all the received information for the retransmission until the destination successfully decodes the message [1]. For the node-cooperative stop and wait (NCSW) ARQ scheme [2], all the neighboring nodes that have enough resources can assist the source by retransmitting the data frame simultaneously. The adaptively selected relay and the source will jointly perform the retransmission using the distributed space-time coding [8]. However, synchronization between the best relay and the source is not straightforward. In order to maximize the spectral efficiency under the delay and error performance constraints, Liu *et al*. developed a cross-layer design scheme which combines adaptive modulation and coding at the physical layer with truncated ARQ at the data link layer [3]. For the wireless network composed of one source, one relay and one destination, three cooperative truncated ARQ protocols which combine incremental relaying and selection relaying were proposed in [4]. Based on the legacy IEEE 802.11 MAC, the persistent relay carrier sensing multiple access (PRCSMA) protocol is proposed to resolve the scheduling and medium access problems among the relays via a distributed cooperative ARQ scheme [5].

With a priori knowledge about the spatial distribution of the nodes, an optimal uncoordinated cooperation strategy is studied in [9] to maximize the probability of success decoding. In [9], a relay is automatically selected to do the retransmission without any coordination, and the performance is shown to be comparable to or even better than the scheme with relays preselected. Ganti *et al.* proposed four heuristic decentralized uncoordinated relay selection methods to forward the source data to the destination in a two-hop TDMA wireless system [10]. However, the retransmission probability of each relay is directly defined without theoretical backing. In [10], multiple concurrent transmissions are considered with interference caused on each other, and the success probability is approximately analyzed.

In this paper, considering the communication between a pair of source and destination, we propose three uncoordinated

C. Zhai and W. Zhang are with the School of Electrical Engineering and Telecommunications, The University of New South Wales, Sydney, Australia (e-mail: chao.zhai@student.unsw.edu.au; wzhang@ee.unsw.edu.au). Their research was supported under Australian Research Council's Discovery Projects funding scheme (project number DP1094194 and DP120102030). Part of this work was presented at the IEEE International Conference on Communications (ICC), Ottawa, Canada, June 2012.

G. Mao is with the School of Electrical and Information Engineering, The University of Sydney, Australia (e-mail: guoqiang.mao@sydney.edu.au).

cooperative truncated ARQ schemes based on the local information of relay position or channel SNR, i.e., the distance based scheme, the sectorized scheme, and the local SNR based scheme. If the original transmission between the source and the destination fails, each potential relay accesses the channel independently according to its own retransmission probability without any coordination with other nodes. With prior knowledge of the network parameters, such as node density and transmission power etc., the retransmission probability of each potential relay is judiciously computed in a distributed fashion. If none of the relays successfully access the channel, the source will perform the retransmission. Collision does not occur if the retransmission is performed by only one node, i.e., either one potential relay or the source. The destination node combines the original erroneously received signal from the source and the retransmitted signal from either the potential relay or the source using the maximal ratio combining (MRC) technique. System success probabilities are derived for the sectorized and local SNR based schemes, respectively. Numerical results show that the proposed local SNR based scheme has the best performance, while the distance based scheme outperforms the sectorized scheme. The uncoordinated cooperation schemes always outperform the traditional truncated ARQ scheme with the source performing the possible retransmissions.

The rest of this paper is organized as follows. In Section II, the system model and relay protocol is introduced. In Section III, three uncoordinated cooperative truncated ARQ schemes are proposed and the retransmission probabilities are studied. Section IV derives the system success probabilities of the sectorized and local SNR based schemes. Numerical and simulation results are given in Section V. Finally, Section VI concludes this paper.

II. System Model and Relay Protocol

We consider the wireless communication between one source node (denoted by S) and one destination node (denoted by D), which is assisted by the intermediate relay nodes if necessary. Each relay node makes decision independently on whether to participate in the cooperative communication without any coordination with other nodes.

A. System Model

In our system model, the locations of source and destination are fixed, and the distance between them is a deterministic value R. The relay nodes are modeled as a homogeneous Poisson Point Process (PPP) Φ with intensity λ. The source and destination do not belong to the point process Φ. For the data transmission between a certain transmitter located at x and a certain receiver located at y, the SNR of the received signal is written as

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

where P_0 is the transmission power, N_0 denotes the power of AWGN, and h_{xy} represents the small-scale channel fading which is exponentially distributed with unit mean. The path-loss coefficient is modeled as $g_{xy} = \|x-y\|^{-\alpha}$, where $\|x-y\|$ is the Euclidean distance, and α is the path-loss exponent. The data transmission is deemed successful when the instantaneous SNR is no less than a threshold T_0.

B. Relay Protocol

The source S sends a data packet to the destination D. Due to the broadcast nature of wireless channels, the intermediate nodes and the destination can all possibly receive the packet. Those intermediate nodes that correctly receive the data packet are referred to as *potential* relays and they are denoted by

$$\Phi_r = \{x | x \in \Phi, \gamma_{sx} \geq T_0\}, \tag{2}$$

where γ_{sx} is the instantaneous SNR of the channel between S and the relay node located at x.

When the data packet is correctly decoded by the destination, a positive acknowledgment (ACK) frame will be released. After receiving the ACK frame, all the potential relays in Φ_r will flush their memory of the stored original data packet and the source will continue to transmit a new data packet. However, when the data packet is erroneously decoded by the destination, a negative acknowledgement (NACK) frame will be broadcast by the destination. On receiving the NACK frame, all the potential relays will try to retransmit the data packet to the destination. Whether a potential relay should retransmit the data packet or not is determined independently by the retransmission probability of itself. In this phase, the following three cases may be encountered.

- If more than one potential relays simultaneously access the channel for the data retransmission, collisions occur and the retransmission is considered to be unsuccessful.
- If none of the potential relays accesses the channel in the listening period of the source, i.e., the channel keeps idle for a duration of SIFS (shorter inter-frame space), the source will retransmit the data packet.
- If only one potential relay accesses the channel to retransmit the data packet, which is the preferred scenario, the source will keep silent after sensing that the channel is busy.

The destination combines the retransmitted signal and the original erroneously received signal using the maximal ratio combining (MRC) technique. If the instantaneous SNR of the combined signal is no less than the threshold T_0, the retransmission is considered to be successful. Otherwise, the retransmission is deemed unsuccessful. Therefore, the retransmission probability of each potential relay should be judiciously determined in a decentralized way to reduce the collisions and maximize the success probability. The retransmission probability will be investigated in the next section. The flow chart of the operation sequence is shown in Fig. 1.

In this paper, the following assumptions are made. The maximum retransmission attempts are set to be one. That is, a packet will be discarded if it is still incorrectly received by the destination after one retransmission. This assumption is suitable for real-time traffic, which can tolerate a certain packet loss rate but requires very small delay [4]. The channel between any two nodes undergoes independent Rayleigh block fading, which remains invariant for the duration of two

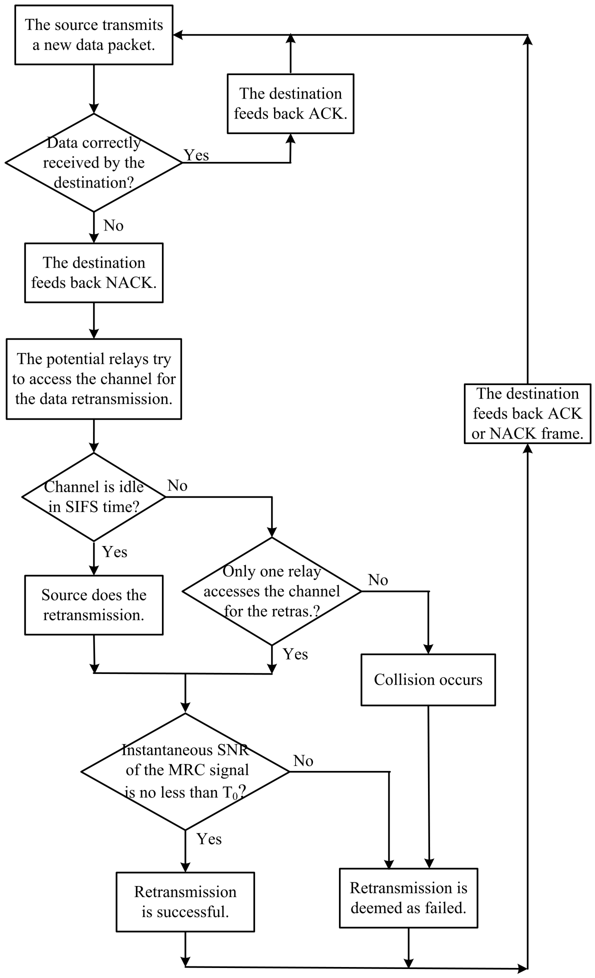


Fig. 1. Flow chart of the uncoordinated cooperative truncated ARQ schemes.

successive data packets. Moreover, the destination has enough memory to combine the original erroneously received signal and the retransmitted signal using the MRC technique for the decoding. With low rate and powerful error control, the feedback control channel is deemed as error-free [3], so the control packets can reliably reach the neighboring nodes. As the collisions are dominated by the simultaneous retransmissions of the nearby relay nodes, the data retransmission is considered as failed when collisions occur.

III. Uncoordinated Cooperative Communication Schemes

As mentioned before, on receiving the NACK frame, each potential relay independently decides whether it should occupy the channel or not according to its own retransmission probability. In this section, three different uncoordinated cooperative communication schemes are proposed.

A. Distance Based Scheme

In this scheme, we assume that each potential relay knows the distance between itself and the destination. The distance can be estimated by measuring the average strength of the received control signals from the destination, or it can be computed using the position information obtained via GPS or wireless localization techniques [14]. Positions of the destination can be included into the control packets, e.g. ACK and NACK, which can be reliably overheard by all the nearby relay nodes. In addition, each potential relay also knows the necessary parameters of the wireless network, such as the node density λ and the source-destination distance R.

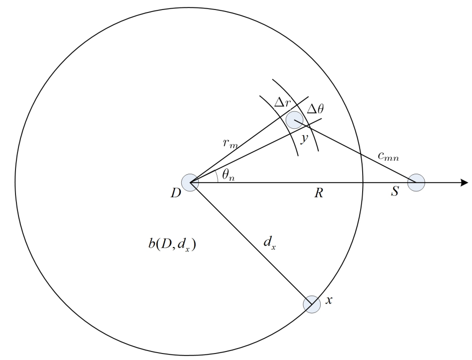


Fig. 2. The coordinate system with the destination located at the origin.

A particular node, say node $x \in \Phi_r$ [1], will retransmit the packet with probability $\tau_1(x)$ that no other potential relays lie in $b(D, d_x)$, which is a disk centered at D with radius d_x, i.e., the distance between x and the destination. Therefore,

$$\tau_1(x) = \Pr\left\{y \notin b(D, d_x), \forall y \in \Phi_r \backslash \{x\}\right\}. \qquad (3)$$

The shorter the distance d_x is, the higher the retransmission probability is used. The main rationale behind this setting is as follows. When the potential relay x is closer to the destination, the channel quality between them is better. Moreover, fewer collisions would occur as there are less number of potential relays closer to the destination than x. Equivalently, (3) can be rewritten as,

$$\tau_1(x) = \Pr\left\{y \notin \Phi_r, \forall y \in b(D, d_x) \backslash \{x\}\right\}. \qquad (4)$$

In fact, (3) is the probability that all potential relays except x are not in the disk $b(D, d_x)$, whereas (4) gives the probability that all relay nodes except x in the disk $b(D, d_x)$ are not potential relays.

Suppose that a polar coordinate system with origin at D is used and that a certain relay node $y \in b(D, d_x)\backslash\{x\}$ has the coordinate (r_m, θ_n) as shown in Fig. 2. We divide the disk $b(D, d_x)$ into many small arc regions $\mathcal{A}_{m,n}$, which are the intersections of rings with outer radius r_m ($r_m \leq d_x$) and inner radius $(r_m - \Delta r)$ and sectors with angle from θ_n to $(\theta_n + \Delta\theta)$. Next, we calculate the probability $\Pr\{y \in \Phi_r, y \in \mathcal{A}_{m,n}\}$ $\forall m, n$ with $0 < r_m \leq d_x$ and $-\pi < \theta_n \leq \pi$. It can be computed as $\lambda P_{sy}(r_m, \theta_n)\Delta v + o(\Delta v)$, where Δv denotes the area of the small arc region approximated as $\Delta v \approx (r_m \Delta\theta)\Delta r$. Conditioned on there being one node y in the small arc region $\mathcal{A}_{m,n}$, $P_{sy}(r_m, \theta_n)$ is the probability of node y correctly receiving the signal from S in the original transmission phase, given by

$$P_{sy}(r_m, \theta_n) = \Pr(\gamma_{sy} \geq T_0) = \exp\left(-T_0 N_0 c_{mn}^{\alpha}/P_0\right), \qquad (5)$$

[1] As each node is uniquely determined by its location, we use the location to denote the node without distinction.

where γ_{sy} is the SNR between S and node y, and $c_{mn} = \sqrt{R^2 + r_m^2 - 2Rr_m \cos|\theta_n|}$ is the distance between them.

As $\Delta v \to 0$, the retransmission probability $\tau_1(x)$ in (4) is given by

$$\begin{aligned}\tau_1(x) &= \lim_{\Delta v \to 0} \prod_{m,n} \left[1 - \Pr\left\{y \in \Phi_r, y \in \mathcal{A}_{m,n}\right\}\right] \\ &= \lim_{\Delta v \to 0} \prod_{m,n} \left[1 - \lambda P_{sy}(r_m, \theta_n)\Delta v\right].\end{aligned} \tag{6}$$

It can be further written as

$$\begin{aligned}\tau_1(x) &= \lim_{\Delta v \to 0} \exp\Big[\sum_{m,n} \ln\left(1 - \lambda P_{sy}(r_m, \theta_n)\Delta v\right)\Big] \\ &= \lim_{\Delta r \to 0} \lim_{\Delta\theta \to 0} \exp\Big[\sum_{m,n} \left(-\lambda P_{sy}(r_m, \theta_n) r_m \Delta\theta \Delta r\right)\Big],\end{aligned} \tag{7}$$

where in the second step, $\lim_{z\to 0} \ln(1-z) \sim -z$ is used. With $\Delta r \to 0$ and $\Delta\theta \to 0$, we get

$$\begin{aligned}\tau_1(x) &= \exp\Big\{ -\lambda \int_0^{d_x} r\Big[\int_{-\pi}^{\pi} P_{sy}(r,\theta)d\theta\Big]dr\Big\} \\ &= \exp\Big\{ -2\lambda \int_0^{d_x} r \int_0^{\pi} \exp\big[-T_0 K_0 \times \\ &\qquad (R^2 + r^2 - 2Rr\cos\theta)^{\frac{\alpha}{2}}\big] d\theta\, dr\Big\},\end{aligned} \tag{8}$$

where $K_0 = N_0/P_0$ is used throughout this paper. For the general path-loss exponent, the integral in (8) can only be evaluated numerically and a closed-form expression is difficult to obtain. However, for the special case of $\alpha = 2$, the result is further derived as

$$\begin{aligned}\tau_1(x) &= \exp\Big\{ -2\pi\lambda \exp\left(-T_0 K_0 R^2\right) \times \\ &\qquad \int_0^{d_x} r \exp\left(-T_0 K_0 r^2\right) I_0(2T_0 K_0 R r) dr\Big\} \\ &= \exp\Big\{ -2\pi\lambda \exp\left(-T_0 K_0 R^2\right) \times \\ &\qquad \sum_{k=0}^{\infty} \frac{(T_0 K_0 R)^{2k}}{(k!)^2} \frac{\gamma\left(k+1, T_0 K_0 d_x^2\right)}{2(T_0 K_0)^{k+1}}\Big\},\end{aligned} \tag{9}$$

where $I_0(z)$ is the zero-order modified Bessel function [16, (8.431)] and $\gamma(\mu,\omega)$ is the incomplete Gamma function [16, (8.350.1)]. As $I_0(z) = \sum_{k=0}^{\infty} \frac{1}{(k!)^2} \left(\frac{z}{2}\right)^{2k}$ [16, (8.447)], and $\gamma(\mu,\omega) = (\mu-1)! \left[1 - \exp(-\omega) \sum_{m=0}^{\mu-1} \frac{\omega^m}{m!}\right]$ [16, (8.352.6)], the final result can be numerically computed more efficiently using series summation instead of the integration.

Fig. 3 shows the retransmission probabilities of the distance based scheme with respect to the distance d_x between the potential relay x and the destination D for the given parameters $\alpha = 2$, $T_0 = 5$ and $K_0 = 10^{-4}$. It can be seen that the retransmission probability is a monotonically decreasing function of distance d_x. It means that the potential relays that are closer to the destination have higher retransmission probabilities. Moreover, for a given distance between the source and the destination ($R = 50$m or $R = 70$m), the retransmission probability is larger for the smaller intensity λ. For a given node intensity ($\lambda = 0.02/\mathrm{m}^2$ or $\lambda = 0.002/\mathrm{m}^2$), the retransmission probability is larger for the longer distance R. This is because, when λ is smaller or R is larger, there are a smaller number of potential relays residing in the disk $b(D, d_x)$ hereby reducing the collisions. When the distance between a potential relay node and the destination is comparable to the distance R between source and destination, the retransmission probability is almost zero.

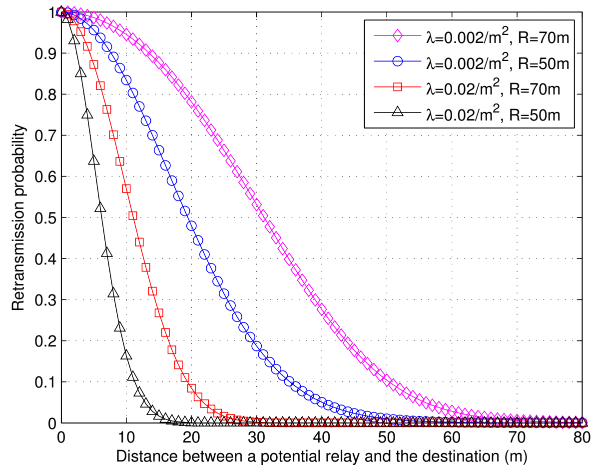


Fig. 3. Retransmission probability of the distance based scheme.

B. Sectorized Scheme

For an efficient multi-hop routing algorithm, the information of source should be transmitted in the right direction to arrive at the destination, i.e., the next-hop neighbor should be closer to the destination [13]. So, the node of the next hop should lie in the angle interval $(-\pi/2, \pi/2)$ symmetric with the source-destination axis. It was shown that by considering this angle information, the uncoordinated cooperative scheme proposed in [10] can achieve a good performance for the two-hop system. For the single-hop communication between S and D with the cooperation of random relays, the sectorized scheme is proposed to reduce collisions. Because the potential relays in the direction of destination are allocated higher retransmission probabilities than those in the opposite direction.

Assume that each potential relay $x \in \Phi_r$ knows the system parameters (λ, P_0, R, etc.) and the angle $\psi_x = \angle xSD$, which can be obtained via estimating the direction of arrival (DOA) of the wanted signals [15] or computed using the positions of the source, the destination and itself. The potential relay x does the retransmission with the probability $\tau_2(x)$ that no other potential relays reside in $\mathcal{S}(2|\psi_x|, c)$, which is a sector with angle spread of $2|\psi_x|$ and edge $c = \infty$. Please see Fig. 4 for an illustration of the sector area. Therefore,

$$\tau_2(x) = \Pr\left\{y \notin \mathcal{S}(2|\psi_x|, \infty), \forall y \in \Phi_r \backslash \{x\}\right\}. \tag{10}$$

The smaller the angle $|\psi_x|$ is, the higher the retransmission probability is used. This is because there are less number of potential relays in the sector area with smaller angle and as a result less collisions would be encountered. Equivalently, (10) can be rewritten as,

$$\tau_2(x) = \Pr\left\{y \notin \Phi_r, \forall y \in \mathcal{S}(2|\psi_x|, \infty) \backslash \{x\}\right\}. \tag{11}$$

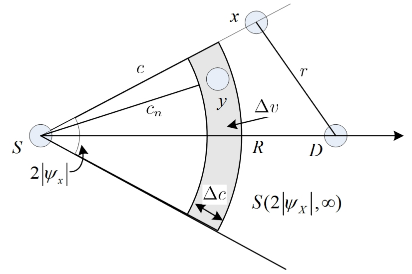


Fig. 4. The coordinate system with source located at the origin.

In fact, (10) is the probability that all potential relays except x are not in the infinite sector $\mathcal{S}(2|\psi_x|,\infty)$, while (11) is the probability that all relay nodes except x in the sector $\mathcal{S}(2|\psi_x|,\infty)$ are not potential relays.

Suppose that a polar coordinate system with origin at S is used and that a certain node $y \in \mathcal{S}(2|\psi_x|,\infty)\backslash\{x\}$ has a distance c_n from the source as shown in Fig. 4. We divide the sector $\mathcal{S}(2|\psi_x|,\infty)$ into many small strips $\mathcal{A}_n$ with inner radius c_n and outer radius $(c_n + \Delta c)$. Hence, it suffices to calculate $\Pr\{y \in \Phi_r, y \in \mathcal{A}_n\}$, $\forall y$ with $0 < c_n < \infty$. It can be computed as $\lambda P_{sy}(c_n)\Delta v + o(\Delta v)$, where Δv denotes the area of the strip approximated as $\Delta v \approx 2|\psi_x|c_n\Delta c$, and $P_{sy}(c_n)$ is the probability that node y in the strip $\mathcal{A}_n$ correctly receives the signal of S in the original transmission phase.

As $\Delta v \to 0$, the retransmission probability $\tau_2(x)$ in (11) is given by

$$\begin{aligned}\tau_2(x) &= \lim_{\Delta v\to 0}\prod_n \left[1-\Pr\{y\in\Phi_r, y\in\mathcal{A}_n\}\right]\\ &= \lim_{\Delta v\to 0}\prod_n \left[1-\lambda P_{sy}(c_n)\Delta v\right],\ 0<c_n<\infty.\end{aligned} \tag{12}$$

Similar to the derivation of (7), we can obtain

$$\begin{aligned}\tau_2(x) &= \lim_{\Delta c\to 0}\exp\Big[\sum_n \left(-\lambda P_{sy}(c_n)2|\psi_x|c_n\Delta c\right)\Big]\\ &= \exp\Big[-2|\psi_x|\lambda\int_0^\infty c\exp\left(-T_0K_0c^\alpha\right)dc\Big]\\ &= \exp\Big[-\frac{2|\psi_x|\lambda\Gamma\left(2/\alpha\right)}{\alpha(T_0K_0)^{2/\alpha}}\Big],\end{aligned} \tag{13}$$

where $\Gamma(z)=\int_0^\infty \exp(-t)t^{z-1}\,dt$ is the Gamma function [16, (8.310.1)]. It can be seen from (13) that, the retransmission probability is an exponentially decreasing function of the absolute angle $|\psi_x|$ and the node density λ. When $|\psi_x|$ or λ becomes larger, there are more potential relays in the infinite sector area $\mathcal{S}(2|\psi_x|,\infty)$ and thereby the retransmission probability gets smaller to reduce the possible collisions. In addition, $\tau_2(x)$ is a monotonously increasing function of the product of T_0 and K_0.

C. Local SNR Based Scheme

In this scheme, we assume that each potential relay only knows the instantaneous SNR of the channel between itself and the destination. It is assumed that pilot signals are transmitted with a constant power over the same frequency band as the data packet. Due to the reciprocity of wireless channels, the SNR information can be obtained by measuring the strength of the pilot signals transmitted by the destination [7].

Different from the aforementioned location-aware schemes where nodes lying in Φ_r can all possibly participate in the retransmission, for this scheme only those nodes lying in the retransmission candidate set $\Phi_N = \{x|x\in\Phi_r, \gamma_{xd}\ge T_0\}$ have the opportunity to assist the retransmission, where γ_{xd} is the instantaneous SNR between the potential relay x and the destination D. Thus, the potential relays in this scheme refer to those nodes belonging to Φ_N, which is a subset of Φ_r, i.e., $\Phi_N \subseteq \Phi_r$.

In the retransmission phase, a potential relay $x\in\Phi_N$ retransmits with probability $\tau_3(x)$ that no other nodes in Φ_N have an SNR larger than γ_{xd}, i.e., the potential relay $x\in\Phi_N$ has the largest instantaneous SNR among all the potential relays. It follows that

$$\tau_3(x) = \Pr\left\{\gamma_{xd}\ge\gamma_{yd}, \forall y\in\Phi_N\backslash\{x\}\right\}, \tag{14}$$

where γ_{yd} is the instantaneous SNR between potential relay y and D. The higher the instantaneous SNR is, the higher the retransmission probability is set for the potential relay x.

Next, in order to calculate $\tau_3(x)$ we need to calculate $\Pr\{\gamma_{yd}>\gamma_{xd}\}$, $\forall y \in \Phi_N\backslash\{x\}$. Suppose that the same coordinate system is used as the one in the distance based scheme (see Fig. 2), where the infinite plane is divided into small arc regions $\mathcal{A}_{m,n}$. Then, it suffices to calculate $\Pr\{\gamma_{yd}>\gamma_{xd}, y\in\Phi_N, y\in\mathcal{A}_{m,n}\}$, $\forall m,n$ with $0 < r_m < \infty$ and $-\pi < \theta_n \le \pi$. It can be computed as $\lambda P_{sy}(r_m,\theta_n)\Pr(\gamma_{yd} > \gamma_{xd})\Delta v + o(\Delta v)$, where Δv denotes the area of the small arc region approximated as $\Delta v \approx r_m\Delta\theta\Delta r$, and $P_{sy}(r_m,\theta_n)$ is the probability of node y correctly receiving the signal from S in the original transmission phase, conditioned on node y being located in $\mathcal{A}_{m,n}$. The retransmission probability $\tau_3(x)$ is computed only when $x\in\Phi_N$.

With $\Delta v\to 0$, the retransmission probability $\tau_3(x)$ in (14) is written as

$$\tau_3(x) = \lim_{\Delta v\to 0}\prod_{m,n}\left[1-\lambda P_{sy}(r_m,\theta_n)\Pr(\gamma_{yd}>\gamma_{xd})\Delta v\right]. \tag{15}$$

Similar to the derivation of (7), with $\Delta v\to 0$, Eq. (15) can be derived as

$$\begin{aligned}\tau_3(x) = \lim_{\Delta r\to 0}\lim_{\Delta\theta\to 0}\exp\Big\{\sum_{m,n}\big[&-\lambda P_{sy}(r_m,\theta_n)\times\\ &\Pr(\gamma_{yd}>\gamma_{xd})r_m\Delta\theta\Delta r\big]\Big\}.\end{aligned} \tag{16}$$

With $\Delta r\to 0$ and $\Delta\theta\to 0$, we get

$$\begin{aligned}\tau_3(x) = \exp\Big\{&-2\lambda\int_0^\infty r\exp\Big[-\frac{\gamma_{xd}}{\bar{\gamma}_{yd}(r)}\Big]\times\\ &\int_0^\pi \exp\big[-T_0K_0(R^2+r^2-2Rr\cos\theta)^{\frac{\alpha}{2}}\big]d\theta dr\Big\},\end{aligned} \tag{17}$$

where $\bar{\gamma}_{yd}(r) = P_0r^{-\alpha}/N_0$ is the average SNR between node y and the destination D. For general values of α, the closed-from expression of the inner integral over θ is difficult to derive and the above integrals in (17) can only be evaluated numerically. However, a succinct expression of $\tau_3(x)$ with $\alpha = 2$ can be derived as follows.

$$\begin{aligned}\tau_3(x) &= \exp\Big\{ -2\pi\lambda \exp\big(-T_0K_0R^2\big)\times \\ &\int_0^\infty r\exp\big[-K_0(\gamma_{xd}+T_0)r^2\big]J_0\big(2iT_0K_0Rr\big)\,dr\Big\} \quad (18)\\ &= \exp\Big[-\frac{\pi\lambda}{K_0(\gamma_{xd}+T_0)}\exp\Big(-T_0K_0R^2+\frac{K_0T_0^2R^2}{\gamma_{xd}+T_0}\Big)\Big].\end{aligned}$$

In this equation, the integral over θ given in (9) is used with $I_0\left(2T_0K_0Rr\right)$ being substituted by the Bessel function $J_0\left(2iT_0K_0Rr\right)$ according to [16, Eq. (8.406.1)], where $i = \sqrt{-1}$. The integral over r is derived with reference to [16, (6.631.4)]. It can be seen from (18) that, the retransmission probability is a monotonically increasing function of the instantaneous SNR γ_{xd}.

IV. System Success Probability

In this section, the system success probability is analyzed for the sectorized scheme and local SNR based scheme, respectively. Similar operation can be applied to derive the success probability of the distance based scheme. The system success probability is denoted as P and given by

$$P = P_1 + P_2 + P_3, \quad (19)$$

where $P_1 = \Pr\{\gamma_{sd} \geq T_0\} = \exp\left(-T_0K_0R^\alpha\right)$ is the success probability of original data transmission between source and destination, P_2 is the probability that the source successfully retransmits when the original transmission fails and all the potential relays keep silent, and P_3 is the probability that only one potential relay successfully retransmits when the original transmission fails.

A. For the Sectorized Scheme

In order to compute P_2 and P_3, we divide the network area into very small regions of size Δv. Suppose that each node lies in the center of a certain region [9]. Define $q(v)$ to be the probability that a potential relay exists in the small region v and retransmits the packet. It is given by

$$q(v) = \lambda P_{sn}(v)\tau_2(v)\Delta v + o(\Delta v), \quad (20)$$

where $P_{sn}(v)$ is the conditional probability that a *n*ode lying in the center of v correctly receives the original data packet given by (5), and $\tau_2(v)$ is the retransmission probability of the node given by (13).

In the retransmission phase, if all the potential relays keep silent, the source will retransmit the original data packet. In this case, the success probability is given as follows.

$$P_2 = \Pr\left\{T_0/2 \leq \gamma_{sd} < T_0\right\} \lim_{\Delta v\to 0}\prod_v \left[1-q(v)\right], \quad (21)$$

where $\Pr\left\{T_0/2 \leq \gamma_{sd} < T_0\right\}$ is the probability that the destination correctly detects the MRC signal from the source conditioned on that the original transmission fails. When the original transmission between source and destination fails, we have $\gamma_{sd} < T_0$. As the channel undergoes block fading, for the source to do the retransmission, the instantaneous SNR of the MRC signal at the destination side is $2\gamma_{sd}$. So, for the correct retransmission from the source, we have $2\gamma_{sd} \geq T_0$, i.e., $\gamma_{sd} \geq T_0/2$. The series product $\prod_v\left[1-q(v)\right]$ in (21) denotes the probability of all the potential relays keeping silent. Similar to the derivation of (13), we continue to have

$$\begin{aligned}P_2 &= \Pr\left\{T_0/2 \leq \gamma_{sd} < T_0\right\}\exp\Big\{-\int_{\mathbb{R}^2}\lambda P_{sn}(v)\tau_2(v)dv\Big\}\\ &= \Pr\left\{T_0/2 \leq \gamma_{sd} < T_0\right\}\exp\Big\{-\lambda\\ &\times\int_0^\infty c\Big[\int_{-\pi}^{\pi}\exp\Big(-\frac{2|\psi|\lambda\Gamma\left(2/\alpha\right)}{\alpha(T_0K_0)^{2/\alpha}}\Big)d\psi\Big]P_{sx}(c)dc\Big\}\\ &= \left[\exp\left(-T_0K_0R^\alpha/2\right)-\exp\left(-T_0K_0R^\alpha\right)\right]\\ &\times\exp\Big[-1+\exp\Big(-\frac{2\pi\lambda\Gamma(2/\alpha)}{\alpha(T_0K_0)^{2/\alpha}}\Big)\Big]. \quad (22)\end{aligned}$$

Remark: By formulating the problem from the perspective of stochastic geometry, the same result can be reached using the probability generating functional (PGFL) [11] [12].

Next, we consider the probability that only one potential relay successfully retransmits. If only one potential relay centered at the small region v retransmits the data packet and all the other potential relays remain silent, with $\Delta v \to 0$, the success probability P_3 is

$$\begin{aligned}P_3 = \lim_{\Delta v\to 0}\sum_v\Big\{q(v)\Pr\{\gamma_{vd}+\gamma_{sd}\geq T_0, \gamma_{sd}<T_0\}\\ \times\prod_{v'\neq v}\left[1-q(v')\right]\Big\}, \quad (23)\end{aligned}$$

where $q(v)$ is given by (20). Conditioned on the existence of a potential relay node in the center of the small area v, $\Pr\{\gamma_{vd}+\gamma_{sd}\geq T_0, \gamma_{sd}<T_0\}$ is the probability that the destination correctly detects the MRC signal with the retransmission performed by this potential relay when the original transmission between source and destination fails. Specifically,

$$\begin{aligned}&\Pr\{\gamma_{vd}+\gamma_{sd}\geq T_0, \gamma_{sd}<T_0\} = \frac{R^\alpha}{R^\alpha - r^\alpha}\times\\ &\exp(-T_0K_0r^\alpha)\big\{1-\exp\left[-T_0K_0(R^\alpha-r^\alpha)\right]\big\},\end{aligned} \quad (24)$$

where r is the distance between the potential relay and the destination.

In (23), with $\Delta v \to 0$, the probability that all the potential relays except the conditional one lying in the small region v keep silent in the retransmission phase is computed as

$$\begin{aligned}\lim_{\Delta v\to 0}\prod_{v'\neq v}\Big[1-q(v')\Big] &= \lim_{\Delta v'\to 0}\prod_{v'\neq v}\Big[1-\lambda P_{sn}(v')\tau_2(v')\Delta v\Big]\\ &= \lim_{\Delta v'\to 0}\exp\Big\{\sum_{v'}\log\left[1-\lambda P_{sn}(v')\tau_2(v')\Delta v\right]\Big\}\\ &= \lim_{\Delta v'\to 0}\exp\Big\{-\sum_{v'}\lambda P_{sn}(v')\tau_2(v')\Delta v\Big\}\\ &= \exp\Big\{-\int_{\mathbb{R}^2}\lambda P_{sn}(v')\tau_2(v')dv'\Big\}, \quad (25)\end{aligned}$$

which is independent of v. $\lim_{\Delta v\to 0}\prod_{v'\neq v}\left[1-q(v')\right]$ in (23) has the same result as $\lim_{\Delta v\to 0}\prod_v\left[1-q(v)\right]$ in (21), and this reflects the infinitesimal impact of a single excluded point in a continuous space [9]. In fact, P_3 given by (23) can also be formulated from the perspective of stochastic geometry, and the conditional PGFL of the PPP equals the PGFL according to Slivnyak's Theorem [11] [12]. Hence, without distinction between v and v', P_3 of (23) can be further derived as

$$\begin{aligned} P_3 &= \exp\Big[-\int_{\mathbb{R}^2}\lambda P_{sn}(v)\tau_2(v)dv\Big] \\ &\times \int_{\mathbb{R}^2}\lambda P_{sn}(v)\tau_2(v)\Pr\{\gamma_{vd}+\gamma_{sd}\ge T_0, \gamma_{sd}<T_0\}dv \\ &= \exp\Big[-1+\exp\big(-\frac{2\pi\lambda\Gamma(2/\alpha)}{\alpha(T_0K_0)^{2/\alpha}}\big)\Big]\int_0^\infty\int_{-\pi}^{\pi}\lambda \\ &\times \exp(-T_0K_0c^\alpha)\exp\Big[-\frac{2|\psi|\lambda\Gamma(2/\alpha)}{\alpha(T_0K_0)^{2/\alpha}}\Big]\frac{R^\alpha}{R^\alpha-r^\alpha} \\ &\times \exp(-T_0K_0r^\alpha)\Big\{1-\exp\big[-T_0K_0(R^\alpha-r^\alpha)\big]\Big\}c\,d\psi\,dc, \end{aligned} \tag{26}$$

where the relationship between r and c as shown in Fig. 4, i.e., $r=\sqrt{R^2+c^2-2Rc\cos(|\psi|)}$, is adopted, and the two-dimensional integral over ψ and c can be computed numerically.

B. For the Local SNR Based Scheme

To derive P_2 and P_3, the infinite plane is also divided into a cascade of small regions with area Δv. The probability that one potential relay of Φ_N lies in the center of a small region v and retransmits the packet is given as $\lambda\Pr(\gamma_{sv}\ge T_0)\mathbb{E}\left[\mathbf{1}(\gamma_{vd}\ge T_0)\tau_3(v)\right]\Delta v+o(v)$, where $\mathbf{1}(\gamma_{sv}\ge T_0)$ is the indicator random variable, which equals 1 if $\gamma_{sv}\ge T_0$, and 0 otherwise.

When the original transmission between the source and the destination fails, if all the potential relays keep silent in the retransmission phase, the source will retransmit. The success probability P_2 is given as follows with $\Delta v\to 0$.

$$\begin{aligned} &P_2=\Pr\{T_0/2\le\gamma_{sd}<T_0\}\times \\ &\lim_{\Delta v\to 0}\prod_v\Big\{1-\lambda\Pr(\gamma_{sv}\ge T_0)\mathbb{E}\left[\mathbf{1}(\gamma_{vd}\ge T_0)\tau_3(v)\right]\Delta v\Big\}, \end{aligned} \tag{27}$$

where the series product is the probability of all the potential relays being silent. The expectation is taken over the random variable γ_{vd}, i.e. the SNR of channel $v\to D$, given by

$$\mathbb{E}\left[\mathbf{1}(\gamma_{vd}\ge T_0)\tau_3(v)\right]=\int_{T_0}^\infty\tau_3(v)f_{\Gamma_{vd}}(\gamma_{vd})\,d\gamma_{vd}, \tag{28}$$

where $f_{\Gamma_{vd}}(\gamma_{vd})$ is the probability density functions (PDF) of the instantaneous SNR γ_{vd}. The expression of the integral (28) with $\tau_3(v)$ given by (17) for the general α is complex. However, for the special case of $\alpha=2$, we have a relatively succinct expression as follows.

$$\begin{aligned} &\mathbb{E}\left[\mathbf{1}(\gamma_{vd}\ge T_0)\tau_3(v)\right]=\frac{1}{\overline{\gamma}_{vd}}\exp\big(\frac{T_0}{\overline{\gamma}_{vd}}\big)\times \\ &\int_{2T_0}^\infty\exp\Big\{-\frac{t}{\overline{\gamma}_{vd}}-\frac{\pi\lambda}{K_0t}\exp\Big[-T_0K_0R^2\big(1-\frac{T_0}{t}\big)\Big]\Big\}\,dt, \end{aligned} \tag{29}$$

where $\overline{\gamma}_{vd}$ is the average SNR between destination and the node located in the center of v. After taking the integral over the infinite plane, we can further get

$$\begin{aligned} P_2 &= \Pr\{T_0/2\le\gamma_{sd}<T_0\} \\ &\times \exp\Big\{-\int_{\mathbb{R}^2}\lambda\Pr(\gamma_{sv}\ge T_0)\mathbb{E}\left[\mathbf{1}(\gamma_{vd}\ge T_0)\tau_3(v)\right]dv\Big\}. \end{aligned} \tag{30}$$

The succinct expression of (30) with $\alpha=2$ is written as

$$\begin{aligned} P_2 &= \big[\exp\big(-T_0K_0R^2/2\big)-\exp\big(-T_0K_0R^2\big)\big] \\ &\times \exp\Big\{-\frac{\pi\lambda}{K_0}\exp(-T_0K_0R^2)\int_{2T_0}^\infty\Big(\frac{K_0T_0^2R^2}{t^3}+\frac{1}{t^2}\Big) \\ &\times \exp\Big\{\frac{K_0T_0^2R^2}{t}-\frac{\pi\lambda}{K_0t}\exp\big[-K_0T_0R^2(1-\frac{T_0}{t})\big]\Big\}\,dt\Big\} \end{aligned} \tag{31}$$

Next, if only one potential relay of Φ_N occupies the channel to retransmit the data while all the other potential relays keep silent, the system success probability P_3 is given by

$$\begin{aligned} P_3 &= \Pr\{\gamma_{sd}<T_0\} \\ &\times \lim_{\Delta v\to 0}\sum_v\lambda\Pr(\gamma_{sv}\ge T_0)\mathbb{E}\left[\mathbf{1}(\gamma_{vd}\ge T_0)\tau_3(v)\right]\Delta v \\ &\times \prod_{v'\ne v}\Big\{1-\lambda\Pr(\gamma_{sv'}\ge T_0)\mathbb{E}\left[\mathbf{1}(\gamma_{v'd}\ge T_0)\tau_3(v')\right]\Delta v\Big\}, \end{aligned} \tag{32}$$

where $\Pr\{\gamma_{sd}<T_0\}=1-\exp(-T_0K_0R^\alpha)$ is the probability that the original transmission between the source and the destination is unsuccessful. If the retransmission is performed by a potential relay, with $\gamma_{vd}\ge T_0$, the MRC technique is not needed for the signal detection in the local SNR based scheme. As the series summation and product can be reduced to the integral and exponential integral with $\Delta v\to 0$, (32) can be further derived as

$$\begin{aligned} P_3 &= \big[1-\exp(-T_0K_0R^\alpha)\big] \\ &\times \int_{\mathbb{R}^2}\lambda\Pr(\gamma_{sv}\ge T_0)\mathbb{E}\left[\mathbf{1}(\gamma_{vd}\ge T_0)\tau_3(v)\right]dv \\ &\times \exp\Big[-\int_{\mathbb{R}^2}\lambda\Pr(\gamma_{sv}\ge T_0)\mathbb{E}\left[\mathbf{1}(\gamma_{vd}\ge T_0)\tau_3(v)\right]dv\Big], \end{aligned} \tag{33}$$

where the integral is taken over the infinite plane, and according to (30), for the special case of $\alpha=2$, it is given by

$$\begin{aligned} &\int_{\mathbb{R}^2}\lambda\Pr(\gamma_{sv}\ge T_0)\mathbb{E}\left[\mathbf{1}(\gamma_{vd}\ge T_0)\tau_3(v)\right]dv \\ &= \frac{\pi\lambda}{K_0}\exp(-T_0K_0R^2)\int_{2T_0}^\infty\Big(\frac{K_0T_0^2R^2}{t^3}+\frac{1}{t^2}\Big) \\ &\times \exp\Big\{\frac{K_0T_0^2R^2}{t}-\frac{\pi\lambda}{K_0t}\exp\Big[-K_0T_0R^2\big(1-\frac{T_0}{t}\big)\Big]\Big\}\,dt. \end{aligned} \tag{34}$$

For the general path-loss exponent α, P_3 can also be numerically computed.

V. Numerical and Simulation Results

In this section, numerical and simulation results of the proposed uncoordinated cooperative communication schemes are presented and compared. In the comparison, the traditional truncated ARQ scheme with source performing the retransmission is also included. In the simulation, a circular area with radius 500m is considered with the destination located at the origin, and the source is located R away from the destination. All the relay nodes are uniformly distributed in the circular area, and the number of relay nodes follows Poisson distribution with mean $\lambda\pi 500^2$. The path-loss exponent $\alpha=2$ is used in the simulation.

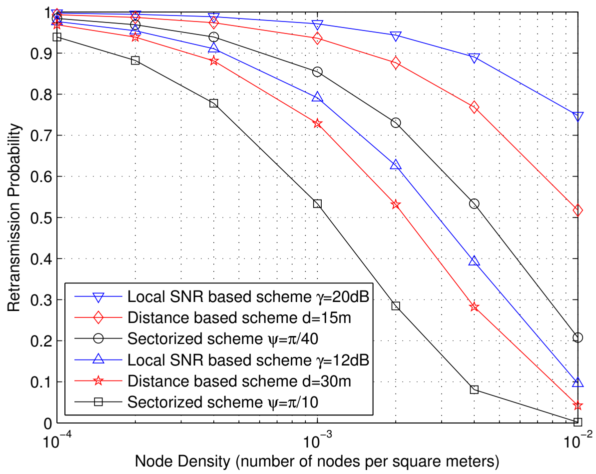


Fig. 5. Retransmission probability vs. Node density. The transmitter SNR is 40dB, the S-D distance is $R = 70$m, and the decoding threshold is $T_0 = 5$.

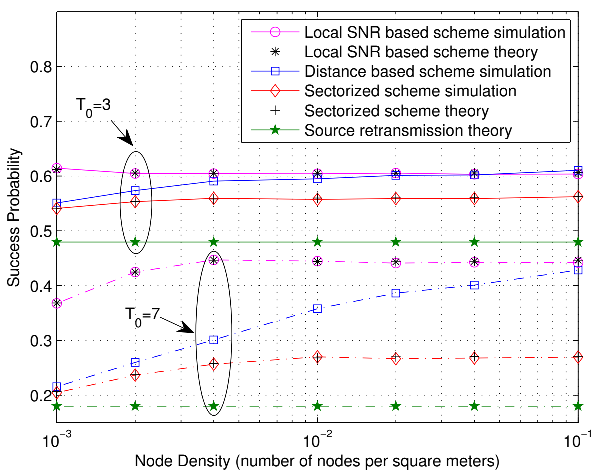


Fig. 6. Success probability vs. Node density. The source-destination distance is $R = 70$m and the transmitter SNR is 40dB.

In Fig. 5, the retransmission probabilities of the proposed schemes are shown with respect to the node density λ. Note that the theoretical retransmission probabilities of the distance based scheme, sectorized scheme, and local SNR based scheme are given in (9), (13), and (18), respectively. It can be seen that with the increase of λ, the retransmission probability of each scheme becomes smaller. For the distance based scheme, the retransmission probability gets smaller when the distance d between a potential relay and the destination increases from 15m to 30m. For the sectorized scheme, the retransmission probability turns smaller when the angle ψ increases from $\pi/40$ to $\pi/10$. For the local SNR based scheme, the retransmission probability becomes smaller when the instantaneous SNR γ between a potential relay and the destination is reduced from 20dB to 12dB.

Fig. 6 shows the system success probabilities of the proposed uncoordinated schemes against the node density with different SNR thresholds, while Fig. 7 shows the performance

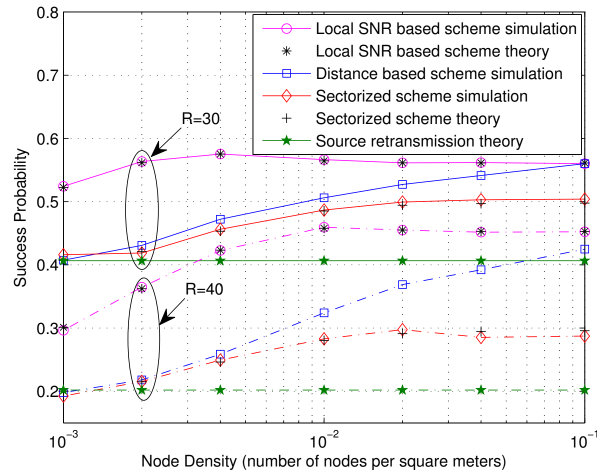


Fig. 7. Success probability vs. Node density. The transmitter SNR is 30dB and the decoding threshold is $T_0 = 2$.

with different source-destination distances. The original erroneously received signal and the retransmitted signal are combined at the destination by using the MRC technique for the detection. The distance between the source and the destination is set as $R = 70$m in Fig. 6. The SNR threshold of signal detection is set as $T_0 = 2$ in Fig. 7. For the sectorized and local SNR based schemes, we can see that the simulation results match well with the theoretical results presented in Section IV. Also, we can observe that, the local SNR based scheme has the best performance in general, because collisions can be greatly alleviated by allocating the retransmission task only to the nodes that have good instantaneous channel state towards the destination. Moreover, it is observed that the distance based scheme outperforms the sectorized scheme. The proposed uncoordinated cooperative truncated ARQ schemes outperform the source retransmission scheme.

In the whole range of λ, the performance of each scheme does not change greatly. The rational behind this phenomenon is explained as follows. The retransmission probabilities of the potential relays given in Section III are monotonically decreasing functions of the node density λ. When the node density λ gets larger, although more potential relays will exist in the vicinity of the source and the destination, it will not necessarily cause more collisions. This is because the retransmission probabilities of the potential relays becomes smaller with the increase of λ, as shown in Fig. 5. Consequently, the probability of only one potential relay accessing the channel for the data retransmission changes slightly with respect to different node densities. As T_0 denotes the SNR threshold of successfully decoding the received signal, we can expect that more errors can be tolerated for smaller T_0. Hence, the system success probability becomes better when T_0 turns smaller from 7 to 3. With the increase of R from 30m to 40m, the average channel quality between source and destination deteriorates, so the system success probability gets worse.

Fig. 8 compares the success probabilities of the proposed schemes with respect to the source-destination distance R for $T_0 = 3$ and $T_0 = 7$. The node density is set as $\lambda = 0.002/\mathrm{m}^2$

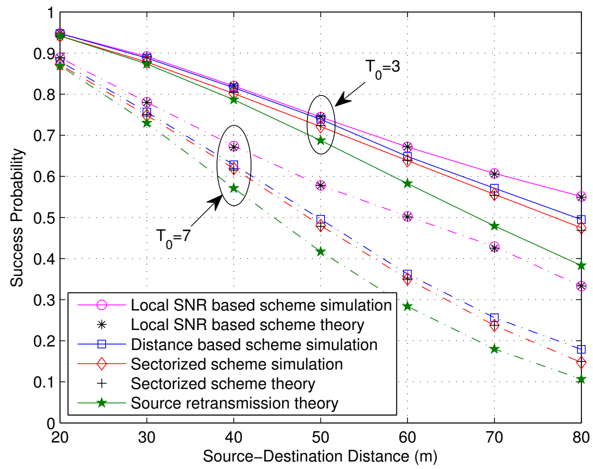


Fig. 8. Success probability vs. Source-destination distance. The node density is $\lambda = 0.002/\mathrm{m}^2$ and the transmitter SNR is 40dB.

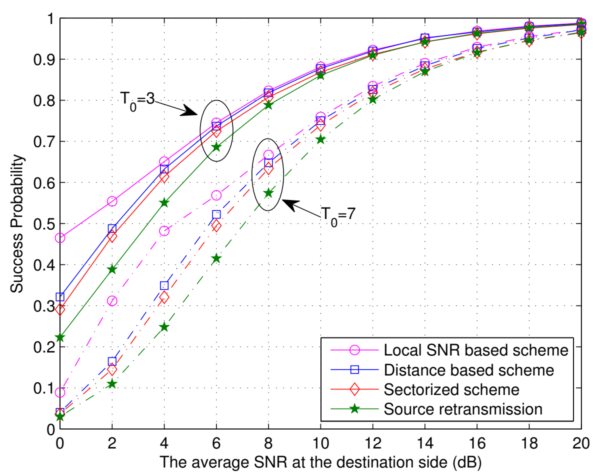


Fig. 9. Success probability vs. Average SNR at the destination. The node density is $\lambda = 0.002/\mathrm{m}^2$ and the source-destination distance is $R = 70\mathrm{m}$.

and the transmitter side SNR is 40dB. When the distance R is short, the original transmission between the source and the destination is successful almost all the time. However, with the increase of distance R, the success probability becomes smaller. It can be seen that the local SNR based scheme has the best performance in the whole distance range. The distance based scheme slightly outperforms the sectorized scheme. The uncoordinated schemes have a better performance than the traditional truncated ARQ scheme with only the source performing the retransmission. Because space diversity can be achieved if the signal is retransmitted by a relay node other than the source node. Apparently, when the SNR threshold becomes smaller from 7 to 3, the performance gets better. Moreover, we can observe that the numerical results coincide with the simulation results well for the sectorized and local SNR based schemes. It validates the theoretical analysis in Section IV.

The system success probabilities of the proposed schemes with respect to the average SNR at the destination side are shown in Fig. 9. The node density is set as $\lambda = 0.002/\mathrm{m}^2$, and the distance between the source and the destination is fixed as $R = 70\mathrm{m}$. The system success probability is small when the average SNR is very low, because the transmission power is very low. The performance improves with the increase of the average SNR. In the low to middle SNR range, we can see that the local SNR based schemes outperforms all the other schemes, and that the distance based schemes performs better than the sectorized scheme. The source retransmission schemes has the worst performance, due to its lack of cooperative diversity. When the transmission power is high enough, the original transmission between the source and the destination is successful with very high probability. Hence, in the high SNR range, the performance of all the schemes is very close.

VI. Conclusion

In this paper, we have proposed three uncoordinated cooperative truncated ARQ schemes in a large wireless network. If the original data packet is erroneously received by the destination, all the potential relays compete the channel for the data retransmission in a distributed fashion without coordination. Whether a potential relay should access the channel or not is determined independently by its retransmission probability, which is computed based on the local information of the potential relay, such as position or channel SNR towards the destination. Numerical and simulation results show that the local SNR based scheme has the best performance, and the distance based scheme is superior to the sectorized scheme.

References

[1] B. Zhao and M. C. Valenti, "Practical relay networks: a generalization of hybrid-ARQ," *IEEE J. Sel. Areas Commun.*, vol. 23, pp. 7–18, Jan. 2005.

[2] M. Dianati, X. Ling, K. Naik, and X. Shen, "A node-cooperative ARQ scheme for wireless ad hoc networks," *IEEE Trans. Veh. Technol.*, vol. 55, pp. 1032–1044, May 2006.

[3] Q. Liu, S. Zhou, and G. B. Giannakis, "Cross-layer combining of adaptive modulation and coding with truncated ARQ over wireless links," *IEEE Trans. Wireless Commun.*, vol. 3, pp. 1746–1755, Sep. 2004.

[4] G. Yu, Z. Zhang, and P. Qiu, "Cooperative ARQ in wireless networks: protocols description and performance analysis," in *Proc. IEEE International Conference on Communications (ICC)*, Istanbul, Turkey, Jun. 2006, pp. 3608–3614.

[5] J. Alonso-Zárate, E. Kartsakli, Ch. Verikoukis, and L. Alonso, "Persistent RCSMA: a MAC protocol for a distributed cooperative ARQ scheme in wireless networks," *EURASIP Journal on Advanced Signal Processing*, pp. 1–13, Dec. 2008.

[6] A. S. Ibrahim, A. K. Sadek, W. Su, and K. J. Ray Liu, "Cooperative communications with relay-selection: when to cooperate and whom to cooperate with?" *IEEE Trans. Wireless Commun.*, vol. 7, pp. 2814–2827, Jul. 2008.

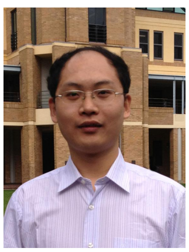
[7] A. Bletsas, A. Khisti, D. P. Reed, and A. Lippman, "A simple cooperative diversity method based on network path selection," *IEEE J. Sel. Areas Commun.*, vol. 24, pp. 659–672, Mar. 2006.

[8] W. Zhang and K. B. Letaief, "Full-rate distributed space-time codes for cooperative communications," *IEEE Trans. Wireless Commun.*, vol. 7, pp. 2446–2451, Jul. 2008.

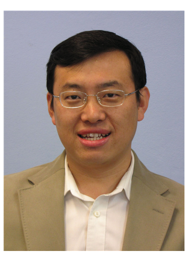
[9] L. Xiong, L. Libman, and G. Mao, "On cooperative communication in ad-hoc networks: the case for uncoordinated location-aware retransmission strategies," in *Proc. IEEE Conference on Local Computer Networks (LCN)*, Zürich, Switzerland, Oct. 2009, pp. 554–561.

[10] R. K. Ganti and M. Haenggi, "Analysis of uncoordinated opportunistic two-hop wireless ad hoc systems," in *Proc. IEEE International Symposium on Information Theory (ISIT)*, Seoul, Korea, Jun. 2009, pp. 1020–1024.

[11] M. Haenggi and R. K. Ganti, "Interference in Large Wireless Networks," *Foundations and Trends in Networking (NOW Publishers)*, vol. 3, pp. 127–248, 2008.
[12] M. Haenggi, J. G. Andrews, F. Baccelli, O. Dousse, and M. Franceschetti, "Stochastic geometry and random graphs for the analysis and design of wireless networks," *IEEE J. Sel. Areas Commun.*, vol. 27, pp. 1029–1046, Sep. 2009.
[13] M. Haenggi, "On distances in uniformly random networks," *IEEE Trans. Inf. Theory*, vol. 51, pp. 3584–3586, Oct. 2005.
[14] G. Mao, B. Fidan, and B. Anderson, "Wireless sensor network localization techniques," *Computer Networks*, vol. 51, pp. 2529–2553, Jul. 2007.
[15] Z. Chen, G. Gokeda, and Y. Yu, *Introduction to Direction-of-Arrival Estimation*, Artech House, 2010.
[16] I. S. Gradshteyn and I. M. Ryzhik, *Talbe of Integrals, Series, and Products*, 7th Edition, Academic Press, 2007.



Chao Zhai (S'12) received the B.Sc. degree in communication engineering and M.Sc. degree in communication and information system, both from Shandong University, China, in 2007 and 2010, respectively. From July 2011 to January 2012, he was a visiting student at the Chinese University of Hong Kong. He is currently working toward the Ph.D. degree in electrical engineering at the University of New South Wales, Sydney, Australia. His research interests include cooperative communications and spectrum sharing in cognitive radio networks.



Wei Zhang (S'01-M'06-SM'11) received the Ph.D. degree in electronic engineering from The Chinese University of Hong Kong in 2005. He was a Research Fellow with the Department of Electronic and Computer Engineering, Hong Kong University of Science and Technology, during 2006-2007. From 2008, he has been with the School of Electrical Engineering and Telecommunications, The University of New South Wales, Sydney, Australia, where he is a Senior Lecturer. His current research interests include cognitive radio, cooperative communications, space-time coding, and multiuser MIMO.

He received the best paper award at the 50th IEEE Global Communications Conference (GLOBECOM), Washington DC, in 2007 and the IEEE Communications Society Asia-Pacific Outstanding Young Researcher Award in 2009. He is Co-Chair of Communications Theory Symposium of International Conference on Communications (ICC 2011), Kyoto, Japan. He is an Editor of the IEEE Transactions on Wireless Communications and an Editor of the IEEE Journal on Selected Areas in Communications (Cognitive Radio Series).

Guoqiang Mao received PhD in telecommunications engineering in 2002 from Edith Cowan University. He joined the School of Electrical and Information Engineering, the University of Sydney in December 2002 where he is a Senior Lecturer now. His research interests include wireless localization techniques, wireless multihop networks, graph theory and its application in networking, and network performance analysis. He is a Senior Member of IEEE and an Associate Editor of IEEE Transactions on Vehicular Technology.