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Methods of increasing two-way transmission capacity of wireless ad hoc networks

Kan Yu¹, Guangshun Li^{2*}, Jiguo Yu² and Lina Ni¹

Abstract

Two-way communication is required to support control functions like packet acknowledgement and channel feedback. Most previous works on the transmission capacity of wireless ad hoc networks, however, focused on one-way communication; reverse communication from the destination to the source was ignored. In this paper, we first establish mathematical expression for two-way transmission capacity under the fixing transmission distance (i.e., the distance between the source and the destination is a constant), by introducing the concept of two-way outage and setting different rate requirements in both directions. Next, based on the concept of guard zone and cooperative communication, methods of increasing two-way transmission capacity are proposed. Simulation results show that the proposed methods can improve two-way transmission capacity significantly.

Keywords: Two-way transmission capacity, Guard zone, Cooperative communication

1 Introduction

Recently, more and more attentions have focused on Internet of Things (IoT) applications. The coexistence of a massive number of IoT devices poses a challenge in maximizing the successful transmission capacity of the overall network alongside reducing the multi-hop transmission delay in order to support mission critical applications [1, 2]. As one of the most important and critical part of the IoTs, considerable progress has been made in the field of wireless ad hoc networks, particularly with respect to improving their transmission performance [3]. Two-way communication is one of the fundamental communication methods, such as state feedback among IoT devices, data acknowledgement or route initiation, and update requests. Two-way transmission capacity of a wireless ad hoc network refers to the maximum number of successful transmissions existing per unit network area, constrained by two-way outage probability. The transmission capacity provides a framework to derive closed-form bounds for the interference distribution by using stochastic geometry when the locations of nodes form a Poisson point process

(PPP). Most of the previous works on deriving transmission capacity only focused on one-way transmission capacity (reverse communication from the destination to the source is ignored), which considered the effect of various physical and medium access layer techniques such as successive interference cancellation [4], multiple antennas [5–8], guard zone-based scheduling [9], and cooperative relaying [10, 11].

In the landmark work [12], Truong et al. developed the concept of transmission capacity of two-way communication in wireless ad hoc networks with the concept of a two-way outage. Specifically, they derived an upper bound and an approximation for two-way transmission capacity, which are shown to be relatively tight for small outage probability constraints. Finally, they concluded that the two-way capacity loss is considerable by numerical and simulation results.

First, we consider two-way transmission in a wireless ad hoc network, where each source destination pair has data to exchange from each other and their locations are modeled as a PPP. The success probability with two-way transmission is the probability that the communication in both directions (from source to destination and from destination to source) is successful simultaneously. Then, the two-way outage probability is 1—success probability.

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However, the interference received in both directions is correlated, since the distance between the source and the receiver of interfering transmission and another distance between the destination and the sender of interfering transmission are not independent from each other. Moreover, explicitly computing the correlation between the above two kinds of distances is also a hard problem. In [12], Truong et al. assumed that the interference received in both directions is independent to derive the exact outage probability and transmission capacity of two-way simply.

Instead, to get a meaningful insight into two-way transmission capacity without the simple assumption of independence, we derive lower and upper bounds for outage probability and transmission capacity of two-way. The main contributions of this paper can be summarized as follows:

Considering correlation of interference in both directions and using tools of stochastic geometry, we derive lower and upper bounds for outage probability and transmission capacity of two-way. Specifically, the difference between the lower and upper bounds of two-way transmission capacity is only constrained by a constant $\frac{1}{2} + \frac{1}{\alpha}$, which is consistent with the result in [13], where α is the path-loss exponent.

To increase two-way transmission capacity, we introduce the concept of guard zone, which can be modeled as a disc of radius φ centered at the receiving node; interfering transmissions cannot be allowed to exist within this disc. Specifically, the difference between the lower and upper bounds of two-way transmission capacity in this case is still $\frac{1}{2} + \frac{1}{\alpha}$. By setting properly a guard zone size, we can ignore safely the interference outside φ .

Next, combining cooperative communication with guard zone, two-way transmission capacity can further be increased. Under decode-and-forward relaying scheme, we give a method to find the optimal relay node to achieve maximum successful transmitting nodes per unit area to satisfy outage probability and data rates.

Finally, theoretical analyses are evaluated by simulation results.

2 Methods

For the purpose of deriving expression of two-way transmission capacity in a wireless network, considering guard zone and cooperative communication strategies, we apply FKG inequality, Cauchy-Schwarz inequality to derive outage probability, and two-way transmission capacity. Finally, we utilize the simulator MATLAB to evaluate the performance of guard zone and cooperative communication.

The results of this paper in part have been presented in [12] and [13]. The differences between [12] and [13] and the present paper are as follows. For simplification

of analysis, [12] assumed that the successful reception events in two directions are independent. The independence assumption was removed in [13] and the upper and lower bounds on two-way transmission capacity were shown to be tight. Compared to [13], the present paper introduces the concept of guard zone and cooperative communication to quantify the increment in bidirectional transmission capacity. In addition to this, this paper offers more additional simulation results for more insights into the effects of two-way communication.

The rest of this paper is organized as follows. We summarize the related work in Section 3. In Section 4, we introduce network model and definitions. In Sections 5, 6, and 7, we give the expression of two-way transmission capacity of a wireless ad hoc network. Simulation results are shown in Section 8. Finally, the conclusion and future work are given in Section 9.

3 Related work

In the past few years, most of previous works focused on the transmission capacity of one way (e.g., [4, 5, 9, 14–20]). The concept of one-way transmission capacity was first introduced in [14] and [15] as a way to evaluate the performance of specific communication strategies and different MAC protocols. This performance metric can be used to characterize a decentralized wireless ad hoc network under an outage constraint [14].

By using tools of stochastic geometry to quantify the interference among multiple nodes in the network, in [15], Weber et al. determined the relationship between the optimal spatial density and success probability of transmissions in the network and presented tight upper and lower bounds on transmission capacity via lower and upper bounds on outage probability of one-way. Finally, they applied these results to show how transmission capacity can be used to better understand scheduling, power control, and the deployment of multiple antennas in a decentralized network.

However, these prior works all concentrated on investigating transmission capacity in one-way ad hoc networks (communication from the destination to the source is ignored). Specifically, two-way communication is needed, such as state feedback, packet acknowledgement, and update request. In [12], Truong et al. first developed the concept of transmission capacity of two-way communication in wireless ad hoc networks. An improved version was extended in [13]. In [13], Vaze et al. derived the lower and upper bounds of two-way transmission capacity. The obtained bounds are used to derive the optimal solution for bidirectional bandwidth allocation that maximizes two-way transmission capacity, which is shown to perform better than allocating bandwidth proportional to the desired rate in both directions. Specifically, they showed that an intuitive strategy that allocates the bandwidth in

proportion to the desired rate in each direction is optimal only for symmetric traffic (same rate requirement in both directions) and performs poorly for asymmetric traffic in comparison to the optimal strategy. However, they did not consider the problem of how to increase two-way transmission capacity.

Cooperative communication is one of the popular ways to increase transmission capacity. In [10], Lee et al. analyzed the transmission capacity for dual-hop relaying in a wireless ad hoc network in the presence of both co-channel interference and thermal noise. Specifically, they first presented the exact outage probability for amplify-and-forward and decode-and-forward protocols in a Poisson field of interferers, and then, they derived transmission capacity of such networks. For cognitive radio networks, in [11], Jing et al. proposed a cooperative framework in which a primary sender, being aware of the existence of the secondary network, may select a secondary user that is not in transmitting or receiving mode to relay its traffic. The feasible relay location region and optimal power ratio between the primary network and the secondary network are derived in the underlay spectrum sharing model. Based on the optimal power ratio, they derived the maximum achievable transmission capacity of the secondary network under the outage constraints from both the primary and the secondary network with or without cooperative relaying. However, reverse communication from the destination to the source is ignored.

In fact, two-way communication is closely related to full-duplex scheme. In other words, a successful probability of a half-duplex transmission considers one-way success probability from a sending node to a receiving node, which is not suitable for full-duplex transmission cases; both of these successful probabilities of sending and receiving messages are considered. In [21], Tong and Haenggi considered a wireless network of nodes with both half-duplex and full-duplex capabilities and derived an optimal throughput by using tools of stochastic geometry. In [22], Marašević et al. introduced a new realistic model of a small form-factor (e.g., smartphone) full-duplex receiver and quantified the rate gain as a function of the remaining self-interference and SNR values by considering the multi-channel case. However, their successful probability of a transmission was based on half-duplex rather than full-duplex within the same frequency band and time.

4 Models and definitions

First, we give the definition of Poisson point process (PPP) as follows.

Definition 1 [23] *The PPP Φ of intensity measure Λ is defined by means of its finite-dimensional distributions:*

$$Pr[\Phi(A_1) = n_1, \dots, \Phi(A_k) = n_k] = \prod_{i=1}^k \left(e^{-\Lambda(A_i)} \frac{\Lambda(A_i)^{n_i}}{n_i!} \right),$$

for every $k = 1, 2, \dots$ and all bounded, mutually disjoint sets A_i for $i = 1, \dots, k$. If $\Lambda(dx) = \lambda dx$ is a multiple of Lebesgue measure (volume) in \mathbb{R}^d , Λ is a locally finite non-null measure on \mathbb{R}^d , we call Φ a homogeneous PPP, and λ is its intensity parameter.

It is notable that the Poisson network model can nicely capture the random geometric properties of networks and enable the analytical modeling of network interference statistics in general [24].

4.1 Network model

Consider a wireless ad hoc network consisting of N transmissions, where the sender and its receiver want to exchange data between each other. All senders and receivers construct sender set Φ_T and receiver set Φ_R , respectively. We assume that each node has a single antenna and applies full-duplex scheme. We consider a slotted Aloha random access protocol, where at any given time, the pair of sender-receiver transmits data to each other with an access probability p_a , and the distance between them is fixing value, i.e., d .

The set Φ_T is modeled as a homogenous PPP on a two-dimensional plane with intensity λ_0 , similar to [13] and [25]. Due to one-to-one correspondence relationship of each sender-receiver pair, the set Φ_R is also a homogenous PPP on a two-dimensional plane with intensity λ_0 . According to the assumed Aloha random access protocol, locations of the active senders and receivers Φ_T^a and Φ_R^a are homogenous PPPs on a two-dimensional plane with intensity $\lambda = p_a \lambda_0$.

4.2 The residual self-interference (RSI)

The existence of self-interference is a main challenge in applying full-duplex scheme. Since the interference cancellation is a challenging problem and the number of self-interference cancellation is often related to the wireless network capacity, the residual self-interference has negative effects on the network capacity. Although previous results generally assumed that self-interference can be completely eliminated, in the realistic applications, the self-interference only can be eliminated to the level of noise in the best case. In this paper, we will describe the residual self-interference as a constant fraction of the transmission power P , that is $RSI = gP$, where g is a constant fraction [21] and P is transmission power of all transmitting nodes.

4.3 Interference model

Specifically, we consider the interference-limited wireless networks where the noise power is ignored. Signal

prorogation between senders and receivers is considered under the Rayleigh fading channel. Namely, the strength of received power at receiver r_i transmitted by sender s_i can be represented as Ph_{ii}/d^α , α denotes the path-loss exponent, and h_{ii} denotes the channel fading gain between s_i and r_i , which is an exponentially distributed random variable with unit mean, i.e., $h_{ii} \sim \exp(-1)$ [25, 26]. Furthermore, the received signal-to-interference ratios (SIRs) for the transmissions from s_i to r_i and from r_i to s_i are respectively

$$\gamma_i^f = \frac{Ph_{ii}/d^\alpha}{\sum_{t_j \in \Phi_T^a} Ph_{ji}/d_{ji}^\alpha + gP} \quad (1)$$

and

$$\gamma_i^r = \frac{Ph'_{ii}/d^\alpha}{\sum_{r_j \in \Phi_R^a} Ph'_{ji}/d_{ji}^\alpha + gP}, \quad (2)$$

where d_{ji} and h_{ji} are the distance and channel fading gain between sender s_j and receiver r_i , respectively. Similarly, d'_{ji} and h'_{ji} are the distance and channel fading gain between receiver r_j and sender s_i , respectively. gP is the remaining self-interference.

The network employs frequency duplexing to support two-way communication, i.e., two separate frequency carriers, of which the bandwidths W_f and W_r are used to transmit data in two directions between each pair of nodes. We have used the subscripts “ f ” and “ r ” to indicate the directions, namely *forward direction* and *reverse direction*, respectively. We also refer to the nodes sending information in forward direction as *senders* and their partners as *receivers* [12].

We denote the SIR thresholds in two directions β_f and β_r . The relationship between a decoding threshold and the corresponding transmission rate, i.e., the *forward transmission rate* R_f and the *reverse transmission rate* R_r , can be given by the following equations [12]:

$$R_f = W_f \log_2(1 + \beta_f) \text{bits/sec}, \quad (3)$$

$$R_r = W_r \log_2(1 + \beta_r) \text{bits/sec}. \quad (4)$$

In this study, we employ the following performance metrics: the probability of failure for two-way transmissions, denoted as the probability that the signal reception is failed in at least one direction of a two-way communication, is given by [12, 13]

$$p_{out} = 1 - \Pr \left[\gamma_i^f \geq \beta_f, \gamma_i^r \geq \beta_r \right];$$

the concept of two-way transmission capacity, as shown in the following definition.

Definition 2 [13] *Two-way transmission capacity, denoted by τ , is defined as*

$$\tau = (1 - \epsilon) p_{out}^{-1}(\epsilon) \left(\frac{R_f + R_r}{W_{total}} \right) \text{bits/sec/Hz/m}^2, \quad (5)$$

where ϵ is outage probability constraint, $p_{out}^{-1}(\epsilon)$ denotes the inverse, the maximum spatial density of simultaneously successful two-way links subject to an outage probability constraint of ϵ , and

$$\mu_2(\epsilon) = \max\{\lambda | p_{out} \leq \epsilon\} = p_{out}^{-1}(\epsilon),$$

$W_{total} = W_f + W_r$ is the total available bandwidth.

5 Analysis of two-way transmission capacity

In this section, we derive the upper and lower bounds of two-way transmission capacity.

Lemma 1 *The two-way outage probability of a two-way transmission can be upper-bounded and lower-bounded by*

$$1 - \exp \left[-gd^\alpha (\beta_f + \beta_r) - \lambda\pi C(\alpha) (s_f^\delta + s_r^\delta) \right],$$

and

$$1 - \exp \left[-gd^\alpha (\beta_f + \beta_r) - \lambda\pi \left(\frac{1}{2} + \frac{1}{\alpha} \right) C(\alpha) (s_f^\delta + s_r^\delta) \right],$$

respectively, where $C(\alpha) = \Gamma(1 + \delta)\Gamma(1 - \delta)$, $\Gamma(a) = \int_0^{+\infty} t^{a-1} e^{-t} dt$ is the gamma function, $s_f = d^\alpha \beta_f$, $s_r = d^\alpha \beta_r$, and $\delta = \frac{2}{\alpha}$.

Proof From Slivnyak’s theorem [23], the distribution of a point process is unaffected by adding a reference receiver at the origin, from which the sender is d distance away. Therefore, the interference measured at the reference receiver under this conditional point process is the same as the one measured at any place under a homogeneous PPP. Thus, for a forward direction, the received SIR at the reference receiver is given by \square

$$\gamma_o^f = \frac{Ph/d^\alpha}{\sum_{t_j \in \Phi_T^a} Ph_{jo}/d_{jo}^\alpha + gP}, \quad (6)$$

where h is the channel fading gain between the sender and the reference receiver and h_{ko} and d_{ko} are respectively the channel fading gain and the distance between an interferer k the reference receiver.

By shifting the entire point process so that the corresponding sender of the reference receiver lies at the origin, the received SIR at this sender for reverse direction is given by

$$\gamma_o^r = \frac{Ph'/d^\alpha}{\sum_{r_j \in \Phi_R^a} Ph'_{j_o}/d'_{j_o}{}^\alpha + gP}. \quad (7)$$

The derived process for upper bound of two-way outage probability is given in Formula (8).

$$\begin{aligned} p_{out}(\beta_f, \beta_r) &= 1 - \Pr[\gamma_f' \geq \beta_f, \gamma_r' \geq \beta_r] \\ &= 1 - \Pr[\gamma_f' \geq \beta_f, \gamma_r' \geq \beta_r] \\ &= 1 - \Pr\left[\frac{Phd^{-\alpha}}{\sum_{t_j \in \Phi_T^a} Ph_{j_o}/d'_{j_o}{}^\alpha + gP} \geq \beta_f, \frac{Ph'd^{-\alpha}}{\sum_{r_j \in \Phi_R^a} Ph'_{j_o}/d'_{j_o}{}^\alpha + gP} \geq \beta_r\right] \\ &= 1 - \Pr\left[h \geq d^\alpha \beta_f \left(\sum_{t_j \in \Phi_T^a} h_{j_o} d'_{j_o}{}^{-\alpha} + g\right), h' \geq d^\alpha \beta_r \left(\sum_{r_j \in \Phi_R^a} h'_{j_o} d'_{j_o}{}^{-\alpha} + g\right)\right] \\ &\stackrel{(*)}{=} 1 - \exp(-gd^\alpha(\beta_f + \beta_r)) \mathbb{E}\left[\exp\left(-s_f \sum_{t_j \in \Phi_T^a} h_{j_o} d'_{j_o}{}^{-\alpha}\right) \cdot \exp\left(-s_r \sum_{r_j \in \Phi_R^a} h'_{j_o} d'_{j_o}{}^{-\alpha}\right)\right] \\ &\stackrel{(**)}{\leq} 1 - \exp(-gd^\alpha(\beta_f + \beta_r)) \mathfrak{L}_{\Phi_T^a, I}(s_f) \cdot \mathfrak{L}_{\Phi_R^a, I}(s_r) \\ &= 1 - \exp(-gd^\alpha(\beta_f + \beta_r)) \exp[-\lambda\pi\Gamma(1+\delta)\Gamma(1-\delta)(s_f^\delta + s_r^\delta)] \end{aligned} \quad (8)$$

where $\mathfrak{L}_{\Phi_T^a, I}(s_f)$ and $\mathfrak{L}_{\Phi_R^a, I}(s_r)$ denote the Laplace transform of the interference evaluated at s_f and s_r , respectively, $s_f = d^\alpha \beta_f$ and $s_r = d^\alpha \beta_r$.

Based on the fact that d_{j_o} and d'_{j_o} are not independent [13], although we cannot establish an equation to evaluate the expectation with respect to d_{j_o} and d'_{j_o} in Formula (8), we derive an upper bound by applying FKG inequality [27], i.e., inequality (**) holds in Formula (8). Moreover, term (*) holds since $\Pr[h_{xy} \geq z] = \exp(-z)$ for an exponentially distributed random h_{xy} with unit mean [26].

Using the Cauchy-Schwarz inequality, we derive the lower bound of two-way outage probability, as shown in Formula (9).

$$\begin{aligned} p_{out}(\beta_f, \beta_r) &\stackrel{(*)}{=} 1 - \exp(-gd^\alpha(\beta_f + \beta_r)) \mathbb{E}\left[\exp\left(-s_f \sum_{t_j \in \Phi_T^a} h_{j_o} d'_{j_o}{}^{-\alpha}\right) \cdot \exp\left(-s_r \sum_{r_j \in \Phi_R^a} h'_{j_o} d'_{j_o}{}^{-\alpha}\right)\right] \\ &= 1 - \exp(-gd^\alpha(\beta_f + \beta_r)) \mathbb{E}\left[\prod_{t_j \in \Phi_T^a} \exp(-s_f h_{j_o} d'_{j_o}{}^{-\alpha}) \prod_{r_j \in \Phi_R^a} \exp(-s_r h'_{j_o} d'_{j_o}{}^{-\alpha})\right] \\ &\stackrel{(**)}{\geq} 1 - \exp(-gd^\alpha(\beta_f + \beta_r)) \left\{ \mathbb{E}\left[\prod_{t_j \in \Phi_T^a} [\exp(-s_f h_{j_o} d'_{j_o}{}^{-\alpha})]^2\right] \right. \\ &\quad \left. \mathbb{E}\left[\prod_{r_j \in \Phi_R^a} [\exp(-s_r h'_{j_o} d'_{j_o}{}^{-\alpha})]^2\right] \right\}^{\frac{1}{2}} \\ &= 1 - \exp(-gd^\alpha(\beta_f + \beta_r)) \exp\left[-\lambda\pi\left(\frac{1}{2} + \frac{1}{\alpha}\right)s_f^\delta \Gamma(1-\delta)\Gamma(1+\delta)\left(s_f^{\frac{2}{\alpha}} + s_r^{\frac{2}{\alpha}}\right)\right] \end{aligned} \quad (9)$$

where inequality (**) holds according to the Cauchy-Schwarz inequality, and calculating process is given in Eq. (11).

For the Laplace transform of the interference in Formula (8), we flip the order of integration and expectation, and $\lambda'(r) = 2\pi\lambda r$ is the intensity function of PPP Φ_T^a . Then, we calculate the integral, corresponding calculating process given in Eq. (10).

$$\begin{aligned} \mathbb{E}\left[\exp\left(-s_f \sum_{t_j \in \Phi_T^a} h_{j_o} d'_{j_o}{}^{-\alpha}\right)\right] &= \exp\left\{-\mathbb{E}\left[\int_0^\infty (1 - \exp(-s_f h r^\alpha)) \lambda'(r) dr\right]\right\} \\ &= \exp\left\{-\mathbb{E}\left[\lambda\pi \int_0^\infty (1 - \exp(-s_f h x^{-1})) \delta x^{\delta-1} dx\right]\right\}, \delta = \frac{2}{\alpha}, x = r^{\frac{1}{\alpha}} \\ &= \exp\left\{-\lambda\pi \mathbb{E}\left[(s_f h)^\delta \int_0^\infty t^{(1-\delta)-1} \exp(-t) dt\right]\right\}, t = s_f h x^{-1} \\ &= \exp\left\{-\lambda\pi \mathbb{E}\left[(s_f h)^\delta \Gamma(1-\delta)\right]\right\} = \exp\left\{-\lambda\pi s_f^\delta \mathbb{E}\left[h^\delta\right] \Gamma(1-\delta)\right\} \\ &\stackrel{(*)}{=} \exp\left[-\lambda\pi s_f^\delta \Gamma(1+\delta)\Gamma(1-\delta)\right], \end{aligned} \quad (10)$$

where (*) holds due to $\mathbb{E}[h^\delta] = \Gamma(1+\delta)$ under Rayleigh fading [28].

$$\begin{aligned} \mathbb{E}\left[\prod_{t_j \in \Phi_T^a} \exp(-(s_f h_{j_o} d'_{j_o}{}^{-\alpha})^2)\right] &\stackrel{(*)}{=} \exp\left[-\lambda \int_{R^2} 1 - \left(\frac{1}{1 + s_f x^{-\alpha}}\right)^2 dx\right] \\ &= \exp\left[-2\pi\lambda \int_R \left(\frac{s_f^2 x^{-2\alpha+1} + 2s_f x^{-\alpha+1}}{(1 + s_f x^{-\alpha})^2}\right) dx\right]^{\frac{1}{2}}, \delta = \frac{2}{\alpha}, x = r^{\frac{1}{\alpha}} \\ &\stackrel{(**)}{=} \exp\left(-\lambda\pi\left(\frac{1}{2} + \frac{1}{\alpha}\right)s_f^\delta \Gamma(1-\delta)\Gamma(1+\delta)\right), \end{aligned} \quad (11)$$

where (*) functional of PPP [29], (**) holds according to results in [13].

Theorem 1 *Two-way transmission capacity is lower and upper-bounded by*

$$\begin{aligned} \tau &\geq (1-\epsilon) \frac{\ln\left(\frac{1}{1-\epsilon}\right) - gd^\alpha(\beta_f + \beta_r)}{\pi C(\alpha)(s_f^\delta + s_r^\delta)} \left(\frac{R_f + R_r}{W_{total}}\right) \\ \tau &\leq (1-\epsilon) \frac{\ln\left(\frac{1}{1-\epsilon}\right) - gd^\alpha(\beta_f + \beta_r)}{\pi C(\alpha)\left(\frac{1}{2} + \frac{1}{\alpha}\right)(s_f^\delta + s_r^\delta)} \left(\frac{R_f + R_r}{W_{total}}\right), \end{aligned}$$

respectively.

Most importantly, we can see that the upper and lower bounds of two-way transmission capacity only differ by a constant.

6 Two-way transmission capacity with guard zone

In ad hoc networks, it may be helpful to suppress interfering transmissions around the receiving nodes in order to increase the probability of successful communication. In this section, we introduce the concept of a guard zone, defined as the region around each receiving node where interfering transmissions are inhibited. Using stochastic geometry, the relationship between guard zone size and two-way outage probability (or two-way transmission capacity) is established.

Define the guard zone of a receiving node as a disc of radius φ , denoted by D_φ ; potential transmissions inside this disc are inhibited. Before transmitting data, nodes with some fraction of transmission power broadcast message *stop* to interrupt transmissions within their guard

zone. Thus, for a forward direction, the received SIR at the reference receiver is given by

$$\gamma_{o,\varphi}^f = \frac{Ph/d^\alpha}{\sum_{t_j \in \Phi_T \cap \bar{D}_\varphi} Ph_{j_o}/d_{j_o}^\alpha + gP},$$

where $t_j \in \Phi_T \cap \bar{D}_\varphi$ denotes the set of nodes transmitting simultaneously while potential senders inside the disc D_φ are inhibited, where \bar{D}_φ denotes the area out of the guard zone.

The only difference on calculating outage probability is the lower bound of integration, and we get Eq. (12).

$$\begin{aligned} E\left[\exp\left(-s_f \sum_{t_j \in \Phi_T} h_{j_o} d_{j_o}^{-\alpha}\right)\right] &= \exp\left\{-E\left[\int_\varphi^\infty (1 - \exp(-s_f h r^\alpha)) \lambda'(r) dr\right]\right\} \\ &= \exp\left\{-\lambda\pi E\left[\int_{\varphi^{1/\delta}}^\infty (1 - \exp(-s_f h x^{-1})) \delta x^{\delta-1} dx\right]\right\} \delta = \frac{2}{\alpha} \text{ and } x = r^{1/\delta} \\ &= \exp\left\{-\lambda\pi E\left[\int_{\frac{sh}{\varphi^{1/\delta}}}^\infty t^{(1-\delta)-1} \exp(-t) dt\right]\right\} t = shx^{-1} \\ &= \exp\left[-\lambda\pi s_f^\delta \Gamma(1 + \delta) \Gamma\left(1 - \delta, s \frac{1}{\varphi^{1/\delta}}\right)\right], \end{aligned} \tag{12}$$

where $\Gamma(s, x) = \int_x^\infty t^{s-1} e^{-t} dt$ being the upper incomplete gamma function.

Lemma 2 Using the guard zone, the two-way outage probability of a two-way transmission can be upper-bounded and lower-bounded by

$$1 - \exp\left[-gd^\alpha(\beta_f + \beta_r) - \lambda\pi C(\alpha, \varphi) (s_f^\delta + s_r^\delta)\right],$$

and

$$1 - \exp\left[-gd^\alpha(\beta_f + \beta_r) - c (s_f^\delta + s_r^\delta)\right],$$

respectively, where $C(\alpha, \varphi) = \Gamma(1 + \delta)\Gamma(1 - \delta, \varphi)$, $c = \lambda\pi \left(\frac{1}{2} + \frac{1}{\alpha}\right) C(\alpha, \varphi)$ and $\Gamma(s, x) = \int_x^{+\infty} t^{s-1} e^{-t} dt$ is the upper incomplete gamma function.

Theorem 2 Two-way transmission capacity with guard zone is lower and upper-bounded by

$$\begin{aligned} \tau &\geq (1 - \epsilon) \frac{\ln\left(\frac{1}{1-\epsilon}\right) - gd^\alpha(\beta_f + \beta_r)}{\pi C(\alpha, \varphi) (s_f^\delta + s_r^\delta)} \left(\frac{R_f + R_r}{W_{total}}\right) \\ \tau &\leq (1 - \epsilon) \frac{\ln\left(\frac{1}{1-\epsilon}\right) - gd^\alpha(\beta_f + \beta_r)}{\pi \left(\frac{1}{2} + \frac{1}{\alpha}\right) C(\alpha, \varphi) (s_f^\delta + s_r^\delta)} \left(\frac{R_f + R_r}{W_{total}}\right), \end{aligned}$$

respectively.

Corollary 1 The condition for a positive two-way transmission capacity is given by

$$g \leq \frac{1}{d^\alpha(\beta_f + \beta_r)} \cdot \ln\left(\frac{1}{1 - \epsilon}\right).$$

Lemma 3 If φ satisfies the following inequality, the outage probability of forward transmission is at most σ ,

$$\Gamma(1 - \delta, \varphi) \geq g\beta_f d^\alpha - \frac{\ln\left(\frac{1}{1-\sigma}\right)}{\lambda\pi d^2 \beta_f^\delta \Gamma(1 + \delta)}.$$

In theory, outage probability can never be 0 due to the existence of channel fading. Using guard zone, we consider a transmission as successful if its success probability is greater than $1 - \sigma$; corresponding size of guard zone is denoted by φ_σ .

7 Two-way transmission capacity with cooperative communication and guard zone

Let S_{relay} denote the set of all relay nodes. We consider a two-phase cooperative protocol. During the broadcasting phase, the sender first broadcasts *probing* message with some fraction of transmission power; the relays which can successfully decode the transmitted signal form a decoding set $C_{dec} \subset S_{relay}$, then the sender, its receiver, and selected relay (selecting process will be given as follows) broadcast *stop* message to interrupt interfering transmissions within φ_σ . In the transmission phase, the sender sends data to the selected relay, and then, the latter transmits towards the receiver. By using the guard zone, interference outside φ_σ can be safely ignored (by using Lemma 3), and there are no interfering transmissions by message broadcasting, then the received SNR at selected relay and receiver are $\frac{Ph_{SR} \cdot d_{SR}^{-\alpha}}{gP}$ and $\frac{Ph_{RD} \cdot d_{RD}^{-\alpha}}{gP}$, respectively.

The received SINR of decode-and-forward (DF) with relay R and guard zone of size φ_σ can be written as [10]

$$\begin{aligned} \gamma_{SD} &= \min\left\{\frac{Ph_{SR} \cdot d_{SR}^{-\alpha}}{gP}, \frac{Ph_{RD} \cdot d_{RD}^{-\alpha}}{gP}\right\} \\ &= \min\{\gamma_{S,R(S)}, \gamma_{R(S),D}\}, \end{aligned}$$

and the forward transmission rate R_f is

$$R_f^{DF} = W_f \min\{\log_2(1 + \gamma_{S,R(S)}), \log_2(1 + \gamma_{R(S),D})\}.$$

To maximize R_f , the optimal relay for forward transmission, denoted by R^* , must satisfy the following condition

$$R^* : \max\{R \in C_{dec} \mid \min\{\gamma_{S,R(S)}, \gamma_{R(S),D}\}\}.$$

Using R^* as the optimal relay for reverse communication for simplification of analysis.

Proposition 1 If X_1 is an independent and identically distributed (i.i.d.) exponential random variable with parameter λ_1 , the probability density function (PDF) of the new random variable $X = \frac{X_1}{a}$ for constant a is given by

$$p_X(x) = \begin{cases} \lambda_1 a e^{-\lambda_1 a x}, & x \geq 0 \\ 0, & \text{otherwise} \end{cases} \tag{13}$$

Proposition 2 If X_1 and X_2 are two i.i.d. exponential random variables with parameters λ_1 and λ_2 , the PDF of the new random variable $X = \min\{X_1, X_2\}$ is given by

$$p_X(x) = \begin{cases} (\lambda_1 + \lambda_2)e^{-(\lambda_1+\lambda_2)x}, & x \geq 0 \\ 0, & \text{otherwise.} \end{cases}$$

Proof Due to independence of random variables X_1 and X_2 , we have

$$\begin{aligned} F_X(x) &= \Pr[X \leq x] = 1 - \Pr[X > x] \\ &= 1 - \Pr[X_1 > x, X_2 > x] \\ &= 1 - \Pr[X_1 > x] \cdot \Pr[X_2 > x] \\ &= 1 - (1 - F_{X_1}(x))(1 - F_{X_2}(x)), \end{aligned}$$

where $F_X(\cdot)$ is the cumulative distribution function of random variable X . \square

Applying Propositions 1 and 2, the outage probability, considering high SNR, can be written as

$$\begin{aligned} p_{out} &= \Pr[\min\{\gamma_{SR}, \gamma_{RD}\} < R_f, \min\{\gamma_{DR}, \gamma_{RS}\} < R_r] \\ &= \Pr[\min\{\gamma_{SR}, \gamma_{RD}\} < R_f] \cdot \Pr[\min\{\gamma_{DR}, \gamma_{RS}\} < R_r] \\ &= (\lambda_1 + \lambda_2)^2 \int_0^{R_f} e^{-(\lambda_1+\lambda_2)x} dx \cdot \int_0^{R_r} e^{-(\lambda_1+\lambda_2)x} dx \\ &= [1 - e^{-(\lambda_1+\lambda_2)R_f}] \cdot [1 - e^{-(\lambda_1+\lambda_2)R_r}] \\ &= [1 - e^{-g(d_{SR}^{-\alpha} + d_{RD}^{-\alpha})R_f}] \cdot [1 - e^{-g(d_{SR}^{-\alpha} + d_{RD}^{-\alpha})R_r}] \\ &\leq [1 - e^{-g(d_{SR}^{-\alpha} + d_{RD}^{-\alpha})R_{max}}]^2, \end{aligned}$$

where $R_{max} = \max\{R_f, R_r\}$.

Therefore, to satisfy the given outage probability ϵ and data rate (i.e., quality of service (QoS)), relay node must be properly selected with the following constraint

$$\frac{1}{d_{SR}^\alpha} + \frac{1}{d_{RD}^\alpha} \leq \frac{1}{gR_{max}} \ln\left(\frac{1}{1 - \epsilon^{\frac{1}{2}}}\right), R \in C_{dec}. \quad (14)$$

Theorem 3 Two-way transmission capacity with cooperative communication is lower bounded by

$$\tau \geq (1 - \epsilon)\lambda \left(\frac{R_f + R_r}{W_{total}}\right) \text{ bits/sec/Hz/m}^2$$

if the selected relay satisfies Inequality (14).

8 Results and discussion

8.1 Results

Simulations are carried out on networks constructed by randomly placing nodes on $100 \times 100\text{m}^2$. The distance between a sender and its corresponding receiver is 10 m; related SIR parameters are set to $P = 1$ mW, $\beta_f = 1$ dB, $\beta_r = 1$ dB, $W_f = 0.99$ MHz, $W_r = 0.01$ MHz, $\alpha = 4$, and $g = 0$, as shown in Table 1. Based on Slivnyak's theorem, we place an additional sender on the origin and the coordinate of its

Table 1 Parameters and meanings

Symbol	Meaning
Φ_T	PPP of sender set
Φ_R	PPP of receiver set
ρ_a	Access probability
d	Fixing distance between the source and the destination
h_{ij}	Channel fading gain between sender s_j and receiver r_i
τ	Two-way transmission capacity
R_f	Forward transmission rate
R_r	Reverse transmission rate
ϵ	Outage probability constraint
φ	Radius of guard zone

receiver is (10, 0). The density of relay nodes is set to 0.1, $\epsilon = 0.1$ and guard zone size is set to 10 m. Each reported result in the following parts is the average of 1000 runs, unless otherwise specified.

We first consider the impact of node density on two-way outage probability, as shown in Fig. 1. Outage probability increases over node density increasing, since cumulative interference gets greater at the typical receiver. Moreover, outage probability by using cooperative communication decreases largely compared with results in [12, 13] and that of using guard zone, which means that the theoretical analysis for cooperative communication is effective. On average, the decrements are 91.36% and 74.96%, respectively.

Next, we consider the influence of the transmission distance. As shown in Fig. 2, over d increasing, two-way outage probability increases. This is because, on the one

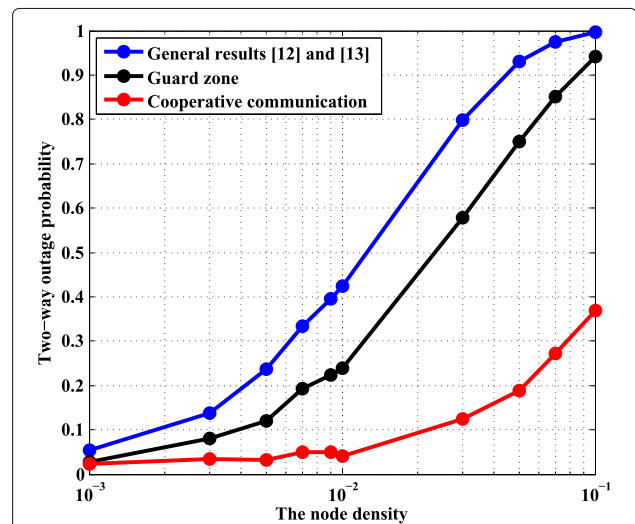


Fig. 1 Two-way outage probability vs. node density. Legends: blue solid line denotes results in [12, 13]; black and red solid lines are results with guard zone and cooperative communication, respectively

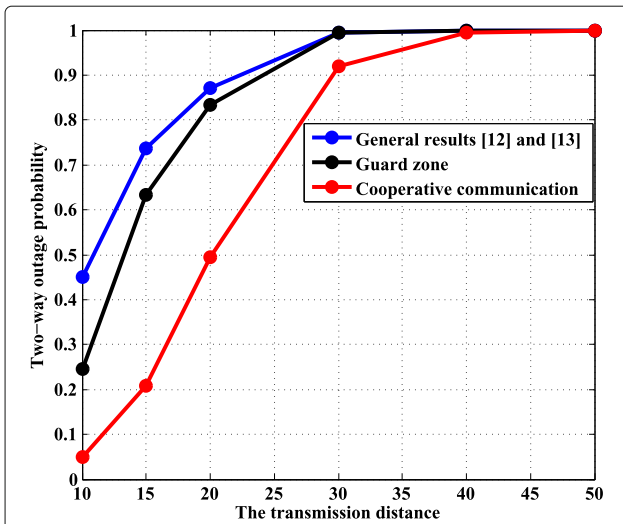


Fig. 2 Two-way outage probability vs. transmission distance. Legends: blue solid line denotes results in [12, 13]; black and red solid lines are results with guard zone and cooperative communication, respectively

hand, the strength of received signal at the typical receiver increases due to longer transmission distance; on the other hand, guard zone size is set to 10 m; when transmission distance is greater than 10 m, there may exist more interferers within d and outside φ , and the typical receiver suffers from more interference. Setting $d = 10$ m, the influence of guard zone size is shown in Fig. 3. We can see that a greater guard zone leads to a smaller two-way outage, since, on the one hand, guard zone interrupts interfering transmissions within φ around the typical receiver;

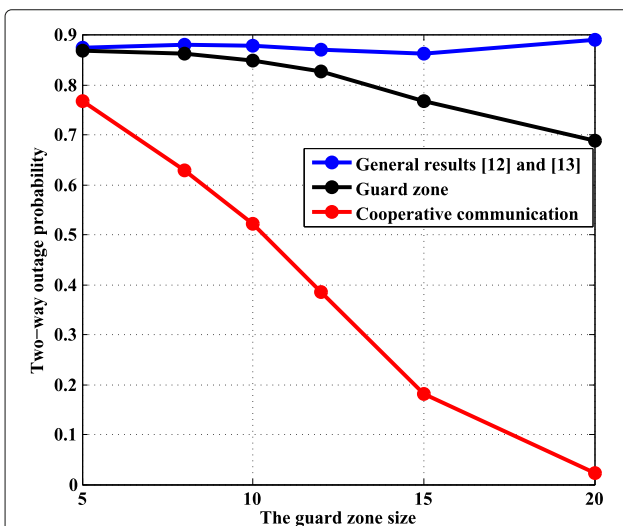


Fig. 3 Two-way outage probability vs. guard zone size. Legends: blue solid line denotes results in [12, 13]; black and red solid lines are results with guard zone and cooperative communication, respectively

on the other hand, cooperative communication selects an optimal relay to increase the strength of received signal at the typical receiver.

Finally, we consider the impact of two-way outage probability two-way transmission capacity. As shown in Figs. 4 and 5, two-way transmission capacity first increases and then decreases. The reason is that capacity expressions are proportional to $(1 - \epsilon) \ln\left(\frac{1}{1-\epsilon}\right)$. Intuitively, as the outage probability ϵ approaches towards 1, a high density of links is allowed in a unit area; however, most of the links fail; therefore, the amount of successfully received information actually decreases.

Compared with results in [12, 13], the proposed methods can decrease two-way outage probability obviously, then two-way transmission capacity is increased according to Theorems 1, 2, and 6.

8.2 Discussion

To simplify deriving process of outage probability, we assume that the distance between the source and the destination is fixing. In our future research, we will tackle the following two limitations that exist in almost all existing research: first, our theoretical analysis considers a more practical case where the distance between an arbitrary source-destination pair is random; second, our analysis ignores the impacts of noise power and node mobility.

9 Conclusion

In this paper, we study two-way transmission capacity of a wireless ad hoc network by using the tools of stochastic geometry. Furthermore, to increase it, we introduce

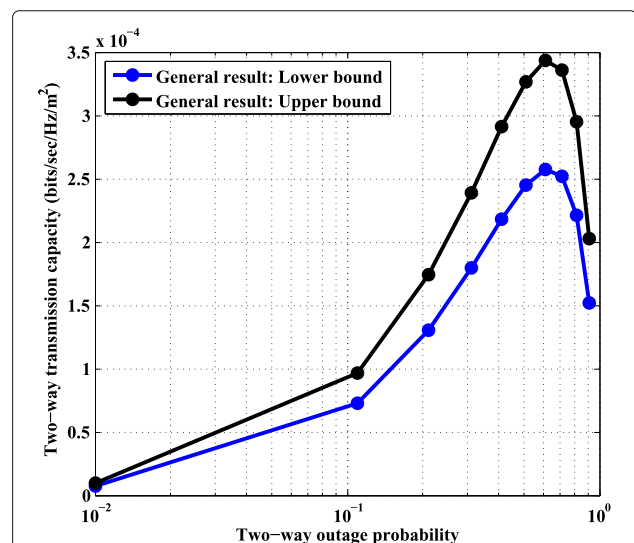
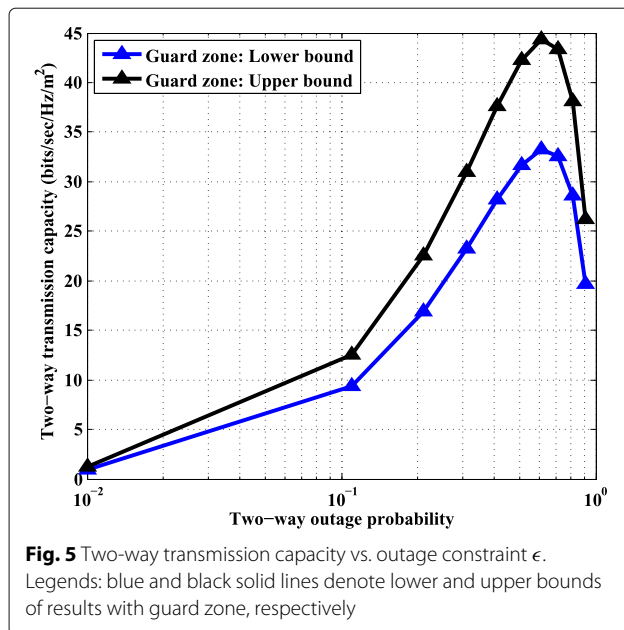


Fig. 4 Two-way transmission capacity vs. outage constraint ϵ . Legends: blue and black solid lines denote lower and upper bounds of results in [12, 13], respectively



the concepts of guard zone and cooperative communication; theoretical analysis and simulation results show that the proposed scheme can effectively decrease two-way outage and increase two-way transmission capacity. Remarkably, we give a method of how to select an optimal relay.

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Authors' contributions

KY and JY designed and analyzed the strategies. GL and KY designed the simulations. JY, GL, KY, and LN wrote the paper. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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