Journal of Southeast University (English Edition) Vol. 28, No. 1, pp. 8 – 13 Mar. 2012 ISSN 1003—7985

Relay selection region and system performance analysis for interfered cooperative ad-hoc networks

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Abstract: The performance of interfered cooperative ad-hoc networks is analyzed by stochastic geometry analysis and a selection region of relay is presented. First, assuming that the distribution of nodes in the random network follows the Poisson point process (PPP), a closed-form expression of the outage probability is derived for the best relay selection (BRS) scheme. Secondly, the capacity of the network is presented for this scheme. Finally, a performance factor is defined to evaluate the performance gain obtained from the BRS. By using this factor, a relay selection region is found to guarantee the performance gain from the BRS. The analysis and simulation results show that the performance of the BRS not only depends on the densities of source nodes and relay nodes but also on the factors of networks such as the path loss factor and the decoding threshold. And the BRS has a greater advantage than direct transmission (DT) in hush environments such as the long transmission distances, much interference and the high decoding thresholds.

Key words: cooperation; interference; relay selection; outage probability; transmission capacity; stochastic geometry analysis

doi: 10.3969/j. issn. 1003 – 7985. 2012. 01. 002

Cooperation is a useful technique to exploit the spatial diversity without installing multiple antennas on a device. It encourages single-antenna devices to cooperatively share their antennas such that a virtual antenna array can be constructed, thereby, enabling performance to be significantly boosted. The best relay selection (BRS) is an attractive alternative of the cooperative schemes, wherein each source is paired with a single best relay chosen from a set of potential ones. The best relay provides the highest capacity between it and the destination. Compared with multi-relay strategies such as distributed space-time coding, BRS strategies are simpler and more efficient[1-3]. It has been proved that the BRS can achieve full-order spatial diversity while avoiding the reduction of spectral efficiency compared with multiple-relay cooperation. The outage performance of the BRS scheme in a point-to-point system has been studied in previous work[4-5].

However, previous analyses for a point-to-point system are not suitable for a large-scale random wireless network such as an overlaid wireless ad-hoc network, a spectrum sharing cognitive radio network or a heterogeneous network constituted by both ultra wide band (UWB) and normal wideband (NWB). On the one hand, interference is a non-ignorable issue in such networks with a large number of concurrent transmissions. On the other hand, the topology is random due to the mobility, death and new arrivals of nodes which leads to random large-scale fading. Thus, both interference and random distances between nodes need to be considered to evaluate the performance of the BRS in a large-scale ad-hoc network. Stochastic geometry[6] provides a natural way of defining and computing macroscopic properties of large-scale networks by averaging over all the potential geometrical patterns of nodes. Based on this theory, several works have been done to extend the investigation from a point-to-point system to a network. Outage performance is presented for the case of non-cooperation communication in Refs. [7 – 8]. For the cooperation case, the outage performance and transmission capacity are investigated without relay selection[9]. Then a relay selection region is presented for decode-and-forward cooperation which is based on a uniformly distributed relay set for each source[10]. But this assumption cannot guarantee that the best relay will be selected. In this paper, the assumptions discussed above for a point-to-point system are removed and the analysis of the BRS is extended to a random network. Then the average outage probability of the BRS and the transmission capacity are presented. Finally, the relay selection region is discussed to find the appropriate density of relay nodes for benefit.

1 System Model and Best Relay Selection

1.1 System model

A wireless ad-hoc network is considered as shown in Fig. 1, which consists of a large number of transmitters distributed over a large plane. The number of transmitters follows a homogeneous Poisson point process (PPP) at a snapshot in time. This assumption is roughly equivalent

Received 2011-10-12.

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Foundation items: The National Science and Technology Major Project (No. 2011ZX03005-004-03), the National Natural Science Foundation of China (No. 61171081), the Science and Technology Support Program of Jiangsu Province (No. BE2011187).

Citation: Xu Yanli, Xia Weiwei, Shen Lianfeng. Relay selection region and system performance analysis for interfered cooperative ad-hoc networks[J]. Journal of Southeast University (English Edition), 2012, 28 (1): 8 – 13. [doi: 10.3969/j. issn. 1003 – 7985. 2012. 01. 002]

as the transmitting nodes are independently and uniformly distributed, which is often reasonable for networks with indiscriminate node placement or substantial mobility[11]. Transmitters select themselves as source nodes, potential relay nodes or free nodes (at sleeping mode) with some fixed probabilities. According to the thinning theory of the Poisson point process[12], the distributions of source nodes and potential relay nodes still follow homogeneous PPPs, which are denoted by $\Theta(\rho_s)$ and $\Theta(\rho_r)$ with node density ρ_s and ρ_r, respectively. The set of receivers is disjoint with that of the transmitters, and each source node has a unique intended receiver at a distance d_0. In this paper, a symbol standing for a node can also be used for denoting the location of this node; e. g., the location of node j is also denoted by j. For easy explanation, a receiver D located at the origin and its associated source S in $\Theta(\rho_s)$ is considered as the reference communication link. The statistical property of this reference communication link can also be applied to others due to stationary character[12].

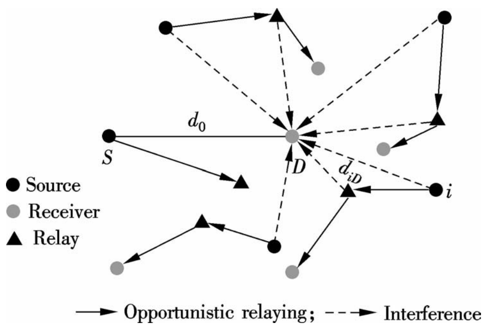

Fig. 1 An example of a wireless ad-hoc network

Signals are subject to large-scale path loss proportional to $d^{-\alpha}$ for distance d and exponent $\alpha>2$ as well as small-scale fading following the Rayleigh distribution with unit variance. Let H_{ij} and d_{ij} characterize the fading power factor and the distance between nodes i and j, respectively. For example, d_{iD} denotes the distance between i and D, and then the probability density function (PDF) of H_{ij} can be written as

$$f(H_{ij}) = e^{-H_{ij}} \qquad H_{ij} \geqslant 0 \tag{1}$$

For such a channel, the received power at j from the transmitter i is

$$p_{ij} = p_t H_{ij} d_{ij}^{-\alpha} \tag{2}$$

where p_t is the transmission power. Then the interference at j induced by other simultaneous source nodes except its source S_j can be expressed as

$$I_{\Theta(\rho_s)} = \sum_{i \in \Theta(\rho_s),\, i \neq S_j} p_{ij} = \sum_{i \in \Theta(\rho_s),\, i \neq S_j} p_t H_{ij} d_{ij}^{-\alpha} \tag{3}$$

where $I_{\Theta(\rho_s)}$ denotes the sum of the interferences induced by simultaneous transmissions. The link between nodes i and j is outage when the signal interference ratio (SIR) at receiver j is below a certain decoding threshold η_{th}, i. e.,

$$P_{out} = P\{\mathrm{SIR} < \eta_{th}\} = P\left\{\frac{p_t H_{ij} d_{ij}^{-\alpha}}{I_{\Theta(\rho_s)}} < \eta_{th}\right\} = P\left\{\frac{H_{ij} d_{ij}^{-\alpha}}{\sum_{i \in \Theta(\rho_s),\, i \neq S_j} H_{ij} d_{ij}^{-\alpha}} < \eta_{th}\right\} \tag{4}$$

From Eq. (4), it can be seen that the outage probability is independent of the transmission power. Hence in the following analyses, the transmission power will be ignored as many previous works have done[13-14] and the comparison between the BRS and the direct transmission (DT) will also be equal without the consideration of the transmission power.

1.2 Cooperation with best relay selection in ad-hoc networks

In the protocol of the decode-and-forward BRS, nodes which decode data from the source correctly will constitute a decoded set. And the best relay is the one with the best channel to the receiver in this set. It is demonstrated that for a broad class of fading distributions, the strongest signal strength at the receiver comes from the closest node at the low and the medium regions of the outage probability[14]. Hence, in this paper the nearest node is selected as the sole best relay to aid the transmission of the reference link. The selection process is divided into two phases. During the first phase, each source node in $\Theta(\rho_s)$ sends its data. The potential relay node in $\Theta(\rho_r)$ tries to decode the data and evaluates the distance from it to the destination. And then the best relay is selected according to its distance to the receiver. As indicated in Ref. [15], it is nearly impossible for a source to have the same relay. In the second phase, each selected relay node acts as a transmitter and helps its source node send data to the destination.

2 Performance Analysis and Relay Selection Region

In our strategy, the source node transmits its data in the first time slot and then the best relay is selected according to the distance to the destination. In the second time slot, the relay retransmits data to the destination. Since both the destination D and the potential relay nodes in $\Theta(\rho_r)$ directly receive data from S, the receiving set of S is defined to be $\Psi = D \cup \Theta(\rho_r)$. Concerning the outage probability, the following proposition is obtained.

Proposition 1 Denote the receiving set of S to be $\Psi = D \cup \Theta(\rho_r)$. For $\forall j \in \Psi$, the outage probability is

$$P_{out,Sj} = 1 - \exp(-c\pi d_{Sj}^2) \tag{5}$$

where $c = \rho_s \kappa \eta_{th}^{m}$, $\kappa = m\Gamma(m)\Gamma(1-m)$, $m = 2/\alpha$ and $\exp(\cdot)$ denotes the exponent function. Let $j = D$, and then the outage probability of the DT can be obtained.

Proof According to Eq. (4) and the definition of the Laplace transform function for a random variable, the outage probability can be written as

$$P_{\mathrm{out},Sj} = P\left\{\frac{H_{Sj}d_{Sj}^{-\alpha}}{I_{\Theta(\rho_s)}} < \eta_{\mathrm{th}}\right\} = 1 - E[\exp(-\eta_{\mathrm{th}}d_{Sj}^{\alpha}I_{\Theta(\rho_s)})] = 1 - L(\eta_{\mathrm{th}}d_{Sj}^{\alpha}) \tag{6}$$

where $E(\cdot)$ and $L(\cdot)$ are the expect value and the Laplace transform function for random variable $I_{\Theta(\rho_s)}$, respectively. And the Laplace transform of the integrated noise $I_{\Theta(\rho_s)}$ can be written as [8]

$$L(w) = \exp(-\pi\rho_s\kappa w^m) \tag{7}$$

Let $w = \eta_{\mathrm{th}}d_{Sj}^{\alpha}$ and substitute the value of $L(\eta_{\mathrm{th}}d_{Sj}^{\alpha}) = \exp(-\pi\rho_s\kappa\eta_{\mathrm{th}}^{m}d_{Sj}^{\alpha})$ into Eq. (6). Then the proof completes.

Denote the subset of $\Theta(\rho_r)$ to be D_s in which the node can decode data from S correctly. Then the distribution of D_s is presented in the following proposition.

Proposition 2 The locations of relay nodes in set D_s follow a nonhomogeneous PPP with intensity measure $\Lambda(A) = \int_A \rho_r\exp(-c\sigma)\mathrm{d}\sigma$, where $A\subset\mathbf{R}^2$ is a closed area.

Proof Define σ to be the area surrounded by the circle whose center is S and the radius is r. Let $\mathrm{d}\sigma$ be an infinitely small area on the interval $[r, r+\mathrm{d}r]$. According to Eq. (6), for a node r away from S, the probability that it can decode data from S correctly is $\exp(-c\pi r^2)$. This means that the node in D_s chooses the location $\mathrm{d}\sigma$ with the probability $\rho_r\exp(-c\pi r^2)$. Thus, for a closed area $A\subset\mathbf{R}^2$, the average number $\Lambda(A)$ of nodes decoding data correctly from S is

$$\Lambda(A) = \int_A \rho_r\exp(-c\sigma)\mathrm{d}\sigma \tag{8}$$

From the above proposition, it is shown that the distribution of the decoded nodes of S follows a nonhomogeneous Possion process which is often assumed to be uniform distributed in previous work. In the BRS scheme, the node in D_s which is the closest to the receiver will be selected as the relay; i. e., $R = \arg\min_{j\in\Theta(\rho_r)}\{d_{jD}\}$. Before analyzing the outage performance for the BRS, the cumulative distribution function (CDF) of the distance d_{RD} from the best relay to the destination D is presented as follows.

Proposition 3 The CDF of the distance d_{RD} from relay node R to the destination D is

$$F_{d_{RD}}(x) = \frac{1 - \exp\left(-\frac{\rho_r\exp(-c\pi d_0^2 - cx^2)}{c}\sum_{k=0}^{\infty}(c\pi d_0)^{2k}\frac{x^{2k}}{k!}\sum_{l=0}^{k}\frac{1}{l!}\right)}{1 - \exp\left(-\frac{\rho_r}{c}\right)} \tag{9}$$

Proof According to the definition of the CDF, $F_{d_{RD}}(x)$ can be written as

$$F_{d_{RD}}(x) = P\{d_{RD}\leqslant x \mid D_s\neq\varnothing\} + P\{d_{iD}\leqslant x \mid D_s = \varnothing\} = P\{d_{RD}\leqslant x \mid D_s\neq\varnothing\} = \frac{1 - P\{d_{RD} > x, D_s\neq\varnothing\}}{P\{D_s\neq\varnothing\}} \tag{10}$$

The event $\{d_{RD} > x, D_s\neq\varnothing\}$ means that there is no node in the circle whose center is D and the radius is x. Since the transmission nodes follow the Possion distribution, the probability of $\{d_{RD} > x, D_s \neq \varnothing\}$ is $\exp(-\Lambda(\pi x^2))$. Thus, the numerator in Eq. (10) can be obtained as

$$1 - P\{d_{RD} > x, D_s\neq\varnothing\} = 1 - \exp(-\Lambda(\pi x^2)) \tag{11}$$

The distance x between node j and D can be expressed by d_{Sj}, d_0 and the included angle θ between them,

$$x^2 = d_{Sj}^2 + d_0^2 - 2d_{Sj}d_0^2\cos\theta \tag{12}$$

Then substituting Eqs. (8) and (12) into Eq. (11) yields

$$\begin{aligned} &1 - P\{d_{RD} > x, D_s \neq \varnothing\} = \\ &1 - \exp\left(-\int_{2\pi}^{0}\mathrm{d}\theta\int_0^x r\rho_r\exp(-c\pi(r^2 + d_0^2 - 2rd_0\cos\theta))\mathrm{d}r\right) = \\ &1 - \exp(-\pi\rho_r\exp(-c\pi d_0^2)\int_0^x 2r\mathrm{e}^{-c\pi r^2}I_0(2c\pi d_0 r)\mathrm{d}r) = \\ &1 - \exp\left(-\frac{\rho_r\exp(-c\pi d_0^2 - cx^2)}{c}\sum_{k=0}^{\infty}(c\pi d_0)^{2k}\frac{x^{2k}}{k!}\sum_{l=0}^{k}\frac{1}{l!}\right) \end{aligned} \tag{13}$$

In a similar way, the denominator in Eq. (10) can be calculated by

$$\begin{aligned} &P\{D_s \neq \varnothing\} = \\ &1 - \exp\left(-\int_0^{2\pi}\mathrm{d}\theta\int_0^{\infty} r\rho_r\exp(-c(r^2 + d_0^2 - 2rd_0\cos\theta))\mathrm{d}r\right) = \\ &1 - \exp\left(-\frac{\rho_r}{c}\right) \end{aligned} \tag{14}$$

Then substituting Eqs. (13) and (14) into Eq. (10) completes the proof.

There are infinite series in Eq. (13) which can quickly converge according to d'Alembert's ratio test. Hence the following formula can be used for approximating it by using the former L factors and then the CDF of the nearest distance d_{RD} can be written as

$$F_{d_{RD}}(x) = \frac{1 - \exp\left(-\frac{\rho_r\exp(-c\pi d_0^2 - cx^2)}{c}\Phi(x)\right)}{1 - \exp\left(-\frac{\rho_r}{c}\right)} \tag{15}$$

where $\Phi(x) \approx \sum_{k=0}^{\mathrm{L}}(c\pi d_0)^{2k}\frac{x^{2k}}{k!}\sum_{l=0}^{k}\frac{1}{l!}$.

So far the distribution of the distance d_{RD} has been obtained which will be used for the analysis of the outage performance. According to Eq. (4), the outage probability of the BRS can be expressed as

$$P_{\text{out,BRS}} = P\left\{\frac{H_{RD}d_{RD}^{-\alpha}}{I_{\Theta(\rho_s)}} \leqslant \eta_{\text{th}}\right\} = 1 - P\{H_{RD} > d_{RD}^{\alpha}\eta_{\text{th}}I_{\Theta(\rho_s)}\} =$$

$$1 + \int_0^{\infty} F(d_{RD})\,\mathrm{d}(\exp(-cd_{RD}^2)) \qquad (16)$$

Substituting the CDF of d_{RD} derived in Proposition 3 into Eq. (16) yields the expression for the outage probability as follows:

$$P_{\text{out,BRS}} = \frac{\int_0^1 \exp\left(-\frac{\rho_r\exp(-c\pi d_0^2)x}{c}\sum_{k=0}^{\infty}(c\pi d_0^2)^k\frac{(-\ln x)^k}{k!}\sum_{l=0}^{k}\frac{1}{l!}\right)\mathrm{d}x - \exp\left(-\frac{\rho_r}{c}\right)}{1-\exp\left(-\frac{\rho_r}{c}\right)} \qquad (17)$$

As indicated in the previous part of this paper, the series in above formula converge quickly. Here the first two factors of the series are used and then a simplified expression for the integration in Eq. (17) can be obtained,

$$\int_0^1 \exp\left(-\frac{\rho_r\exp(-c\pi d_0^2)x}{c}\sum_{k=0}^{\infty}(c\pi d_0^2)^k\frac{(-\ln x)^k}{k!}\sum_{l=0}^{k}\frac{1}{l!}\right)\mathrm{d}x \approx$$
$$\int_0^1 \exp\left(-\frac{\rho_r\exp(-c\pi d_0^2)x}{c}(1-2c\pi d_0^2\ln x)\right)\mathrm{d}x =$$
$$\Phi(\rho_r)\gamma\left(\mu,\frac{\mu-1}{2c\pi d_0^2}\right) \qquad (18)$$

where $\Phi(\rho_r) = \left(\frac{\rho_r\exp(-c\pi d_0^2)}{c}\right)^{\mu}$ and $\mu = \frac{\rho_r\exp(-c\pi d_0^2)}{c}$. Thus, the outage probability can be written as

$$P_{\text{out,BRS}} = \frac{\Phi(\rho_r)\gamma\left(\mu,\frac{\mu-1}{2c\pi d_0^2}\right) - \exp\left(-\frac{\rho_r}{c}\right)}{1-\exp\left(-\frac{\rho_r}{c}\right)} \qquad (19)$$

The transmission capacity is defined as the number of successful transmissions per unit area[16], which is an important performance metric for random networks. Given the source node density ρ_s, the transmission capacity of the BRS is

$$\text{TC}_{\text{BRS}} = \rho_s\frac{1-\Phi(\rho_r)\gamma\left(\mu,\frac{\mu-1}{2c\pi d_0^2}\right)}{1-\exp\left(-\frac{\rho_r}{c}\right)} \qquad (20)$$

For comparison, the transmission capacity of the DT is also presented here. The outage probability of the DT can be obtained from Proposition 1. Then the transmission capacity of the DT is

$$\text{TC}_{\text{DRT}} = \rho_s\exp(-c\pi\rho_s d_0^2) \qquad (21)$$

To evaluate the performance gain provided by the BRS, the relay selection gain $G(\rho_r)$ is defined as the ratio of the transmission capacity of the BRS and the transmission capacity of the DT, namely

$$G(\rho_r) = \frac{1-\Phi(\rho_r)\gamma\left(\mu,\frac{\mu-1}{2c\pi d_0^2}\right)}{\left(1-\exp\left(-\frac{\rho_r}{c}\right)\right)\exp(-c\pi\rho_s d_0^2)} \qquad (22)$$

It can be noticed that there is a relay region to guarantee the performance gain from the BRS; i.e., there is a low relay density $\overline{\rho_r}$ to make sure that $G(\overline{\rho_r}) \geqslant 1$. Hence,

$$\overline{\rho_r} \geqslant c\Xi^{-1}(\exp(-c\pi\rho_s d_0^2)) \qquad (23)$$

where

$$\Xi(x) = \frac{1-a^{\mu}\gamma(2c\pi d_0^2 a+1, a)}{1-\mathrm{e}^{-x}}$$
$$a = \exp(-c\pi d_0^2 x)$$

and $\Xi^{-1}(\cdot)$ is its inverse function.

3 Simulation Results

In this section, several results are presented to verify the outage probability and the transmission capacity obtained in Section 2. The simulation parameters considered here include the density of source nodes ρ_s, the density of potential relay nodes ρ_r, the threshold for decoding data correctly η_{th} and the path loss factor α. The following results will evaluate how these parameters impact on the performance of the cooperative random networks.

The outage probabilities vs. the densities of source node ρ_s for different transmission distances d_0 are shown in Fig. 2 when $\rho_r = 1$, $\eta_{\text{th}} = 10$ dB and $\alpha = 3$. By comparing the curves for the DT and the BRS, it can be observed that the outage probabilities are greatly reduced by the BRS. Furthermore, the outage probability decreases with the distance d_0 for the DT which is easy to find. However, the larger path loss fading (larger d_0) has less effect on the BRS, especially, at the region of low ρ_s. It means that when the transmission range is larger, more benefits from the BRS can be obtained.

The transmission capacities vs. the densities of source node ρ_s for different densities of potential relay nodes ρ_r are shown in Fig. 3. The transmission capacity cannot always increase with the density ρ_s although the greater density of simultaneous transmitters brings more space reuse. That is because greater ρ_s can also lead to severer interference, and then communication links are more likely to result in outage. It is also indicated that the maximum gain $G_{\max}$ can be achieved by choosing appropriate ρ_s. Comparing the curves for different ρ_r, it can be found that the transmission capacity largely increases with ρ_r in the

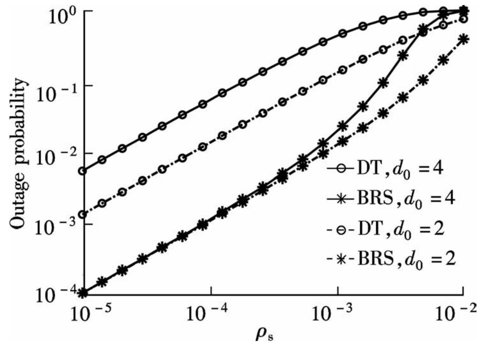

Fig. 2 Outage probability vs. ρ_s for different transmission distances d_0

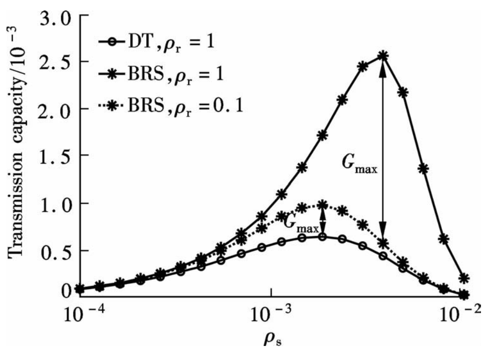

Fig. 3 Transmission capacity vs. ρ_s for different relay densities ρ_r

medium and high intervals of ρ_s while enlarging has little effect on the transmission capacity at the small value of ρ_s.

The performance gain defined in Eq. (22) vs. ρ_r is shown in Fig. 4 when $\rho_s = 10^{-5}$. In this figure, benefit regions are described for different curves which are encircled by dash lines. By using these regions, it is easy to find when to use the BRS for better performance gain. As described in Fig. 4, the BRS cannot always perform better than the DT. That is because the links between the source nodes and the potential relay nodes are more probable to result in outage when ρ_r is small. As for the path loss factor α, the BRS performs better at a smaller α when ρ_r is

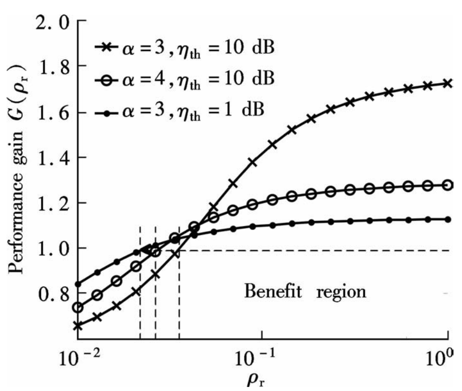

Fig. 4 Performance gain obtained by BRS vs. the density of relay nodes ρ_r with different η_{th} and α

in the benefit region. Concerning the threshold η_{th}, the performance gain increases with η_{th}. From the above results, it can be noticed that the BRS has a greater advantage than the DT in harsh environments such as the long transmission distances, the high decoding thresholds and the large source node densities. These results will be useful for choosing appropriate relay regions for different parameters such as α, η_{th} and ρ_s.

4 Conclusion

In this paper, the performance of a large-scale cooperative ad-hoc network with the BRS has been investigated in the Rayleigh fading environment. Using stochastic geometry theory to handle the spatial distribution of nodes, and considering the influence of interference, the analytical expressions for the outage performance and transmission capacity are derived. Furthermore, a performance factor is defined to evaluate the performance gain supplied by the BRS, which can be used for adjusting the density of relay nodes to benefit from the BRS. This provides us a practical way to guarantee the performance of a cooperative network. The numerical results from the analytical expressions show that the performance of the BRS not only depends on the density of transmitting nodes but also on the transmission distance. Thus, it is important to choose appropriate densities of source nodes and relay nodes to guarantee the performance of the network. Furthermore, the results indicate that the BRS can obtain a better performance gain over the DT in harsh environments such as the large distances needed to transmit, much interference induced by high densities of source nodes and the high required decoding thresholds.

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有扰环境协作自组织网络的中继区域选择及系统性能分析

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摘要:采用随机几何方法,分析了有扰的协作自组织网络的性能并给出中继的选择区域. 首先,假设随机网络中的节点服从泊松分布,得到最佳中继选择算法中断概率的闭式解;其次, 给出了此算法的网络容量;最后,定义性能参数来衡量采用最佳中继选择算法带来的性能增益,并根据此参数得到中继选择区域以保证采用最佳中继选择算法时可以得到的性能增益. 分析和仿真结果表明:最佳中继选择算法的性能不仅取决于源节点和中继节点的密度,还与路径损耗参数和解码门限等网络参数有关,在传输距离较远、干扰较多、解码门限较高等情况下比直接传输具有更大的优势.

关键词:协作; 干扰;中继选择;中断概率;传输容量;随机几何分析

中图分类号:TN915