Reliability Benefit of Location-Based Relay Selection for Cognitive Relay Networks

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***Abstract*—In this article, we develop an analytical framework to study the impact of location-based relay selection strategy on the reliability of cognitive relay networks. By utilizing the tool of stochastic geometry, we first derive a closed-form expression for the reliability-enhanced region (RER), where relaying transmission can achieve higher transmission reliability than direct transmission. Then, we adopt the normalized reliability gain (NRG) to quantify the reliability benefit obtained by using relaying transmission compared to direct transmission, and we obtain the spatial distribution of NRG in the RER. Subsequently, by taking the spatial random nature of relays' distribution into account, we investigate the reliability benefit obtained by secondary networks with the optimal location-based relay selection (OLB-RS) strategy. To reduce the feedback overhead during relay selection, we propose a region-aware relay selection (RA-RS) strategy and obtain the achievable reliability benefit. The results indicate that the reliability is highly dependent on the location of relay, and the OLB-RS strategy is to select the relay closest to the midpoint between the corresponding secondary source and destination.**

***Index Terms*—Cognitive relay networks (CRNs), location-based relay selection, reliability benefit, stochastic geometry.**

I. Introduction

According to the latest statistics released by Cisco [1], the number of global wireless devices will reach 12.3 billion and the global wireless data traffic will grow to 77 exabytes per month by 2022. The large scale of devices being connected to the Internet, where the data are generated by the things without any human intervention, has brought in the notion of the Internet of Things (IoT). IoT has a wide application in several fields, including electrical, medical, transportation, military, environmental protection, home automation, and so on. To accommodate the explosive growth of wireless IoT devices and their traffic, a vast amount of radio-frequency spectrum is needed. However, the radio-frequency spectrum is a scarce resource, and there is little available radio-frequency spectrum remaining for new wireless communication services in the most often used frequency bands (below 6 GHz) [2]. Under this condition, cognitive radio (CR) has been introduced as an effective way to alleviate the spectrum scarcity problem in wireless communications [3]. There are two main types of CR: 1) overlay CR and 2) underlay CR. In underlay CR systems, to provide sufficient protection for primary networks, the transmit power of the secondary transmitter is strictly constrained, which limits the performance of secondary networks. To mitigate such drawbacks, cognitive relay networks (CRNs), where one or more relays assist the transmission between the secondary source and destination, are introduced to enhance the coverage and reliability of secondary networks [4].

In CRNs, the performance is highly dependent on the relay location due to the distance-dependent path loss. Meanwhile, since fading usually changes at a much faster time scale than relay locations, the location-based relay selection can reduce the relay switching rate and the feedback overhead as compared to the conventional relay selection based on the full channel state information (CSI) [5], which will facilitate the deployment of CRNs. Therefore, it is necessary to quantitatively evaluate the impact of the location-based relay selection strategy on the performance of CRNs.

In this article, we provide a tractable analytical framework to characterize the reliability benefit of CRNs with location-based relay selection strategies. Specifically, we first derive the mathematical expressions for the reliability-enhanced region (RER) and the spatial distribution of the normalized reliability gain (NRG). Based on these expressions, we further analyze the achievable reliability benefit of CRNs with different location-based relay selection strategies. Finally, we propose a region-aware relay selection (RA-RS) strategy to further reduce the feedback overhead during relay selection. This work will answer when and how much reliability benefit can be obtained by relaying transmission with only the node's location information in CRNs.

A. Related Works

The prior art on CRNs can be grouped into two categories. One is about the performance analysis and evaluation of CRNs under different scenarios, and the other is about the transmission scheme design of CRNs. For the

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performance analysis, the outage performance and ergodic capacity of CRNs with a single relay had been investigated under the amplify-and-forward (AF) relaying [6], [7], decode-and-forward (DF) relaying [8], [9], two-way relaying [10], and full-duplex relaying protocols [11]. Moreover, the ergodic capacity and outage probability of CRNs with multiple relays were also studied with the best relay selection [12], [13], *N*th best relay selection [14], and imperfect hardware factors [15]. In order to further improve the performance of CRNs, multiantenna technology was introduced in CRNs, and its outage performance was studied in [16]. In addition, the security capacity and energy efficiency of CRNs were evaluated in [17]–[19], respectively. For the transmission scheme design, Zhong and Zhang [20] proposed an opportunistic relay transmission scheme to maximize the outage performance for CRNs. In [21], a relay selection transmission scheme in CRNs was designed to maximize energy efficiency. To optimize the security outage performance of CRNs, Jia *et al.* [22] investigated an efficient transmission scheme based on relay selection. Simultaneous wireless information and power transfer (SWIPT) in CRNs with an aim to optimize different performance metrics was studied [23], [24]. CRNs with nonorthogonal multiple access (NOMA) transmission were also designed to improve the spectral efficiency [25]–[28]. Furthermore, an efficient beamforming transmission scheme with multiple-antenna configuration was investigated under certain performance [29], [30].

The aforementioned works all focus on the cases where relays' locations are fixed and known, and they mainly investigate the impact of small-scale fading on the performance and design of CRNs. By taking the spatial random nature of relays' distribution into account due to node mobility, the performance of CRNs is affected not only by the small-scale fading but also by the location of relays. There have been a few works on CRNs with spatial randomly distributed relays (RCRNs) [31], [32]. Dhungana and Tellambura [31] proposed the best relay selection strategy based on fading gain and relay location for RCRNs, and the outage probability was also derived. However, the proposed relay selection strategy in [31] requires the location information and CSI of all relays, which may be unavailable in practice due to the high feedback overhead during relay selection. In order to reduce the feedback overhead of relay selection, an efficient relay selection strategy based on partial location information and CSI of good relays was presented in [32]. However, the total feedback overhead is still very high because of frequent feedback resulting from highly dynamic CSI.

It is noted that the evolution rate of small-scale fading is much faster than that of relay location in RCRNs, which indicates that the variations of CSI and relay locations are under different time scales. Consequently, compared to the conventional relay selection strategies based on the instantaneous CSI or both CSI and relay locations (such as [31] and [32]), the relay selection-based only on relay locations can further reduce the feedback overhead and the relay switching rate, which will facilitate the deployment of CRNs. Nevertheless, to the best of our knowledge, how much reliability benefit can be obtained by the location-based relay selection in RCRNs has not been well understood.

B. Our Work and Contribution

Motivated by these key observations, in this article, by considering the time-scale separation between fading and relay locations, we investigate the impact of relay location and location-based relay selection strategy on the reliability in RCRNs. The main contributions of this article can be summarized as follows.

1) RER where relays can be selected to improve the reliability compared to the direct transmission is mathematically described. The RER is shown to be a disk centered at the midpoint between the secondary source and destination with radius $d_s/2$, where d_s is the distance from the secondary source to its destination.
2) NRG is defined for quantifying the reliability benefit, and the spatial distribution of NRG in RER is obtained. The NRG decreases with the distance from the relay to the midpoint between the secondary source and destination, and the reliability gain contours are concentric circles.
3) For RCRNs, the achievable NRG of the random relay selection (R-RS) strategy and the optimal location-based relay selection (OLB-RS) strategy is obtained. Furthermore, the selection gain of OLB-RS with respect to R-RS is also evaluated.
4) To further reduce the feedback overhead, an RA-RS strategy is presented, and its achievable NRG is obtained.

C. Organization and Notations

The remainder of this article is organized as follows. Section II presents the system model. The RER is proposed, and the spatial distribution of NRG in RER is derived in Section III. On this basis, in Section IV, we investigate the reliability benefit of the OLB-RS strategy and R-RS strategy. For comparison, the reliability benefit of the R-RS strategy is also analyzed. In Section V, to further reduce the feedback burden, an RA-RS scheme is proposed and its achievable reliability benefit is also evaluated. Numerical results are provided in Section VI. Finally, a brief conclusion is drawn in Section VII.

Notations: $\mathbb{E}[X]$ and $\mathcal{L}(X)$ represent the mean and the Laplace transform of random variable (RV) X, respectively. The exponential function is denoted as $\exp(\cdot)$.

II. SYSTEM MODEL

In this section, we present the network model and channel model of the CRN with spatial randomly distributed nodes.

A. Network Model

We consider an RCRN as illustrated in Fig 1, where the primary network shares the licensed spectrum with the secondary network with the underlay mode and satisfying the primary network outage constraint η_{th}. The primary network incorporates a good deal of primary transmitter–receiver pairs. We

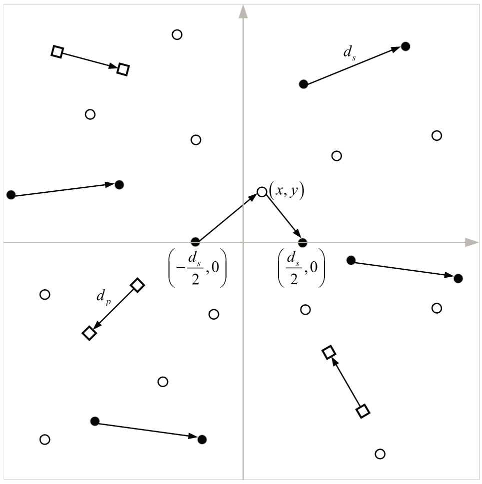

Fig. 1. System model, where squares and solid circles are primary and secondary nodes, and hollow circles are relays in the secondary network.

model the distribution of the primary transmitters (PTs) as a Poisson point process (PPP) Φ_{pt} in the 2-D plane $\mathbb{R}^2$ with density λ_p. The primary receivers (PRs) are assumed to be located at a distance d_p from their transmitters in a random direction, which also form a PPP Φ_{pr} with density λ_p. The secondary network includes multiple secondary source–destination pairs and relays. The spatial distribution of secondary source (*SS*) nodes follows a PPP Φ_s with density λ_s, and each *SS* is associated with a secondary destination (*SD*) node located at a distance d_s in a random direction. Moreover, the spatial distribution of relays which have the DF capability follows another PPP Φ_r with density λ_r. An SS can transmit messages to its *SD* directly or with the help of a half-duplex DF relay, and the relay selection is performed by a central control node (such as *SS*). The transmit power of PTs and *SSs* is P_p and P_s, respectively.

B. Channel Model

The wireless channel between the transmitter and receiver consists of large-scale path loss and small-scale fading. The large-scale path loss is modeled with a general power-law path-loss model with loss exponent α ($\alpha > 2$). Therefore, the path loss between the transmitter a and receiver b is $d_{ab}^{-\alpha}$, where $d_{ab} = |a-b|$ denotes the distance between a and b. The small-scale fading is modeled with the independent and identically distributed (i.i.d.) Rayleigh fading model with unit mean power. Thus, the channel fading power gain follows exponential distribution with unit mean, which can be expressed as exp(1). It is assumed that the system is interference limited and, therefore, the thermal noise can be neglected.

III. Reliability Enhanced Region and Spatial Distribution of Reliability Gain

In this section, we first derive the successful transmission probability of secondary networks with direct transmission and relaying transmission, respectively. Then, we derive the expression of RER, where relays can be selected to improve the reliability compared to the direct transmission. Finally, we define the NRG and derive the spatial distribution of reliability gain in RER.

A. Successful Transmission Probability

Without loss of generality, for a typical secondary source–destination pair, it is assumed that *SS* and *SD* are located at the Cartesian coordinates $(-[d_s/2], 0)$ and $([d_s/2], 0)$, respectively. Moreover, it is assumed that a relay *SR* is located at (x, y). We assume each node is aware of its own location either through some localization techniques or the GPS/Beidou system. In underlay CR paradigms, the communication between *SS* and *SD* is not only interfered by the transmission of other secondary source–destination pairs but also by the transmission of the primary network. Therefore, while *SS* transmits messages to *SD* directly, the received signal-to-interference ratio (SIR) at *SD* can be expressed as

$$\gamma_{sd} = \frac{P_s d_s^{-\alpha} g_{sd}}{I_{ss} + I_{ps}} \tag{1}$$

where g_{sd} denotes the small-scale fading of the channel between *SS* and *SD*. $I_{ss} = \sum_{i \in \Phi_s \backslash 0} P_s d_{is}^{-\alpha} g_{is}$ and $I_{ps} = \sum_{j \in \Phi_{pt}} P_p d_{js}^{-\alpha} g_{js}$ represents the interference from other secondary transmitters and the primary network, respectively. g_{is} and d_{is} are the channel gain and the distance between the ith *SS* to the typical *SD*, respectively. g_{js} and d_{js} are the channel gain and the distance between the jth *PS* to the typical *SD*, respectively. The symbol of "\" represent the meaning of "except."

The successful transmission probability is defined as the probability that the received SIR is not less than the required threshold. Thus, in the direct transmission scenario, the successful transmission probability of the *SS*-*SD* communication pair can be expressed as

$$P_{\text{suc}}^{\text{dir}} = \Pr\left(\gamma_{sd} = \frac{P_s d_s^{-\alpha} g_{sd}}{I_{ss} + I_{ps}} \geq \Gamma_s\right) \tag{2}$$

where Γ_s is the required SIR threshold.

Lemma 1: The success transmission probability of a typical secondary source–destination pair with the direct transmission in RCRNs is given by

$$P_{\text{suc}}^{\text{dir}} = \exp\left(-\mu d_s^2\right) \tag{3}$$

where

$$\mu = \frac{2\pi^2 (\Gamma_s)^{\frac{2}{\alpha}} \ln(1-\eta_{th}) \lambda_s}{\lambda_p 2\pi^2 d_p^2 \left(\Gamma_p\right)^{\frac{2}{\alpha}} + \alpha \sin\left(\frac{2\pi}{\alpha}\right) \ln(1-\eta_{th})} \tag{4}$$

and Γ_p is the required SIR threshold of the primary network.

Proof: The fading gain g_{sd} follows the exponential distribution with unit mean, and it is independent of the interferences I_{ss} and I_{sp}. Thus, (2) can be rewritten as:

$$\begin{aligned} P_{\text{suc}}^{\text{dir}} &= \Pr\left(g_{sd} \geq \frac{\Gamma_s d_s^{\alpha}\left(I_{ss} + I_{ps}\right)}{P_s}\right) \\ &= \mathbb{E}_{I_{ss}}\left[e^{-\frac{\Gamma_s d_s^{\alpha} I_{ss}}{P_s}}\right] \mathbb{E}_{I_{ps}}\left[e^{-\frac{\Gamma_s d_s^{\alpha} I_{ps}}{P_s}}\right] \end{aligned}$$

$$= \mathcal{L}_{I_{ss}}\left(\frac{\Gamma_s d_s^\alpha}{P_s}\right)\mathcal{L}_{I_{ps}}\left(\frac{\Gamma_s d_s^\alpha}{P_s}\right)$$

$$\overset{(a)}{=} \exp\left(-\frac{2\pi^2(\Gamma_s)^{\frac{2}{\alpha}} d_s^2}{\alpha\sin\left(\frac{2\pi}{\alpha}\right)}\left(\lambda_s + \lambda_p\left(\frac{P_p}{P_s}\right)^{\frac{2}{\alpha}}\right)\right) \quad (5)$$

where (a) can be obtained from the Laplace transform of PPP [33].

In RCRNs, the transmission reliability of the primary network should be guaranteed. It is assumed that the successful transmission probability of the primary network cannot be less than η_{th}, and *SS* sends messages to *SD* with the maximum allowed transmit power. Therefore, according to (4) in [32], the ratio of P_p to P_s should satisfy the following equality:

$$\frac{P_p}{P_s} = \left(-\frac{2\pi^2(\Gamma_p)^{\frac{2}{\alpha}} d_p^2 \lambda_s}{2\pi^2(\Gamma_p)^{\frac{2}{\alpha}} d_p^2 \lambda_p + \alpha\sin\left(\frac{2\pi}{\alpha}\right)\ln(1-\eta_{th})}\right)^{\frac{\alpha}{2}}. \quad (6)$$

Then, by substituting (6) into (5), we can obtain (3). ■

In the relaying transmission scenario, *SS* sends data to *SD* in two hops via a DF relay, which locates at (x, y). The successful transmission from *SS* to *SD* occurs while the transmission is successful in both the first and second hops. Hence, under the scenario of relaying transmission, the successful transmission probability of the *SS*-*SD* communication pair can be expressed as

$$P_{\text{suc}}^{\text{relay}} = \Pr(\gamma_{sr} \geq \Gamma_s, \gamma_{rd} \geq \Gamma_s)$$
$$= \Pr\left(\frac{P_s d_{sr}^{-\alpha} g_{sr}}{I_{ss} + I_{ps}} \geq \Gamma_s\right)\Pr\left(\frac{P_s d_{rd}^{-\alpha} g_{rd}}{I_{ss} + I_{ps}} \geq \Gamma_s\right) \quad (7)$$

where $d_{sr} = \sqrt{(x + [d_s/2])^2 + y^2}$ and $d_{rd} = \sqrt{(x - [d_s/2])^2 + y^2}$ represent the distance from *SS* to the relay and from the relay to *SD*, respectively. g_{sr} and g_{rd} denote the fading gain of the first hop and the second hop, respectively.

Similar to the derivation of (3), the exact closed-form expression for successful transmission probability of a typical secondary source–destination pair through relaying is obtained as

$$P_{\text{suc}}^{\text{relay}} = \exp\left(-\mu\left(d_{sr}^2 + d_{rd}^2\right)\right)$$
$$= \exp\left(-\mu\left[\left(x + \frac{d_s}{2}\right)^2 + y^2 + \left(x - \frac{d_s}{2}\right)^2 + y^2\right]\right)$$
$$= \exp\left(-\mu\left(\frac{d_s^2}{2} + 2r^2\right)\right) \quad (8)$$

where $r = \sqrt{x^2 + y^2}$ denotes the distance from the relay to the origin [which corresponds to the midpoint between the secondary source (*SS*) and destination (*SD*)].

Remark 1: From (8), we can observe that the successful transmission probability of the secondary network with relaying transmission decreases with the distance r. It indicates that relay location has a huge impact on transmission reliability, and selecting the relay closer to the midpoint between the secondary source and destination can achieve higher successful transmission probability.

B. Reliability Enhanced Region and Reliability Gain

Since the transmission reliability of secondary network with relaying transmission is related to the location of relay, it is very important to determine the RER, within which a relay selected to assist the transmission of secondary network can improve the reliability compared to the direct transmission.

Lemma 2: The secondary network with relaying transmission can achieve higher reliability compared to the direct transmission, as long as the relay *SR* locates within the RER described in the following inequality:

$$\sqrt{x^2 + y^2} \leq \frac{d_s}{2}. \quad (9)$$

Proof: The condition of reliability enhancement via a relay assistance is $P_{\text{suc}}^{\text{relay}} \geq P_{\text{suc}}^{\text{dir}}$. Accordingly, by substituting (3) and (8) into the above-mentioned inequality, the result in (9) can be obtained. ■

Remark 2: From (9), it is observed that the reliability enhance region is a disk centered at the midpoint between the secondary source and destination with radius $d_s/2$.

To quantitatively evaluate the reliability benefit of relaying transmission comparing to the direct transmission, we define the reliability gain ε, which is defined as the normalized successful transmission probability difference

$$\varepsilon = \frac{P_{\text{suc}}^{\text{relay}} - P_{\text{suc}}^{\text{dir}}}{P_{\text{suc}}^{\text{dir}}}. \quad (10)$$

Lemma 3: While a relay locates r away from the midpoint between the secondary source and its destination, the achievable reliability gain ε by selecting the relay to assist transmission is given by

$$\varepsilon(r) = \exp\left(-\mu\left(2r^2 - \frac{d_s^2}{2}\right)\right) - 1. \quad (11)$$

Proof: Equation (11) can be easily obtained by applying (3) and (8) into (10). ■

Remark 3: From (11), we can find that the reliability gain ε is a monotonically decreasing function of r. Accordingly, the best reliability gain is achieved while the relay is located at the midpoint between the secondary source and its destination, and it is given by

$$\varepsilon_{\max} = \exp\left(\frac{\mu d_s^2}{2}\right) - 1. \quad (12)$$

C. Spatial Distribution of Reliability Gain

The spatial distribution of the reliability gain can be described by a series of equi-gain contours, where all relays located have the same amount of reliability gain. To explore the spatial distribution of the reliability gain inside the RER, we first derive the expression for an reliability gain contour $\mathcal{C}(\varepsilon)$.

Lemma 4: For the reliability gain ε, the corresponding reliability gain contour $\mathcal{C}(\varepsilon)$ in the RER can be described mathematically as

$$x^2 + y^2 = \frac{d_s^2}{4} - \frac{1}{2\mu}\ln(1 + \varepsilon). \quad (13)$$

Proof: By substituting $r^2 = x^2 + y^2$ into (11) and rearranging the expression, (13) can be obtained. ■

Remark 4: From (13), it can be observed that the reliability gain contour $\mathcal{C}(\varepsilon)$ is a circle centered at the origin with radius $\sqrt{(d_s^2/4) - (1/2\mu)\ln(1+\varepsilon)}$. In other words, all relays located on the circle can obtain the same reliability gain ε.

Accordingly, the reliability gain contours in RER are concentric circles centered at the midpoint between the secondary source and its destination.

IV. Relay Selection and Reliability Benefit Analysis in Random Relay Distribution

On the basis of Section II, in this section, considering spatial randomly distributed relays, we propose an OLB-RS strategy in the relay selection region and analyze its achievable reliability gain. For comparison, the achievable reliability gain of the R-RS strategy is also evaluated. Based on these analyzes, the selection gain of the proposed OLB-RS strategy compared to the R-RS is also quantified.

The following analysis needs to use the probability that k relays are in the area $\mathcal{S}$, which is also named as the Poisson probability in PPP. It is given by

$$\Pr(N(\mathcal{S}) = k) = \frac{e^{-\lambda_r|\mathcal{S}|}(\lambda_r|\mathcal{S}|)^k}{k!} \tag{14}$$

where $N(\mathcal{S})$ represents the number of relays in $\mathcal{S}$, and $|\mathcal{S}|$ denotes the area of $\mathcal{S}$.

A. Random Relay Selection in the Relay Selection Region

To evaluate the reliability gain of the R-RS strategy, we first analyze the achievable average reliability gain of a relay inside the relay selection region $\mathcal{A}(0, R)$ (which is a disk centered at the origin with radius R).

Lemma 5: If a single relay is randomly deployed inside the relay selection region $\mathcal{A}(0, R)$, the achievable reliability gain is given as

$$\bar{\varepsilon} = \frac{1}{2\mu R^2} e^{\frac{\mu d_s^2}{2}} \left(1 - e^{-2\mu R^2}\right) - 1. \tag{15}$$

Proof: Since the relay locates anywhere in the relay selection region with equal probability, the distribution of the distance from the relay to the origin is given as

$$f_r(x) = \frac{2x}{R^2}. \tag{16}$$

Combining with (11), (15) can be obtained as follows:

$$\begin{aligned}\bar{\varepsilon} &= \int_0^R \varepsilon(r) f_r(r) dr \\ &= \int_0^R \left[\exp\left(-\mu\left(2r^2 - \frac{d_s^2}{2}\right)\right) - 1\right] \frac{2r}{R^2} dr \\ &= \frac{1}{2\mu R^2} e^{\frac{\mu d_s^2}{2}} \left(1 - e^{-2\mu R^2}\right) - 1. \end{aligned} \tag{17}$$

■

In the R-RS strategy, if more than one relay lies in the relay selection region $\mathcal{A}(0, R)$, a randomly selected relay is utilized to assist the transmission of the secondary network. Otherwise, the direct transmission is used, and it cannot obtain any reliability gain. Accordingly, the achievable reliability gain of the R-RS strategy can be obtained as

$$\begin{aligned}\varepsilon_{\text{rand}} &= \Pr(N(\mathcal{A}) > 0)\bar{\varepsilon} \\ &= [1 - \Pr(N(\mathcal{A}) = 0)]\bar{\varepsilon} \\ &= \left(1 - e^{-\lambda_r \pi R^2}\right)\left[\frac{1}{2\mu R^2} e^{\frac{\mu d_s^2}{2}} \left(1 - e^{-2\mu R^2}\right) - 1\right] \end{aligned} \tag{18}$$

where $N(\mathcal{A})$ represents the number of relays in the relay selection region $\mathcal{A}(0, R)$.

B. Optimal Location-Based Relay Selection in the Relay Selection Region

If only location information of relays can be obtained during relay selection, according to Remark 3, the optimal relay selection strategy is to select the relay closest to the midpoint between *SS* and *SD* in the relay selection region. Therefore, in the OLB-RS strategy, the relay closest to the midpoint is selected to assist transmission while there are relays in the relay selection region. Otherwise, *SS* sends messages to *SD* directly. Therefore, the reliability gain of the OLB-RS strategy can be expressed as

$$\varepsilon_{\text{best}} = \sum_{k=1}^{\infty} \Pr(N(\mathcal{A}) = k)\varepsilon_{\text{best}}^k \tag{19}$$

where $\varepsilon_{\text{best}}^k$ denotes the achievable reliability gain of the secondary network with the OLB-RS strategy while there are k relays in the relay selection region $\mathcal{A}(0, R)$.

Lemma 6: If k relays are spatial randomly distributed inside the relay selection region $\mathcal{A}(0, R)$, the probability density function (PDF) of the distance r from the origin to its nth closest relay is given by

$$f_r^{k,n}(x) = \frac{k!}{(k-n)!(n-1)!} \frac{2x}{R^2} \left(\frac{x^2}{R^2}\right)^{n-1} \left(1 - \frac{x^2}{R^2}\right)^{k-n}. \tag{20}$$

Proof: The probability that the distance from the origin to its nth closest relay is x is equal to the probability that:

1) one relay locates at the circle centered at the origin with radius x;
2) $n-1$ relays lie in the disk centered at the origin with radius x;
3) $k-n$ relays lie in the annulus centered at the origin with inner radius x and outer radius R.

Since relays are randomly located anywhere with equal probability in $\mathcal{A}(0, R)$, the probability of the events in 1, 2, and 3 is $(2x/R^2)$, $(x^2/R^2)^{n-1}$, and $(1 - (x^2/R^2))^{k-n}$, respectively. In addition, the events in 1, 2, and 3 are mutually independent. Therefore, the PDF of r can be written as

$$\begin{aligned} f_r^{k,n}(x) &= \Pr(r = x) \\ &= \binom{k}{1}\binom{k-1}{k-n} \frac{2x}{R^2}\left(\frac{x^2}{R^2}\right)^{n-1}\left(1 - \frac{x^2}{R^2}\right)^{k-n}. \end{aligned} \tag{21}$$

After some simplification, (20) is obtained. ■

Using (11) and (20), $\varepsilon_{\text{best}}^k$ can be obtained as

$$\varepsilon_{\text{best}}^k = \int_0^R \varepsilon(r) f_r^{k,1}(r) dr$$

$$= \int_0^R \left[\exp\left(-\mu\left(2r^2 - \frac{d_s^2}{2}\right)\right) - 1\right] \frac{2kr}{R^2}\left(1 - \frac{r^2}{R^2}\right)^{k-1} dr$$
$$\overset{(b)}{=} e^{\frac{\mu d_s^2}{2}} - 1 - \int_0^R 4\mu r\left(1 - \frac{r^2}{R^2}\right)^k e^{-\mu\left(2r^2 - \frac{d_s^2}{2}\right)} dr \quad (22)$$

where the derivation of step (b) is obtained from the partial integration.

Finally, by applying (14) and (22) into (19), the achievable reliability gain of the OLB-RS strategy can be obtained as

$$\varepsilon_{\text{best}} = \sum_{k=1}^{\infty} \left\{ \frac{e^{-\lambda_r \pi R^2}\left(\lambda_r \pi R^2\right)^k}{k!} \left[e^{\frac{\mu d_s^2}{2}} - 1 - \int_0^R 4\mu r\left(1 - \frac{r^2}{R^2}\right)^k \times e^{-\mu\left(2r^2 - \frac{d_s^2}{2}\right)} dr \right] \right\}$$
$$= \left(e^{\frac{\mu d_s^2}{2}} - 1\right) e^{-\lambda_r \pi R^2} \sum_{k=1}^{\infty} \frac{\left(\lambda_r \pi R^2\right)^k}{k!} + e^{-\lambda_r \pi R^2}$$
$$\times \int_0^R 4\mu r e^{-\mu\left(2r^2 - \frac{d_s^2}{2}\right)} \sum_{k=1}^{\infty} \frac{\left(\lambda_r \pi R^2\right)^k \left(1 - \frac{r^2}{R^2}\right)^k}{k!} dr$$
$$\overset{(c)}{=} e^{-\lambda_r \pi R^2} - 1 + \frac{\lambda_r \pi}{2\mu + \lambda_r \pi} e^{\frac{\mu d_s^2}{2}} \left[1 - e^{-(2\mu + \lambda_r \pi) R^2}\right] \quad (23)$$

where the derivation of step (c) is obtained from the Taylor series expansion of the exponential function.

In the OLB-RS strategy, how to determine the relay selection range R is an important problem. Statistically, larger R means a larger relay selection range, and more relays participate in the relay selection process, which increases the selection complexity and feedback overhead.

Lemma 7: In the OLB-RS strategy, for a given target reliability gain requirement ε_{th}, the minimum relay selection range is determined by

$$R_{\min}(\varepsilon_{th}) = \inf\{R : \varepsilon_{\text{best}}(R) \geq \varepsilon_{th}\}. \quad (24)$$

Proof: Taking the derivative of $\varepsilon_{\text{best}}$ with respect to R, we have

$$\frac{d\varepsilon_{\text{best}}}{dR} = 2\lambda_r \pi R e^{-\lambda_r \pi R^2}\left(e^{\frac{\mu}{2} d_s^2 - 2\mu R^2} - 1\right). \quad (25)$$

In the reliability enhance region, the relay selection range R satisfies $0 \leq R \leq d_s/2$. Therefore, the derivation $(d\varepsilon_{\text{best}}/dR)$ is larger than 0. It is indicated that $\varepsilon_{\text{best}}$ is a monotonically increasing function of relay selection range R in the RER. Accordingly, the minimum R for a given ε_{th} can be obtained. ■

Combining with (23), we can easily obtain the result of (24) with the numerical scheme.

C. Selection Gain

We define the selection gain for comparing the reliability gain of the OLB-RS strategy with that of the R-RS strategy.

Definition 1: The selection gain is defined as the successful transmission probability ratio while the relay density becomes infinite, and it can be expressed as

$$\delta = \lim_{\lambda_r \to \infty}\left(\frac{P_{\text{suc}}^{\text{best}}}{P_{\text{suc}}^{\text{rand}}}\right) = \lim_{\lambda_r \to \infty}\left(\frac{1 + \varepsilon_{\text{best}}}{1 + \varepsilon_{\text{rand}}}\right) \quad (26)$$

where $P_{\text{suc}}^{\text{best}}$ and $P_{\text{suc}}^{\text{rand}}$ represent the successful transmission probability of the secondary network with the OLB-RS strategy and R-RS strategy, respectively.

According to the definition, the selection gain can be obtained as

$$\delta = \lim_{\lambda_r \to \infty}\left(\frac{e^{-\lambda_r \pi R^2} + \frac{\lambda_r \pi}{2\mu + \lambda_r \pi} e^{\frac{\mu d_s^2}{2}}\left[1 - e^{-(2\mu + \lambda_r \pi)R^2}\right]}{\frac{e^{\frac{\mu d_s^2}{2}}}{2\mu R^2}\left(1 - e^{-2\mu R^2}\right)\left(1 - e^{-\lambda_r \pi R^2}\right) + e^{-\lambda_r \pi R^2}}\right)$$
$$= \frac{2\mu R^2}{1 - e^{-2\mu R^2}}. \quad (27)$$

From (27), it is observed that the selection gain is related with the relay selection range, but not with the relay density.

V. Region-Aware Relay Selection Strategy and its Reliability Benefit Analysis

To further reduces the feedback overhead and operation complexity during relay selection, in this section, we propose an RA-RS strategy for RCRNs in practical deployment, and its achievable reliability gain is also evaluated.

A. Region-Aware Relay Selection Strategy

In the aforementioned OLB-RS strategy, the exact location information of relays is needed during relay selection. However, the exact location information may not always be obtained due to the estimation error or feedback limitation in practical networks. Therefore, the OLB-RS strategy may not be useful in practice. To address this issue, we propose an RA-RS strategy for RCRNs, which only needs the region information of relays rather than its exact location information. Thus, the feedback burden and operation complexity during relay selection can be reduced significantly.

As introduced in Section III, the RER is a disk centered at the origin with radius $(d_s/2)$. We divide the RER into 2^L concentric rings with equal area, and use L bits code to denote these zones. Without loss of generality, as illustrated in Fig. 2, define the concentric rings as $U_1, U_2, \ldots, U_i, \ldots, U_{2^L}$ from inside to outside. Accordingly, for the ith concentric ring U_i, its inner radius and outer radius are $\sqrt{(i - 1/2^L)}(d_s/2)$ and $\sqrt{(i/2^L)}(d_s/2)$, respectively. The proposed RA-RS strategy is described in Algorithm 1.

B. Reliability Gain Analysis

In the RA-RS strategy, different relays with different locations may lie in the same divided region. Therefore, there may be multiple relays in the region with a minimum region code.

Lemma 8: While there are k ($k > 0$) relays in the RER, the probability that there are m ($1 \leq m \leq k$) relays in the region with a minimum region code is given by

$$\mathbb{P}_m^k = \begin{cases} \binom{k}{m}\left(\frac{1}{2^L}\right)^m \sum_{i=1}^{2^L-1}\left(1 - \frac{i}{2^L}\right)^{k-m}, & m < k \\ \left(\frac{1}{2^L}\right)^{k-1}, & m = k. \end{cases} \quad (28)$$

Proof: Let U_i denote the existing relays region with minimum region code, and the selected relay lies in the region.

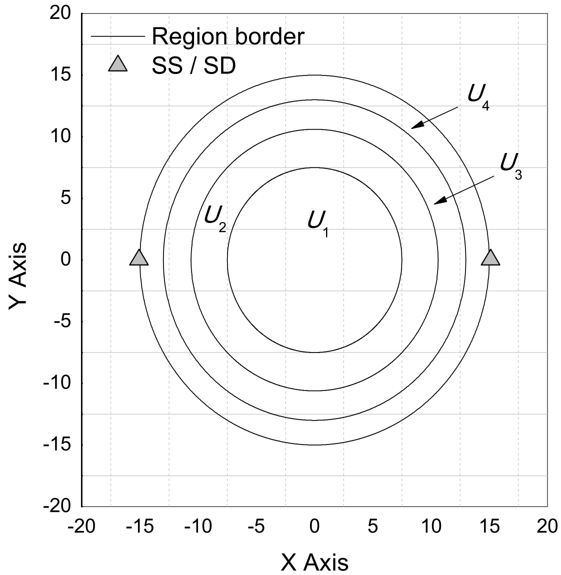

Fig. 2. RER is divided into 4 concentric rings with equal area ($L = 2$).

Algorithm 1: RA-RS Strategy for RCRNs

if *there are relays in the reliability enhanced region* **then**
  Utilize the relaying transmission mode;
  Each relay in the reliability enhanced region feeds back its corresponding L bits region code to the control node via error-free feedback channels;
  The control node selects the relay with minimum region code to assist transmission (if there are multiple relays with minimum region code, select a relay randomly among them);
else
  Utilize the direct transmission mode;

The probability that there are m relays in the region with the minimum region code is calculated as the following two cases.

Case I: For $m < k$, there are m relays lie inside the region U_i [where $i \in (1, 2, \ldots, 2^L - 1)$] and the other $k-m$ relays locate at the regions $U_{i+1}, U_{i+2}, \ldots, U_{2^L}$. Therefore, the probability of m relays in the region with the minimum region code is given by

$$\mathbb{P}_m^k = \binom{k}{m}\left(\frac{1}{2^L}\right)^m \sum_{i=1}^{2^L-1}\left(1 - \frac{i}{2^L}\right)^{k-m}. \tag{29}$$

Case II: For $m = k$, all the relays lie inside the region U_i [where $i \in (1, 2, \ldots, 2^L)$]. Thus, the probability of m relays in the region with the minimum region code is obtained as

$$\mathbb{P}_m^k = 2^L\left(\frac{1}{2^L}\right)^k = \left(\frac{1}{2^L}\right)^{k-1}. \tag{30}$$

In summary, (28) can be obtained. ■

The relays in the region with minimum region code feed back the same region code to the control node (such as *SS*), and the control node can only select one relay among them. Under the condition without any prior information, the control node has to select one relay among them randomly. The selected relay may be the best relay (the closest relay to the origin), the second best relay (the second closest relay to the origin),…, or the nth best relay (the nth closest relay to the origin). Therefore, the achievable reliability gain is the expectation of that under different cases.

Lemma 9: Let $\varepsilon_{\text{region}}^k$ denote the obtainable reliability gain of the secondary network with the RA-RS strategy under the condition that there are k relays in the RER. Then, $\varepsilon_{\text{region}}^k$ is given by (31), shown at the bottom of the page, where

$$\Psi(x) = \sum_{j=0}^{k-n}\left\{\frac{k!(-1)^j\left[\frac{e^{\frac{\mu d_s^2}{2}}}{(2\mu)^{n+j}}\gamma\left(n+j, 2\mu x^2\right) - \frac{x^{2(n+j)}}{(n+j)}\right]}{j!(k-n-j)!(n-1)!\left(\frac{d_s}{2}\right)^{2(n+j)}}\right\}. \tag{32}$$

Proof: While the nth best relay is selected to assist transmission, its obtainable reliability gain can be written as

$$\varepsilon_n = \int \varepsilon(r) f_r^{k,n}(r)dr \tag{33}$$

where r represents the distance from the selected relay to the origin. As introduced in the proof of Lemma 8, for $m < k$, r belongs to the interval $[0, \sqrt{(2^L - 1/2^L)}(d_s/2)]$. Otherwise, i.e., $m = k$, r belongs to the interval $[0, (d_s/2)]$. Therefore, (33) can be rewritten as

$$\varepsilon_n = \begin{cases} \int_0^{\sqrt{\frac{2^L-1}{2^L}}\frac{d_s}{2}} \varepsilon(r) f_r^{k,n}(r)dr, & m < k \\ \int_0^{\frac{d_s}{2}} \varepsilon(r) f_r^{k,n}(r)dr, & m = k. \end{cases} \tag{34}$$

By substituting (11) and (21) into (34), and after some algebraic manipulations, ε_n is obtained as

$$\varepsilon_n = \begin{cases} \Psi\left(\sqrt{\frac{2^L-1}{2^L}}\frac{d_s}{2}\right), & m < k \\ \Psi\left(\frac{d_s}{2}\right), & m = k. \end{cases} \tag{35}$$

Then, combining these two cases, the obtained reliability gain $\varepsilon_{\text{region}}^k$ can be expressed as

$$\varepsilon_{\text{region}}^k = \underbrace{\sum_{m=1}^{k-1}\sum_{n=1}^{m}\left(\frac{1}{m}P_m^k \varepsilon_n\right)}_{(A)} + \underbrace{\sum_{n=1}^{k}\left(\frac{1}{k}P_m^k \varepsilon_n\right)}_{(B)} \tag{36}$$

where part (A) corresponds to the case of $m < k$, and part (B) corresponds to the case of $m = k$.

$$\varepsilon_{\text{region}}^k = \sum_{m=1}^{k-1}\sum_{n=1}^{m}\sum_{i=1}^{2^L-1}\left[\frac{\binom{k}{m}}{m}\left(\frac{1}{2^L}\right)^m\left(1 - \frac{i}{2^L}\right)^{k-m}\Psi\left(\sqrt{\frac{2^L-1}{2^L}}\frac{d_s}{2}\right)\right] + \sum_{n=1}^{k}\left[\frac{1}{k}\left(\frac{1}{2^L}\right)^{k-1}\Psi\left(\frac{d_s}{2}\right)\right] \tag{31}$$

TABLE I
SYSTEM PARAMETERS

Symbol	Definition	Value
d_p	Distance between primary source and destination	50 m
d_s	Distance between secondary source and destination	30 m
λ_p	Primary Transmitters' density	10^{-5}
λ_s	Secondary Transmitters' density	10^{-4}
λ_r	Relays' density	10^{-2}
α	Path loss factor	4
Γ_p	Target SIR of primary network	3 dB
Γ_s	Target SIR of secondary network	3 dB
η_{th}	Outage constraint of primary network	0.2
P_p	Transmit power of PTs	23 dBm

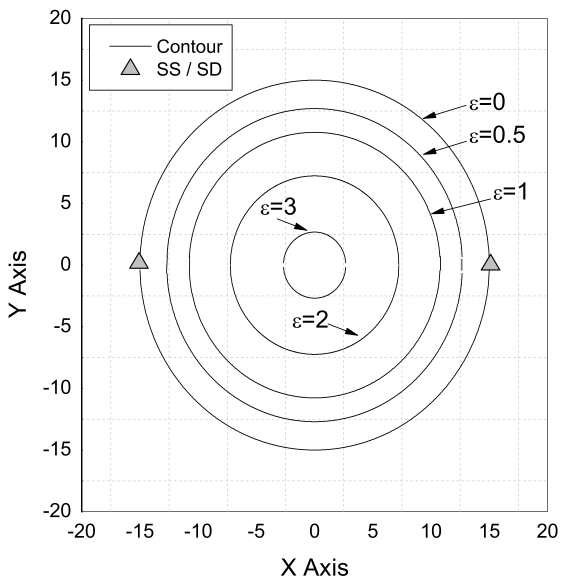

Fig. 3. Spatial distribution of reliability gain in the RER.

Finally, by applying (28) and (34) into (36), and after some rearrangement, (31) is obtained. ■

Considering the random number of relays in the RER, the obtained reliability gain of the proposed RA-RS strategy is

$$\begin{aligned}\varepsilon_{\text{region}} &= \sum_{k=1}^{\infty}\left[\Pr(N(\mathcal{Z})=k)\varepsilon_{\text{region}}^{k}\right]\\ &= \sum_{k=1}^{\infty}\left[\frac{e^{-\frac{\lambda_r\pi d_s^2}{4}}\left(\frac{\lambda_r\pi d_s^2}{4}\right)^k}{k!}\varepsilon_{\text{region}}^{k}\right].\end{aligned} \tag{37}$$

Finally, by substituting (31) into (37), the analytical expression for the reliability gain of the RA-RS strategy can be obtained.

VI. NUMERICAL RESULTS

In this section, we present numerical results for CRNs to evaluate the impact of relay location and location-based relay selection strategies on the obtained reliability benefit. The system parameters for numerical results are given in Table I unless otherwise specified.

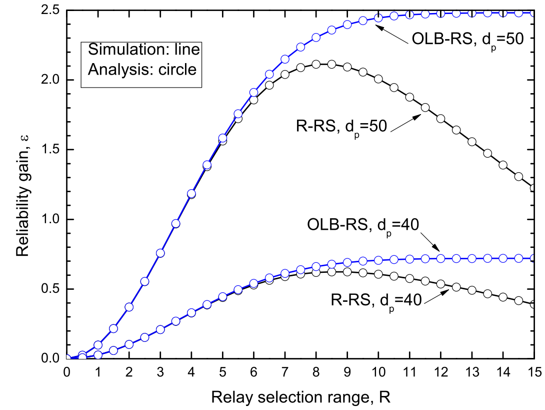

Fig. 4. Reliability gain with the R-RS strategy and the OLB-RS strategy as a function of relay selection range R under different value of d_p.

Fig. 3 shows the spatial distribution of reliability gain in the RER. From this figure, we can see that the RER is a disk centered at the midpoint between SS and SD with radius $d_s/2$, which is the half distance from SS to SD. It shows that the relays in the RER should be selected in order to obtain higher reliability as compared to the direct transmission. Conversely, selecting those relays out of the RER to assist transmission cannot improve the reliability. In addition, we can find that the reliability gain contours are concentric circles, and the achievable reliability gain increases from outer to inside. This indicates that selecting the relay close to the midpoint can obtain higher reliability benefit.

Fig. 4 depicts the impact of relay selection range R on the reliability gain of the R-RS strategy and the optimal location-based relay strategy. From Fig. 4, it can be observed that there is an excellent agreement between the analytical results and simulation results, which validates our theoretical analysis. It is also observed that the reliability gain of the R-RS strategy increases first and then decreases with the increasing of relay selection range R, and there is an optimal R for maximizing the reliability gain. However, for the OLB-RS strategy, its reliability gain increases first and then saturates as R increases. It is also observed that the reliability gain of the optimal location-based relay strategy is close to that of the R-RS strategy for a small R, but it outperforms the R-RS strategy while R is large.

In Fig. 5, the reliability gain of the R-RS strategy and the OLB-RS strategy is plotted as a function of relay density (λ_r) under different d_p. We can see that the reliability gain of both the R-RS strategy and the OLB-RS strategy increases with relay density. This is because there will be more relays in the RER while the density of relays increases, and there will be more chances of relay-assisted transmission for the secondary network. We can also find that the OLB-RS strategy can obtain higher reliability benefit compared to the R-RS strategy under the same condition. In addition, it is observed that the reliability gain decreases as the distance between the PT and its corresponding receiver. This is due to the fact that the primary network can tolerate larger interference while d_p becomes small, which leads to secondary transmitter can send messages with higher transmit power. Consequently, the reliability of the secondary network is improved.

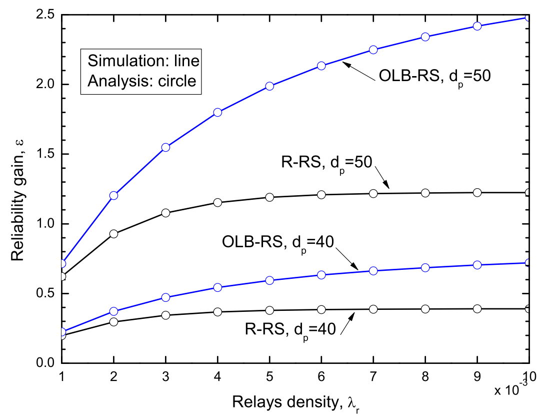

Fig. 5. Reliability gain with the R-RS strategy and the OLB-RS strategy as a function of relay density under different value of d_p.

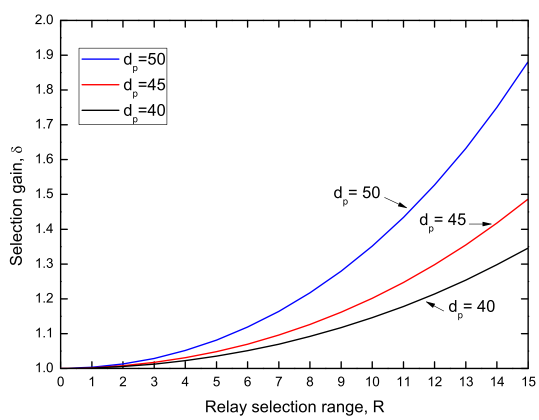

Fig. 6. Selection gain as a function of the relay selection range R under different d_p.

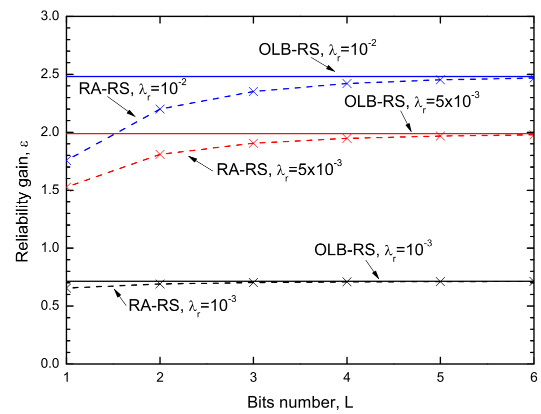

Fig. 7. Reliability gain of the region-based relay selection strategy (RA-RS) as a function of the bit numbers.

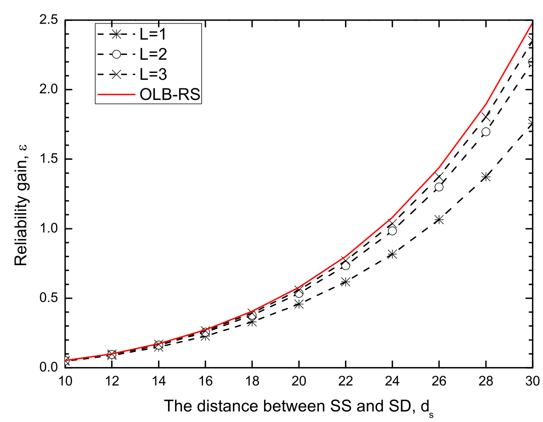

Fig. 8. Reliability gain of the region-based relay selection strategy (RA-RS) as a function of d_s under different L.

Fig. 6 illustrates the selection gain as a function of relay selection range R for different d_p. From this figure, we can see that the selection gain improves as the relay selection range increases. This is because there are more relays for selecting in relay selection region as R increases.

Fig. 7 shows the reliability gain of the region-based relay selection strategy as a function of bits number L (which corresponds to the number of subregions). From this figure, it can be observed that the region-based relay selection strategy with 2-bits feedback can obtain 90% reliability gain of OLB-RS strategy. It is indicated that the proposed region-based relay selection strategy can obtain high reliability with low feedback overhead and operation complexity. Moreover, it can be observed that the reliability gain of the region-based relay selection strategy is closer to that of the OLB-RS strategy as the number of feedback bits increases. This can be attributed to the fact that the selected relay in the region-based relay selection strategy is the closest relay to the midpoint with higher probability as the feedback bits increases.

Fig. 8 depicts the reliability gain of the region-based relay selection strategy as a function of d_s under different L. It is clear that the reliability gain improves with the distance between *SS* and *SD*. This is because larger d_s means a larger relay-enhanced region, and the selected relay locates close to the optimal relay location with higher probability. Consequently, higher reliability gain can be achieved.

VII. Conclusion

We have proposed a spatial geometric framework based on the stochastic geometry for evaluating the reliability benefit of CRNs with spatial randomly distributed nodes. Our work provides quantitative insights into the impact of relay location and location-based relay selection strategy on the reliability of CRNs in terms of NRG. We have also proposed the RA-RS strategy to achieve comparable reliability benefit with lower feedback overhead and operation complexity. For future work, we will consider extending our research to the scenario of CRNs with energy harvesting, and studying distributed relay selection policies to reduce the feedback load.

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