IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received February 8, 2020, accepted March 3, 2020, date of publication March 10, 2020, date of current version March 20, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2979767

Discrete Exclusion Zone for Dynamic Spectrum Access Wireless Networks

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This work was supported by the Wireless Network Research Department, Beijing Laboratory, R&D Center China, Sony (China) Limited, Beijing, China.

ABSTRACT The implementation of a geographic exclusion zone (GEZ) has been a scheme in regulations developed to protect a primary user (PU) in dynamic spectrum access wireless networks, where secondary users (SUs) can transmit only outside the exclusion zone region centered at the PU receiver. After determining the radius of the GEZ, the number of operable nodes in actual deployment is quite uncertain due to the random location of nodes. This poses certain difficulty for SU spectrum sharing planning. In this paper, we propose an alternative PU protection scheme called the discrete exclusion zone (DEZ), which is shapeless. The PU protection is achieved by switching off the first $k-1$ nearest neighboring SUs surrounding the PU. Building on the stochastic geometry of wireless node locations, the conditions under which the mean and the variance of the aggregate interference from SUs to the PU exist are obtained. These conditions define the minimum size of the DEZ. Then, we obtain the closed-form expressions for the mean and the variance as a function of the DEZ size k for a given number of SUs N, including $N \to \infty$. Since it is challenging to obtain a closed-form expression of the density function, we resort to the Gamma distribution to approximate the distribution of the aggregate interference, which is validated by simulations. Finally, the performances of the GEZ and DEZ are investigated in terms of the number of operable SUs outside the GEZ and DEZ, respectively, for achieving a given PU protection requirement. The results show that the DEZ gives a fixed number of operable nodes in the presence of topology randomness associated with the actual SU network deployment.

INDEX TERMS Cognitive radio system (CRS), dynamic spectrum access (DSA), coexistence, aggregate interference, exclusion zone, stochastic geometry, Poisson point process.

I. INTRODUCTION

The world is now entering the fifth generation (5G) communication era, with the fourth generation (4G) period soon coming to an end. The discussion of sixth generation (6G) communication has even started. In this evolution, the dynamic spectrum access (DSA) has always been a key technology for improving spectrum utilization for wireless communication systems [1], [2].

Over the years, extensive research has been done on developing interference avoidance mechanisms that are essential to different systems sharing the same spectrum resources [3]–[6]. With these efforts, DSA has been applied by spectrum regulatory bodies and industry to reuse those frequency bands that have been allocated yet not efficiently utilized, such as the TV band [7]. In these systems, a primary user (PU) is given high priority to use a given chunk of the spectrum, whereas a secondary user (SU) can use the same chunk of the spectrum if the PU protection requirements are satisfied. The PU and SU can be of a multi-tier system and a single-tier system but with different quality of service (QoS) requirements [8].

Two protection approaches have been widely discussed by spectrum regulators in different countries. One is spectrum sensing. Through this approach, an SU senses the radio environment, and its radio transmission is allowed only if no signal of the PU is found. Radio interference from the SU to the PU is prevented if the PU is using the spectrum. However, due to the hidden-node problem and the reliability of spectrum sensing, this method has been considered by regulators as a complementary feature to the other protection approach, i.e., the geolocation database management approach. In this approach, one scheme of PU protection is to control the maximum allowable transmit powers of the SUs so that the

The associate editor coordinating the review of this manuscript and approving it for publication was Xijun Wang.

aggregate interference from these SUs to a PU is kept under a certain level [8], [9]. The other scheme implements the geographic exclusion zone (GEZ) centered at the PU. Then, the database checks the location of each SU and permits its transmission only if the SU is located outside the GEZ [10].

The authors in [11] determine the contour of the PU service area based on the lowest PU signal strength that can maintain the PU service quality using the propagation model, i.e., the minimum received TV signal power acceptable for the TV receiver. In addition to the propagation model, topographic data are processed to obtain a more accurate PU service contour [12]. The GEZ is implemented outside the PU service contour by adding a distance margin. A large margin gives conservative protection to the PU but undermines the spectrum utilization by SUs. However, with a small margin, the interference power aggregated at the service contour might exceed an acceptable value if the density of the SUs outside the GEZ is larger than the presumed value. In [11], a variable margin resultant from a flexible SU transmit power is considered, and its effect on TV white space (TVWS) availability is studied.

In [13]–[22], the GEZ is investigated based on stochastic geometry of wireless nodes, which has been proven to be an accurate and tractable approach [23]. The random locations of wireless nodes are modeled by the Poisson point process (PPP) and its variations according to different access protocols and tiers of spectrum utilization. Particularly, regarding optimization of the GEZ implementation, the GEZ radius centered at the PU receiver is determined by maximizing the density of successful radio transmissions under the PU outage constraint [13]. In [20], the GEZ is implemented over the PU receiver, and the maximum density of SUs is obtained under the PU protection requirement. In [21], multiple GEZs surrounding both the PU and SU receivers are implemented. The PU and SU outages are obtained in terms of the GEZ radius.

Most recently, the FCC announced a new regulation that allows secondary use of the 3.5 GHz band [24], which is enabled by a three-tiered licensing scheme consisting of an incumbent tier, priority access tier and general authorized access (GAA) tier. The priority access licensees are protected from GAA users by applying the GEZ concept, known as the priority access license (PAL) protection area, which is a boundary around a fixed station operated by a holder of the PAL. The GAA users can operate only outside the PAL protection area, and every location in this area is treated as a protection target. Following this, the authors in [22] study the effect of the radius of the PAL protection area on the area spectral efficiency. In the above schemes, the GEZ radius is determined based on the long-term statistic property, i.e., the density of the node spatial distribution. The size of the GEZ is usually calculated as a rule for SUs in the spectrum sharing planning stage by regulatory bodies or spectrum coordinators before the SU wireless nodes are actually deployed. It is difficult to predict the exact number of operable nodes that will be located outside the GEZ in practical deployment due to the random topology of the SU wireless network.

In this paper, we study spectrum sharing between a single PU and multiple SUs. To avoid the aforementioned uncertainty issue in spectrum sharing planning with the GEZ scheme, we propose an alternative protection scheme building on the neighboring relationship between a PU and its surrounding SUs. We call it the discrete exclusion zone (DEZ), which has a variable size k, although it is shapeless. The concepts of both the GEZ and DEZ are illustrated in Fig. 1. When the GEZ is applied for a given snapshot of SU network deployment, as shown in Fig. 1(a), the geolocation database checks the locations of SUs and prohibits the transmission of those SUs that are located inside the exclusion zone. If the DEZ is employed for PU protection, as in Fig. 1(b), the geolocation database checks the distance from each individual SU to the PU. These SUs are listed as the neighbors of the PU, ranked based on their distance to the PU from the nearest to the farthest. PU protection is achieved by switching off the first $k-1$ nearest neighboring SUs surrounding a PU. Note that the value of k is dependent on the density of wireless nodes instead of actual locations. Once the value of k is determined, a network operator that deploys wireless nodes as SUs will know how many nodes need to terminate transmission to protect the PU. Allowing the operator of SUs to know the impairment of their network before deploying the system is important for spectrum sharing planning to succeed since the sharing process needs to be feasible for the SU network operator to gain financial benefits while achieving PU protection. Given the above model, the problem that arises is how to find the value of k for a given protection criterion. To address this issue, we first need to obtain the distribution of aggregate interference as a function of k for a given density of wireless nodes. Then, we obtain the value of k for a protection criterion. To compare the DEZ with the GEZ, we also obtain the size of the GEZ for the same protection criteria. Subsequently, we compare their performances in terms of the number of operable nodes.

II. SYSTEM MODEL

Section II gives the system model of both the GEZ and DEZ. The distribution of the aggregate interference for the DEZ is investigated in Section III. Section IV provides verification of the study and the performance comparison. Finally, the conclusions are drawn in Section V.

A. PRELIMINARY

To reveal the fundamental property of the DEZ, we assume that all the nodes follow an m-dimensional homogeneous PPP with density λ [23]. Without loss of generality, we consider one node as the PU receiver, and the surrounding node set $\Phi = \{X_1, X_2, \ldots, X_N\}$ contains the SU transmitters reusing the spectrum of the PU. N can be finite or infinite. To the best of our knowledge, this is the first time the DEZ is proposed as an alternative to the GEZ. To compare the DEZ with the GEZ in terms of the aggregate interference relative to the PU

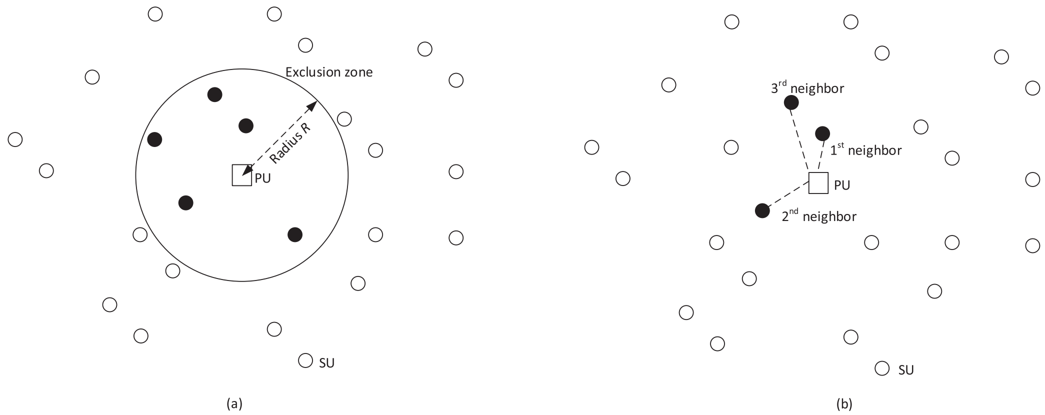

FIGURE 1. Illustration of the (a) GEZ and (b) DEZ concepts.

protection, we focus on the single PU scenario in this paper. The authors in [19] studied the GEZ and extended the single PU scenario to a multiple PU scenario by scattering PUs and SUs as two independent PPPs in the spatial domain. The active nodes operating outside the GEZs are found to form a Poisson hole process (PHP). For the proposed DEZ, the single PU scenario can be extended to the multiple PU scenario with the same approach and with the DEZ applied for each PU. However, it is not straightforward to model the active SUs outside those DEZs as a PHP. The analysis of aggregate interference from these active SUs is left for future work. In industry and regulatory domains such as the TVWS [10] and CBRS [24], the interference is normally gauged by the distance-dependant average power, omitting the fading effect, because path loss is the dominant factor in these spectrum sharing scenarios. Various studies [11], [12], [15] have been carried out to investigate the size of the GEZ from the PU protection perspective based on the path loss model, which ignores both short-term and long-term fading. Since the purpose of this paper is to introduce an alternative PU protection scheme from the regulation point of view, for simplicity but without loss of generality, we use the unbounded path loss model in this paper. Normally, the SU wireless devices are categorized into different types, for example, categories A & B for devices in the CBRS and modes I & II for devices in the TVWS. A maximum equivalent isotropically radiated power (EIRP) is imposed on each type of device. When considering the interference from these SUs to the PU, the worst situation is assumed, i.e., the devices transmit at the maximum power limit. In this study, we assume that the SUs are of the same type and transmit with the same transmit power without considering the antenna directivity factor. The interference I is determined only by the path loss law, i.e., at a given point

$$I = \sum_{n=1}^{\infty} D_n^{-\alpha}, \tag{1}$$

where α denotes the path loss exponent. Here, D_n is the distance from the PU to its nth nearest SU, and it is a random variable. Note that if we confine a given number of nodes inside a given space, the binomial point process is used instead [25].

As we can see in (1), I is the sum of an infinite number of random variables. It is very difficult to obtain its distribution. There have been various studies [14]–[18] on the approximation of aggregate interference from SUs to a PU when the GEZ is applied to protect a PU. Reference [14] considered the contribution to aggregate interference from an SU only if it fails to detect the PU beacon. The authors in [15] applied the Gaussian distribution, considering different numbers of nearby interferences. The studies in [16]–[18] proposed using the Gamma distribution to model aggregate interference including both no-fading and fading conditions. Although the proposed DEZ scheme is different from the GEZ scheme, those previous studies motivated us to use the Gaussian distribution and Gamma distribution for the approximation of the distribution of I. In the next section, we derive its mean and variance. For the Gaussian distribution, the probability distribution function (pdf) and cumulative distribution function (CDF) with given mean μ and variance σ^2 are written as follows:

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{\sigma^2}} \tag{2}$$

and

$$F(x) = \frac{1}{2}\left[1 + \operatorname{erf}\left(\frac{x-\mu}{\sqrt{2\sigma^2}}\right)\right], \tag{3}$$

where $\operatorname{erf}(x)$ is the error function. For the Gamma distribution, the pdf and CDF, with $\theta = \sigma^2/\mu$ and $k = \mu/\theta$, are given as [18]

$$f(x) = x^{k-1}\frac{e^{-x/\theta}}{\theta^k \Gamma(k)}, \tag{4}$$

for $x \geq 0$, and

$$F(x) = \frac{\gamma(k, x\theta)}{\Gamma(k)}, \tag{5}$$

where $\gamma(a, b) = \int_0^b t^{a-1} e^{-t} dt$ is the lower incomplete Gamma function.

B. GEOGRAPHICAL EXCLUSION ZONE

Based on the PPP modeling of randomly located nodes, the interference relative to a particular node from the nodes in a given region can be calculated as given by Lemma A.3 according to Campbell's theorem [26]. For the application of the GEZ, we calculate the interferences from SUs that remain in a region outside the GEZ while assuming that the PU is at the center of the GEZ circle. Let $\mathcal{A}(0, R)$ represent the area of the GEZ with radius R; we can write the aggregate interference received at the PU as

$$I_R = \sum_{n\in\Phi\cap\bar{\mathcal{A}}}^{\infty} D_n^{-\alpha}. \tag{6}$$

According to Lemma A.3 in [26], the mean and variance of the aggregate interference at the PU with a GEZ of radius R can be written as

$$\mathrm{E}\{I_R\} = \lambda\int_R^{\infty} r^{-\alpha}2\pi r dr = \frac{2\pi\lambda R^{2-\alpha}}{\alpha-2} \tag{7}$$

and

$$\mathrm{E}\left\{I_R^2\right\} - \mathrm{E}\{I_R\}^2 = \lambda\int_R^{\infty} r^{-2\alpha}2\pi r dr = \frac{\pi\lambda R^{2(1-\alpha)}}{\alpha-1}. \tag{8}$$

C. DISCRETE EXCLUSION ZONE

For a DEZ with size k, we can write the aggregate interference as follows:

$$I_k = \sum_{n=k}^{\infty} D_n^{-\alpha}. \tag{9}$$

To obtain the statistical information of I_k, we resort to the study in [27], which concludes that the distribution of D_n is the generalized Gamma distribution:

$$f_{Dn}(r) = e^{-\lambda c_m r^m}\frac{m(\lambda c_m r^m)^n}{r\Gamma(n)}, \tag{10}$$

where $c_m r^m$ is the volume of an m-dimensional ball with radius r. The mean and variance of I_k are derived in the next section.

III. ANALYTICAL MODEL

In this section we examine the statistical properties of the aggregate interference from SUs to the PU when the DEZ is implemented. These properties allow us to determine the minimum DEZ size as well as an exact size for a given interference tolerance level at the PU. Moreover, we provide a method for calculating the mean value of the aggregate interference when the GEZ is implemented as an alternative to the method given in II-B.

First, we consider the conditions of the mean and variance of the aggregate interference. Although the study in [27] reveals that $\alpha > m$ is necessary to make the mean value converge, it does not prove whether this is sufficient.

Theorem 1: Once the size of the DEZ is set such that $k > \alpha/m > 1$, the mean value of the aggregate interference from SUs outside a DEZ with size k to the PU must be a finite number. The proof is given in Appendix A.

Theorem 2: The variance of the aggregate interference from SUs outside a DEZ with size k is a finite number if and only if $n > 2\alpha/m > 2$. The proof is given in Appendix B.

Theorem 1 and Theorem 2 give the conditions under which the mean and variance of the aggregate interference from SUs outside the DEZ exist. Using these theorems, we can determine the minimum size of the DEZ. We now give the closed-form expression of the mean and the variance for a given number of neighboring SUs N and the path loss exponent α. As shown in Appendix C, the mean of the aggregate interference can be written as

$$\mathrm{E}\{I_k\} = \frac{(\lambda c_m)^\beta}{\beta-1}\left(\frac{1}{(k-2)\cdots(k-\beta)} - \frac{1}{(N-1)\cdots(N-\beta+1)}\right), \tag{11}$$

where $\beta = \alpha/m$ and

$$\lim_{N\to\infty}\mathrm{E}\{I_k\} = \frac{(\lambda c_m)^\beta}{(\beta-1)(k-2)\cdots(k-\beta)}. \tag{12}$$

In Appendix D, we derive the second-order moment of the aggregate interference for the DEZ in the form of

$$\mathrm{E}\left\{I_k^2\right\} = \mathcal{A}+\mathcal{B}, \tag{13}$$

where

$$\mathcal{A} = \frac{(\lambda c_m)^{2\beta}}{2\beta-1}\left(\frac{1}{(k-2)\cdots(k-2\beta)} - \frac{1}{(N-1)\cdots(N-2\beta+1)}\right), \tag{14}$$

with

$$\lim_{N\to\infty}\mathcal{A} = \frac{(\lambda c_m)^{2\beta}}{(2\beta-1)(k-2)\cdots(k-2\beta)}, \tag{15}$$

and

$$\mathcal{B} = \frac{(\lambda c_m)^{2\beta}}{(\beta-1)^2}\left(\frac{1}{(k-2)\cdots(k-2\beta+1)} - \frac{1}{(N-2)\cdots(N-2\beta+1)}\right) - \frac{2(\lambda c_m)^{2\beta}}{(N-\beta-1)\cdots(N-2\beta+1)(\beta-1)^2} \times\left(\frac{1}{(k-2)\cdots(k-\beta)} - \frac{1}{(N-2)\cdots(N-\beta)}\right), \tag{16}$$

with

$$\lim_{N\to\infty}\mathcal{B} = \frac{(\lambda c_m)^{2\beta}}{(\beta-1)^2(k-2)\cdots(k-2\beta+1)}. \tag{17}$$

Subsequently, the variance in the aggregate interference can be obtained using (11) and (13) as $\mathrm{E}\left\{I_k^2\right\} - (\mathrm{E}\{I_k\})^2$. Both the mean and the variance are functions of the DEZ size k, the number of SUs N and the path loss exponent α. These results allow us to determine a DEZ size for a given PU protection level. In the following section, we examine the effects of these parameters on the aggregate interference.

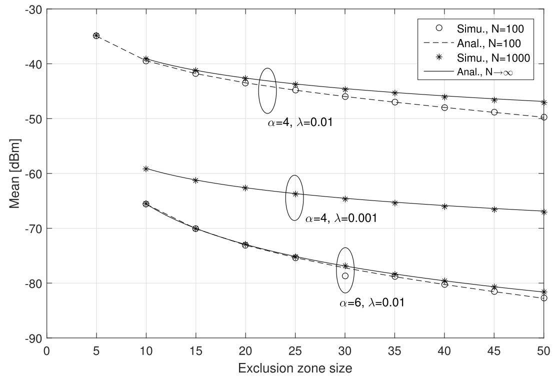

FIGURE 2. The mean of the aggregate interference for different DEZ sizes.

Using the closed-form expression for the mean of the aggregate interference with DEZ I_k, we can also derive the mean of the aggregate interference when the GEZ is implemented as an alternative to the method in Subsection II-B. Given the GEZ radius R, we can calculate the aggregate interference as

$$I_R = \sum_{n=1}^{N} P_n I_{N-n}, \tag{18}$$

where P_n is the probability that there are exactly n out of N nodes inside the circle with radius R as [27]

$$P_n = e^{-\lambda \pi R^2} \frac{(\lambda \pi R^2)^n}{n!}. \tag{19}$$

Therefore, we can obtain the mean of the aggregate interference using (11) as

$$\mathrm{E}\{I_R\} = \sum_{n=1}^{N} P_n \mathrm{E}\{I_{N-n}\}. \tag{20}$$

IV. NUMERICAL RESULTS

We first examine the accuracy of the closed-form expressions for the mean and variance of the aggregate interference when using a DEZ. Then, we use Gaussian and Gamma distributions to model the distribution of the aggregate interference and use a Monte-Carlo simulation to verify the modeling. After that, we investigate the benefits of the proposed scheme in terms of network capacity.

To study the wireless node distribution on the ground plane, we set $m = 2$, and then $c_m = \pi$. The transmit power of each SU is assumed to be 1 Watt. The path loss α is set equal to 4 or 6 in the simulation, as $\alpha = 4.3$ has been observed in the TVWS [28]. If the path loss exponent $\alpha = 4$, according to Theorem 1 and Theorem 2, we know that if $k > 2\alpha/m = 4$, then the mean and the variance of the aggregate interference exist. Thus, we set the DEZ size $k \geq 5$. Similarly, if $\alpha = 6$, we set the DEZ size such that $k \geq 10$. For the value of N, we use a relatively large number compared with k to emulate an infinite number of wireless nodes.

In Fig. 2 and Fig. 3, we plot the mean and standard deviation of the aggregate interference for different DEZ sizes. The close match between the simulation results and the analytical model validates our study. As expected, the aggregate interference reduces when the DEZ size increases. We also

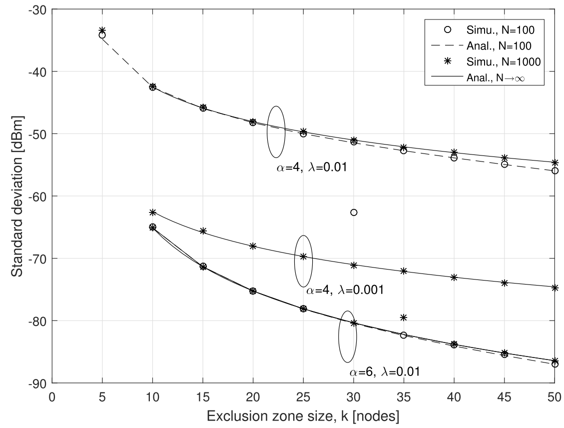

FIGURE 3. The standard deviation of the aggregate interference for different DEZ sizes.

see that when N is large, it has a small effect on the aggregate interference. We found that when $N = 1000$, the mean and variance obtained through a Monte-Carlo simulation are very close to the values obtained using the closed-form expression in (12), (15) and (17), with $N \to \infty$. This outcome occurs because when the number is large, those SUs far from the PU contribute very little to the aggregate interference. The density and the path loss exponent, however, have an apparent influence.

Since the exact expression for the distribution of the aggregate interference cannot be obtained, we use the Gaussian distribution and Gamma distribution to describe the distribution of the aggregate interference with the closed-form expressions for the mean and variance derived in the previous section. In Figs. 4 to 6, we plot the pdfs for different DEZ sizes $k = 5$, 10, and 15. In Fig. 7, we plot the corresponding CDFs. When the size of the DEZ k is small, the interference is dominated by the nearby SUs; hence, the distribution deviates from the Gaussian approximation. As shown in these figures, when the value of k increases, many SUs contribute to the aggregate interference, and the Gaussian approximation improves. Although the proposed DEZ is different from the GEZ, this trend is also found in [16] when the GEZ is applied. We can see that the Gamma distribution gives a good approximation of the distribution of the aggregate interference power compared with the Gaussian distribution. The CDF can be used to determine the DEZ size for PU protection in terms of the maximum allowable interference.

Now, we compare the effects of the GEZ radius and the DEZ size on the mean value of the aggregate interference, respectively, in Figs. 8 and 9. For the GEZ, it is also shown that when $N = 1000$, we can use (20) to approximate the value given by (7). We can also see that for a relatively small GEZ radius and DEZ size, letting $N = 1000$ in the Monte-Carlo simulation will approximate the situation of an infinite number of wireless nodes. For both PU protection schemes, as the GEZ radius and DEZ size increase, the effect of aggregate interference reduction is prominent at the beginning, as the first closest SUs, which are the dominating sources of interference to the PU, are first prohibited

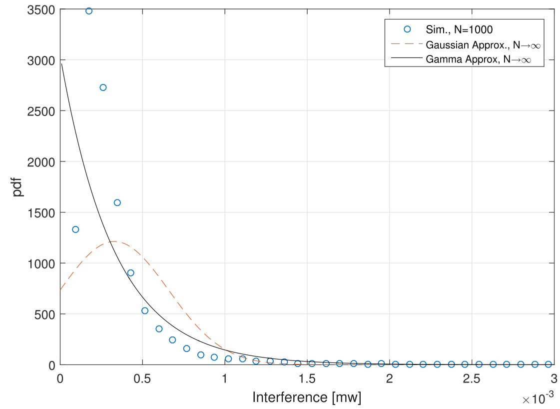

FIGURE 4. pdf of the aggregate interference power for DEZ size $k = 5$, $N = 1000$, $\alpha = 4$ and $\lambda = 0.01$.

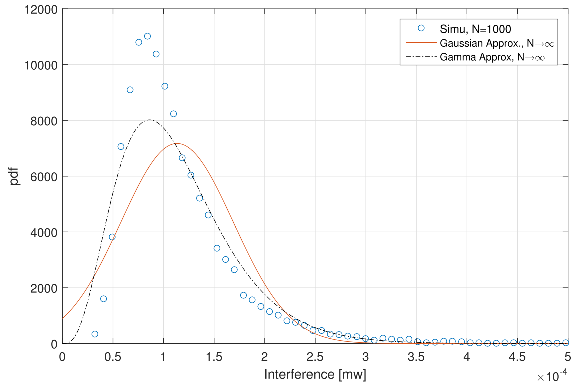

FIGURE 5. pdf of the aggregate interference power for DEZ size $k = 10$, $N = 1000$, $\alpha = 4$ and $\lambda = 0.01$.

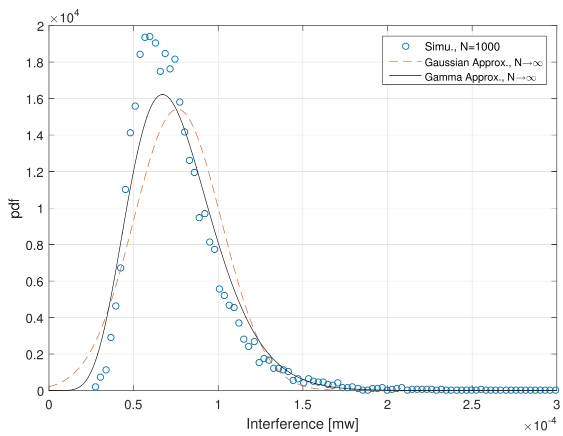

FIGURE 6. pdf of the aggregate interference power for DEZ size $k = 15$, $N = 1000$, $\alpha = 4$ and $\lambda = 0.01$.

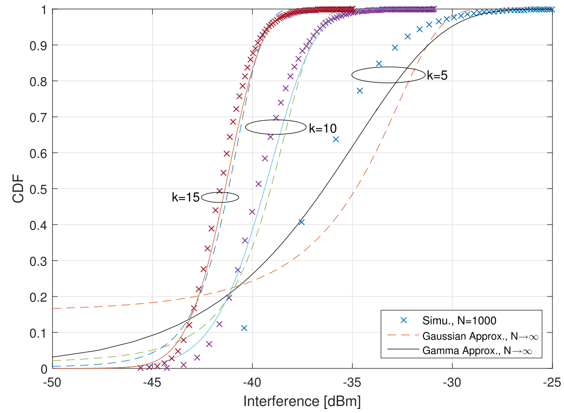

FIGURE 7. CDF of the aggregate interference power for different DEZ sizes, $N = 1000$, $\alpha = 4$ and $\lambda = 0.01$.

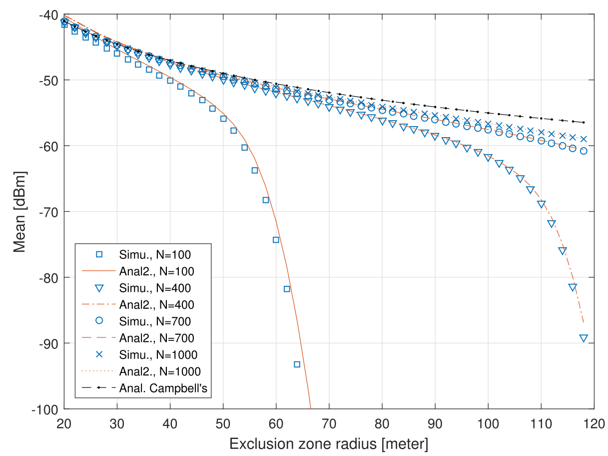

FIGURE 8. Mean of the aggregate interference power with the GEZ implemented, $\alpha = 4$ and $\lambda = 0.01$.

for transmission. If we consider an infinite number of SUs, the further increase in the GEZ radius and DEZ size does not offer significant benefit. These two figures also allow us to compare the GEZ radius and the DEZ size for the same effect of the aggregate interference from SUs to the PU. For example, when $N = 400$, for the mean value of the aggregate interference to reach -70 dBm, the GEZ radius $R = 96$ meters, and the DEZ size $k = 287$.

Finally, we compare the performances of the GEZ and DEZ in terms of the number of operable nodes. By fixing the total number of nodes, e.g., letting $N = 1000$, to represent an infinite number of nodes, the number of operable nodes located outside the GEZ or DEZ gives a measure of the network capacity for network planning. For any given value of the mean of the aggregate interference, we obtain both the GEZ radius and DEZ size using the results plotted in Figs. 8 and 9. As shown in Fig. 10, for the DEZ, as long as the size k is determined, the number of operable SUs is a fixed value and is not influenced by the randomness of the SU locations. For the GEZ, even if the radius is fixed, the number of operable SUs changes due to the randomness of the SU locations over different snapshots. Thus, we use a boxplot to show the range between 20% and 80% of these changes. The comparison shows that to achieve the same average aggregate interference value, i.e., the same level of PU protection, both schemes give the same average network capacity. However, for the GEZ, after the radius is determined, we cannot predict the number of nodes that will be located inside the GEZ. If a spectrum coordinator manages spectrum sharing between a PU and SU nodes over a region, it cannot predict exactly the operable nodes before knowing the actual deployment of the wireless nodes, i.e., their actual locations. The number of operable nodes varies significantly for different snapshots of deployment. This topological randomness poses a difficulty for network planning in the SU spectrum sharing planning

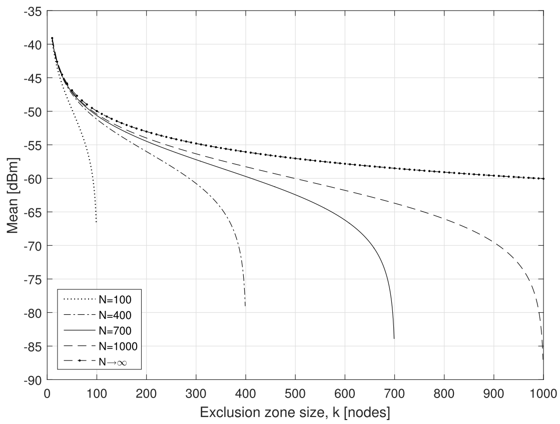

FIGURE 9. Mean of the aggregate interference power with the DEZ implemented, $\alpha = 4$ and $\lambda = 0.01$.

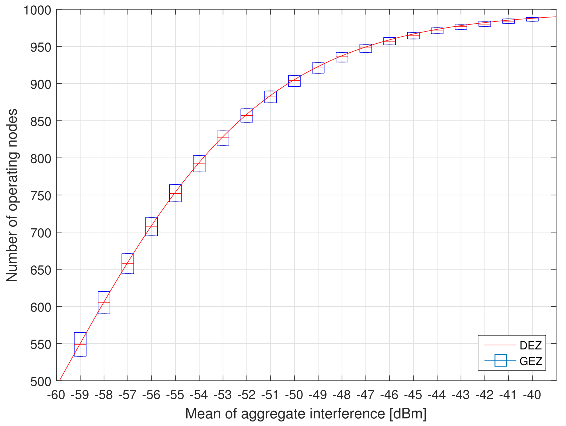

FIGURE 10. Comparing the network capacity in terms of the number of operating SU nodes outside the GEZ and DEZ. $N = 1000$, $\alpha = 4$ and $\lambda = 0.01$.

stage using the GEZ. Under the same PU protection criteria, after determining the size of the DEZ, we have a deterministic knowledge of the number of operable nodes without considering the topological randomness of SU networks. This is beneficial to SU spectrum planning.

V. CONCLUSION

In this paper, we studied the coexistence of multiple wireless networks consisting of a PU and multiple SUs. To control the aggregate interference from these SUs to the PU, the DEZ was proposed based on the neighboring relationship between the PU and those SUs. A DEZ with size k is implemented by terminating transmission of the first k nearest neighboring SUs of the PU.

To evaluate the performance of the proposed DEZ, we obtained the conditions under which the mean and variance of aggregate interference from the SUs to the PU exist. These conditions give insight into the minimum DEZ size. Furthermore, we derived the closed-form expressions of the mean and variance of the aggregate interference for different values of the DEZ size k. We also showed that the Gamma distribution is more preferable than the Gaussian distribution to model the distribution of the aggregate interference when the DEZ is implemented. These results allow us to determine an exact DEZ size for an expected PU protection level in terms of the mean aggregate interference or the maximum aggregate interference.

For a spectrum coordinator managing the spectrum sharing between the PU and SU network with only the knowledge of the density of the SU wireless nodes in the spectrum sharing planning stage, the GEZ gives a way to protect the PU: SUs are prohibited from transmitting if they are located inside the GEZ surrounding the PU. However, the random topology of the SU network deployed by the SU wireless network operator leads to uncertainty in the number of operable nodes for the spectrum coordinator. On the other hand, the DEZ is a shapeless contour. Implementing the DEZ with size k requires only the SU network to shut down the first $k-1$ neighboring SUs surrounding a given PU regardless of the random topology of the actual deployment. Therefore, the number of SU nodes that can reuse the PU spectrum is deterministic. This is beneficial to spectrum sharing planning between a PU and an SU before knowing the actual deployment of the SU networks.

In this paper, the basic property of the DEZ is analyzed. For the proposed DEZ to be widely adopted in industry, the following aspects require further investigation. The modeling of aggregate interference from SUs in the multiple PU scenario is important for defining the size of the DEZ. Moreover, in this paper, we assumed that all SUs have the same transmit power. The study can be extended to heterogeneous networks where SUs belong to different device types having different transmit powers. In this case, we can scatter these SUs following different PPPs in the spatial domain. The aggregate interference of a homogeneous network can be considered as a summation of the interference from separate homogeneous networks. The DEZ size that can be applied to each homogeneous network needs to be studied. A path loss model without fading has been assumed, as it is the main factor in scenarios considered by regulators. The fading effect of the wireless channel between an SU and a PU as well as adaptive power control and beamforming at the SU nodes will be studied in future work before applying the DEZ concept in more DSA application scenarios.

APPENDIXES

APPENDIX A

PROOF OF THEOREM 1

Let $X_n = D_n^m$; we can easily obtain the distribution of X_n as

$$f_{X_n}(x) = \lambda c_m e^{-\lambda c_m x} \frac{(\lambda c_m x)^{n-1}}{\Gamma(n)}. \tag{21}$$

Letting $Y_n = D_n^{-\alpha} = X_n^{-\alpha/m}$, we have $I = \sum_{n=1}^{\infty} Y_n$ and $\mathrm{E}(I) = \sum_{n=1}^{\infty} \mathrm{E}(Y_n)$, where

$$\begin{aligned}
\mathrm{E}(Y_n) &= \int_0^\infty x^{-\alpha/m} \lambda c_m e^{-\lambda c_m x} \frac{(\lambda c_m x)^{n-1}}{\Gamma(n)} dx \\
&= \frac{(\lambda c_m)^n}{(n-1)!} \int_0^\infty x^{n-1-\alpha/m} e^{-\lambda c_m x} dx \\
&= \frac{(\lambda c_m)^{\alpha/m}}{(n-1)!} \int_0^\infty (\lambda c_m x)^{n-1-\alpha/m} e^{-\lambda c_m x} d(\lambda c_m x). \quad (22)
\end{aligned}$$

We know that the integral above is similar to the definition of the Gamma function and that it converges if and only if $n - 1 - \alpha/m > -1 \Rightarrow n > \alpha/m$.

Because $\alpha/m > 1$ is given by [27], for the mean of the aggregate interference to be finite, we have $n > 1$. This means that the SU nearest to the PU must be terminated for transmission. Subsequently, we can obtain

$$\mathrm{E}\{Y_n\} = \frac{(\lambda c_m)^{\alpha/m}}{(n-1)!}\Gamma(n-\alpha/m). \tag{23}$$

The mean of the aggregate interference from SUs outside a DEZ with size k is given by

$$\begin{aligned}\mathrm{E}\{I_k\} &= \sum_{n=k}^{N} \mathrm{E}\{Y_n\} \\ &= (\lambda c_m)^{\alpha/m} \sum_{n=k}^{N} \frac{\Gamma(n-\alpha/m)}{(n-1)!},\end{aligned} \tag{24}$$

where N is the number of neighboring SUs surrounding the PU. Note that N can be ∞. Now, we examine whether $\sum_{n=k}^{\infty} \frac{\Gamma(n-\alpha/m)}{(n-1)!}$ converges. First, let

$$S = \sum_{n=k}^{N} \frac{\Gamma(n-\alpha/m)}{(n-1)!}. \tag{25}$$

If $\alpha/m \geq 2$,

$$\begin{aligned}S &\leq \sum_{n=k}^{N} \frac{\Gamma(n-2)}{(n-1)!} = \sum_{n=k}^{N} \frac{1}{(n-1)(n-2)} \\ &= \sum_{n=k}^{N} \left(\frac{1}{n-2} - \frac{1}{n-1}\right) \\ &= \frac{1}{k-2} - \frac{1}{N-1} \\ &\leq \frac{1}{k-2}.\end{aligned} \tag{26}$$

When $\alpha/m \geq 2$, the mean value of the aggregate interference I_k is a finite number.

If $1 < \alpha/m < 2$, let

$$\alpha/m = 1 + \delta, \tag{27}$$

where

$$0 < \delta < 1. \tag{28}$$

Now,

$$S = \sum_{n=k}^{N} \frac{\Gamma(n-\alpha/m)}{(n-1)!} = \sum_{n=k}^{N} \frac{\Gamma(n-1-\delta)}{(n-1)!} \tag{29}$$

is a function of δ. It is clear that the smaller the value of δ is, the larger S becomes. We need to prove only that for any given small value of δ, the value of S is a finite number. We can always find a large integer q such that $\frac{1}{q} < \delta$.

$$S < \sum_{n=k}^{N} f(n) = \sum_{n=k}^{N} \frac{\Gamma(n-1-\frac{1}{q})}{(n-1)!}, \tag{30}$$

where we define $f(n)$ as

$$f(n) = \frac{\Gamma(n-1-\frac{1}{q})}{(n-1)!}. \tag{31}$$

Then, we need to prove that $\sum_{n=k}^{N} f(n)$ is a finite number. First, using the recursion property of the Gamma function, we can rewrite $f(n)$ as

$$\begin{aligned}f(n) &= \frac{\Gamma\left(n-1-\frac{1}{q}\right)}{(n-1)!} \\ &= \frac{\left(n-2-\frac{1}{q}\right)\left(n-3-\frac{1}{q}\right)\ldots\left(2-\frac{1}{q}\right)\left(1-\frac{1}{q}\right)\Gamma\left(1-\frac{1}{q}\right)}{(n-1)(n-2)(n-3)\ldots 1} \\ &= \frac{g(n)}{n-1},\end{aligned} \tag{32}$$

where $g(n)$ is given in (33), as shown at the bottom of the this page. Then, we can write $(g(n))^q$ as in (34), as shown at the bottom of the this page.

According to the mean inequality, we obtain

$$\begin{aligned}&(qn-q-1)(qn-2q-1)^{q-1} \\ &\quad\leq \left(\frac{(qn-q-1)+(q-1)(qn-2q-1)}{q}\right)^q \\ &\quad= (qn-2q)^q\end{aligned} \tag{35}$$

$$\begin{aligned}g(n) &= \frac{\left(n-2-\frac{1}{q}\right)\left(n-3-\frac{1}{q}\right)\ldots\left(2-\frac{1}{q}\right)\left(1-\frac{1}{q}\right)\Gamma\left(1-\frac{1}{q}\right)}{(n-2)(n-3)(n-4)\ldots 1} \\ &= \frac{\Gamma\left(1-\frac{1}{q}\right)(qn-2q-1)(qn-3q-1)\ldots(2q-1)(q-1)}{(qn-2q)(qn-3q)\ldots q}\end{aligned} \tag{33}$$

$$\begin{aligned}(g(n))^q &= \frac{\Gamma\left(1-\frac{1}{q}\right)^q (qn-2q-1)^q (qn-3q-1)^q \ldots (2q-1)^q (q-1)^q}{(qn-2q)^q (qn-3q)^q \ldots q^q} \\ &= \frac{\Gamma\left(1-\frac{1}{q}\right)^q (qn-q-1)(qn-2q-1)^q (qn-3q-1)^q \ldots (2q-1)^q (q-1)^q}{(qn-2q)^q (qn-3q)^q \ldots q^q (qn-q-1)}\end{aligned} \tag{34}$$

and

$$(qn-2q-1)(qn-3q-1)^{q-1} \le (qn-3q)^q, \quad (36)$$
$$\ldots, \quad (37)$$
$$(2q-1)(q-1)^{q-1} \le q^q. \quad (38)$$

Applying the above inequalities to (34), we obtain

$$(g(n))^q \le \frac{\Gamma\left(1-\frac{1}{q}\right)^q (q-1)}{qn-q-1}, \quad (39)$$

and thus

$$g(n) \le \Gamma\left(1-\frac{1}{q}\right)\left(\frac{q-1}{qn-q-1}\right)^{\frac{1}{q}}. \quad (40)$$

Therefore,

$$\begin{aligned}\sum_{n=k}^{N} f(n) &\le \sum_{n=k}^{N} \Gamma\left(1-\frac{1}{q}\right)\frac{\left(\frac{q-1}{qn-q-1}\right)^{\frac{1}{q}}}{n-1}\\ &= \Gamma\left(1-\frac{1}{q}\right)\sum_{n=k}^{N}\frac{\left(\frac{q-1}{q(n-1)-1}\right)^{\frac{1}{q}}}{n-1}\\ &= \Gamma\left(1-\frac{1}{q}\right)\sum_{m=k-1}^{N}\frac{\left(\frac{q-1}{qm-1}\right)^{\frac{1}{q}}}{m}\\ &\le \Gamma\left(1-\frac{1}{q}\right)\sum_{m=k-1}^{N}\frac{\left(\frac{1}{m}\right)^{\frac{1}{q}}}{m}\\ &= \Gamma\left(1-\frac{1}{q}\right)\sum_{m=k-1}^{N}\frac{1}{m^{1+\frac{1}{q}}}. \end{aligned} \quad (41)$$

Since N can be ∞ and knowing that $\sum_{n}^{\infty}\frac{1}{n^a}$ converges if and only if $a > 1$, we can prove that S converges. As a result of all the above, the mean of aggregate interference I_k converges if and only if $n > \alpha/m > 1$.

APPENDIX B
PROOF OF THEOREM 2

We can write the second-order moment of the aggregate interference as

$$\begin{aligned}\mathrm{E}\left\{I_k^2\right\} &= \mathrm{E}\left\{\left(\sum_{n=k}^{N} Y_n\right)^2\right\}\\ &= \sum_{n=k}^{N}\mathrm{E}\left\{Y_n^2\right\} + \sum_{i,j=k;i\neq j}^{N}\mathrm{E}\left\{Y_iY_j\right\}.\end{aligned} \quad (42)$$

With (23), we know that

$$\mathrm{E}\left\{Y_n^2\right\} = \sum_{n=k}^{N}\frac{(\lambda c_m)^{2\alpha/m}}{(n-1)!}\Gamma(n-2\alpha/m). \quad (43)$$

If $n > 2\alpha/m > 2$, $\sum_{n=k}^{N}\mathrm{E}\left\{Y_n^2\right\}$ is a finite number.

Applying the Cauchy-Schwartz inequality and the mean inequality to the cross term to (47), we obtain

$$\mathrm{E}\left\{Y_iY_j\right\} \le \left(\mathrm{E}\left\{Y_i^2\right\}\mathrm{E}\left\{Y_j^2\right\}\right)^{\frac{1}{2}} \le \frac{1}{2}\left(\mathrm{E}\left\{Y_i^2\right\}+\mathrm{E}\left\{Y_j^2\right\}\right). \quad (44)$$

Thus, we can conclude that when $n > 2\alpha/m > 2$,

$$\sum_{i\neq j}^{N}\mathrm{E}\left\{Y_iY_j\right\} \le \sum_{i\neq j}^{N}\left(\mathrm{E}\left\{Y_i^2\right\}+\mathrm{E}\left\{Y_j^2\right\}\right) < \infty. \quad (45)$$

Therefore, $\mathrm{E}\left\{I_k^2\right\}$ is a finite number if and only if $n > 2\alpha/m > 2$.

APPENDIX C
DERIVATION OF THE MEAN

Under the conditions given in Theorem 1 and Theorem 2, the mean of the aggregate interference with the DEZ in (24) can be rewritten as

$$\begin{aligned}\mathrm{E}\{I_k\} &= \sum_{n=k}^{N}\mathrm{E}\{Y_n\}\\ &= (\lambda c_m)^{\alpha/m}\sum_{n=k}^{N}\frac{\Gamma(n-\alpha/m)}{(n-1)!}\\ &= (\lambda c_m)^{\beta}\sum_{n=k}^{N}\frac{(n-\beta)!}{(n-1)!}\\ &= (\lambda c_m)^{\beta}\sum_{n=k}^{N}\frac{1}{(n-1)\cdots(n-\beta)}\\ &= \frac{(\lambda c_m)^{\beta}}{\beta-1}\sum_{n=k}^{N}\left(\frac{1}{(n-2)\cdots(n-\beta)} - \frac{1}{(n-1)\cdots(n-\beta+1)}\right)\\ &= \frac{(\lambda c_m)^{\beta}}{\beta-1}\left(\frac{1}{(k-2)\cdots(k-\beta)} - \frac{1}{(N-1)\cdots(N-\beta+1)}\right),\end{aligned} \quad (46)$$

where $\beta = \alpha/m$.

APPENDIX D
DERIVATION OF THE SECOND-ORDER MOMENT

We can write the second-order moment of the aggregate interference as

$$\begin{aligned}\mathrm{E}\left\{I_k^2\right\} &= \mathrm{E}\left\{\left(\sum_{n=k}^{N} Y_n\right)^2\right\}\\ &= \sum_{n=k}^{N}\mathrm{E}\left\{Y_n^2\right\} + \sum_{i,j=k;i\neq j}^{N}\mathrm{E}\left\{Y_iY_j\right\}.\end{aligned} \quad (47)$$

It is easy to calculate its first term in (47) as

$$\begin{aligned}\sum_{n=k}^{N}\mathrm{E}\left\{Y_n^2\right\} &= \sum_{n=k}^{N}\frac{(\lambda c_m)^{2\beta}}{(n-1)!}\Gamma(n-2\beta)\\ &= \frac{(\lambda c_m)^{2\beta}}{2\beta-1}\left(\frac{1}{(k-2)\cdots(k-2\beta)} - \frac{1}{(N-1)\cdots(N-2\beta+1)}\right).\end{aligned} \quad (48)$$

To calculate the second term of equation (47), we must first obtain the closed-form expression for $\mathrm{E}\left\{Y_iY_j\right\}$. For this purpose, the distribution of X_i and X_j is derived. Suppose that $i<j$ when $x<y$, and write the CDF as

$$\begin{aligned} P(X_i<x,X_j<y) &= \int_0^x P(X_i<x,X_j<y|X_i=t)f_{X_i}(t)dt \\ &= \int_0^x P(X_j<y|X_i=t)f_{X_i}(t)dt \\ &= \int_0^x P(X_{j-i}<y-t)f_{X_i}(t)dt, \end{aligned} \tag{50}$$

where X_{j-i} denotes X_j-X_i. Since X_n is a time-homogeneous random process with an independent increment [27], we can write the pdf as

$$\begin{aligned} f_{X_i,X_j}(x,y) &= \frac{\partial}{\partial y}\frac{\partial P}{\partial x} \\ &= f_{X_{j-i}}(y-x)f_{X_i}(x) \\ &= \lambda c_m e^{-\lambda c_m(y-x)}\frac{(\lambda c_m(y-x))^{j-i-1}}{(j-i-1)!} \\ &\quad \times\lambda\pi e^{-\lambda\pi x}\frac{(\lambda c_m x)^{i-1}}{(i-1)!} \\ &= (\lambda c_m)^j e^{-\lambda c_m y}\frac{(y-x)^{j-i-1}x^{i-1}}{(j-i-1)!(i-1)!}. \end{aligned} \tag{51}$$

Knowing the joint distribution of X_i and X_j, we can calculate the second term in (47) as

$$\begin{aligned} \mathrm{E}\left\{Y_iY_j\right\} &= \mathrm{E}\left\{\frac{1}{X_i^\beta}\frac{1}{X_j^\beta}\right\} \\ &= \frac{(\lambda c_m)^j}{(j-i-1)!(i-1)!} \\ &\quad\times\int\int\frac{1}{x^\beta y^\beta}e^{-\lambda c_m y}(y-x)^{j-i-1}x^{i-1}dxdy \\ &= \frac{(\lambda c_m)^j}{(j-i-1)!(i-1)!} \\ &\quad\times\int_0^\infty\frac{1}{y^\beta}e^{-\lambda c_m y}dy\int_0^y(y-x)^{j-i-1}x^{i-1-\beta}dx \\ &= \frac{(\lambda c_m)^j}{(j-i-1)!(i-1)!} \\ &\quad\times\int_0^\infty\frac{1}{y^\beta}e^{-\lambda c_m y}y^{j-1-\beta}\frac{\Gamma(i-\beta)\Gamma(j-i)}{\Gamma(j-\beta)}dy \\ &= \frac{(\lambda c_m)^{2\beta}\Gamma(i-\beta)}{(i-1)!\Gamma(j-\beta)} \\ &\quad\times\int_0^\infty e^{-\lambda c_m y}(\lambda c_m y)^{j-1-2\beta}d(\lambda c_m y) \\ &= \frac{(\lambda c_m)^{2\beta}(i-\beta-1)!(j-1-2\beta)!}{(i-1)!(j-\beta-1)!} \\ &= \frac{(\lambda c_m)^{2\beta}}{(i-1)\cdots(i-\beta)(j-\beta-1)\cdots(j-2\beta)}, \end{aligned} \tag{52}$$

where we have utilized the following equation to solve the second integral:

$$\begin{aligned} &\int_0^y(y-x)^{j-i-1}x^{i-1-\beta}dx \\ &\quad= y^{j-1-\beta}\int_0^y\left(\frac{y-x}{y}\right)^{j-i-1}\left(\frac{x}{y}\right)^{i-1-\beta}d\frac{x}{y} \\ &\quad\overset{t=\frac{x}{y}}{=} y^{j-1-\beta}\int_0^1(1-t)^{j-i-1}(t)^{i-1-\beta}dt \\ &\quad= y^{j-1-\beta}B(i-\beta,j-i) \\ &\quad= y^{j-1-\beta}\frac{\Gamma(i-\beta)\Gamma(j-i)}{\Gamma(j-\beta)}. \end{aligned} \tag{53}$$

Based on (52), we can write the second term in (47) as in (49), as shown at the bottom of the this page.

$$\begin{aligned} \sum_{i,j=k,i\neq j}^{N}\mathrm{E}\left\{Y_iY_j\right\} &= 2\sum_{i<j}^{N}\mathrm{E}\left\{Y_iY_j\right\} \\ &= 2(\lambda c_m)^{2\beta}\sum_{i=k}^{N-1}\left(\frac{1}{(i-1)\cdots(i-\beta)}\sum_{j=i+1}^{N}\frac{1}{(j-\beta-1)\cdots(j-2\beta)}\right) \\ &= \frac{2(\lambda c_m)^{2\beta}}{\beta-1}\sum_{i=k}^{N-1}\left(\frac{1}{(i-1)\cdots(i-\beta)}\left(\frac{1}{(i-\beta-1)\cdots(i-2\beta+1)}-\frac{1}{(N-\beta-1)\cdots(N-2\beta+1)}\right)\right) \\ &= \frac{2(\lambda c_m)^{2\beta}}{\beta-1}\sum_{i=k}^{N-1}\frac{1}{(i-1)\cdots(i-2\beta+1)}-\frac{2(\lambda c_m)^{2\beta}}{(\beta-1)(N-\beta-1)\cdots(N-2\beta+1)}\sum_{i=k}^{N-1}\frac{1}{(i-1)\cdots(i-\beta)} \\ &= \frac{(\lambda c_m)^{2\beta}}{(\beta-1)^2}\left(\frac{1}{(k-2)\cdots(k-2\beta+1)}-\frac{1}{(N-2)\cdots(N-2\beta+1)}\right) \\ &\quad-\frac{2(\lambda c_m)^{2\beta}}{(N-\beta-1)\cdots(N-2\beta+1)(\beta-1)^2}\left(\frac{1}{(k-2)\cdots(k-\beta)}-\frac{1}{(N-2)\cdots(N-\beta)}\right) \end{aligned} \tag{49}$$

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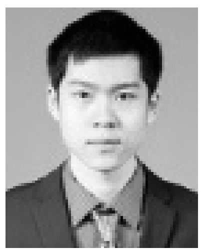

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