Coverage Performance in Cognitive Radio Networks with Self-sustained Secondary Transmitters

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Abstract. In this paper, we investigate the opportunistic spectrum access (OSA) of self-sustained secondary transmitters (STs) in cognitive radio (CR) network to improve both the spectral efficiency and energy efficiency. Particularly, by utilizing energy harvesting, the STs are assumed to be able to collect and store ambient powers for data transmission. An energy harvesting based OSA protocol, namely the EH-PRA protocol, is considered, under which a ST is eventually allowed to launch the transmission only if its battery level is larger than the transmit power and the estimated interference perceived at the active primary receivers (PRs) is lower than a threshold N_{ra}. Given that the battery capacity of STs is infinite, we derive the transmission probability of STs. We then characterize the coverage performance of the CR network. Finally, simulation results are provided for the validation of our analysis.

Keywords: Cognitive radio network · Energy harvesting
Opportunistic spectrum access · Stochastic geometry
Transmission probabilty · Coverage probability · Spatial throughput

1 Introduction

Energy harvesting [1–5], widely believed as a promising solution of power generation for next generation wireless networks, has attracted tremendous interests over recent years. By utilizing energy harvesting as energy sources for wireless networks, the corresponding energy costs as well as the adverse effects to the environment can be significantly reduced. Further, the wireless networks powered by energy harvesting can be flexibly deployed without the need of power grid [6].

In addition to energy efficiency, spectral efficiency is another important issue in mobile networking. Particularly, how to effectively exploiting the underutilized spectrum resources in mobile networks is consider to be the key challenges for the enhancement of spectral efficiency [7,8]. To address this issue, technologies of CR [9,10] based OSA [11–13] are proposed such that the under-utilized spectrum of the primary network can be effectively reused by the secondary network.

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In this paper, to simultaneously improve the energy efficiency and spectral efficiency of the mobile networks [15–17], the energy harvesting based OSA is investigated under the CR paradigm. Particularly, with energy harvesting, the STs become self-sustained. The energy efficiency of the CR network is thereby significantly improved. On the other hand, thanks to the OSA of STs, the spectral efficiency of the CR network can also be improved.

Energy harvesting powered CR networks has been widely studied over recent years [18–24]. In [18], assuming perfect spectrum sensing, the myopic spectrum access policy was studied to maximize the throughput of self-sustained STs powered by energy harvesting. Further, in [19,20], Park *et al.* evaluated the effect of sensing error and temporal correlation of the primary traffic on the throughput of CR network. In [21], Pappas *et al.* investigated the maximum stable throughput region for CR networks with self-sustained primary transmitters (PTs). In [22], Yin *et al.* optimized the cooperation strategy of self-sustained STs to maximize the achievable throughput of the CR network. Further, in [23], with STs powered by energy harvesting, Yin *et al.* proposed a generalized multi-slot spectrum sensing strategy which jointly optimized the save-ratio, sensing duration, sensing threshold as well as fusion rule to protect the primary transmissions. In [24], Chung *et al.* maximized the average throughput of the energy harvesting powered CR network by optimizing the sensing duration and energy detectors sensing threshold of STs. It is worth noting that [18–24] do not consider the impact of the locations of PTs and STs on the performance of the CR network.

In this paper, different from [18–24], we consider the CR networks powered by energy harvesting with Poisson distributed PTs and STs. By applying energy harvesting, the STs are assumed to be able to collect and store ambient powers for data transmissions. Given sufficient energy stored in the batteries, the corresponding STs (denoted by eligible STs) are then allowed to launch the transmissions only if its estimated inference perceived at the active PRs is lower than a predefined threshold N_{ra}. We call this kind of OSA protocol as the energy harvesting based PRA protocol. Given that the battery capacity of STs is infinite, we derive the transmission probability for secondary network. We then characterize the coverage probability of the primary and secondary networks. Finally, simulation results are provided for the validation of our analysis.

2 System Model

We studied a CR network on $\mathbb{R}^2$. The PTs have higher priority for utilizing the spectrum, while the STs can only opportunistically access the spectrum by exploiting the spatial holes of the primary network. The PTs and STs are modeled by two independent HPPPs with intensities given by μ_0 and λ_0, respectively. For each PT, its associated PR is at a distance of d_p away in a random direction. Similarly, for each ST, its associated SR is at a distance of d_s away in a random direction. As such, the PRs and SRs also follow two independent HPPPs with their respective intensities given by μ_0 and λ_0.

With energy harvesting, the STs are assumed to be able to collect and store ambient powers for data transmissions. Particularly, the energy harvested by the

ST located at position $\mathbf{y} \in \mathbb{R}^{\mathbf{2}}$ in the t-th time slot is modeled by a nonnegative random variable $Z_t^s(\mathbf{y})$ as

$$\mathbf{E}\big[Z_t^s(\mathbf{y})\big] = \nu_e^s, \tag{1}$$

$$\mathbf{Var}\big[Z_t^s(\mathbf{x})\big] = \delta_e^s. \tag{2}$$

Further, it is assumed that the PTs, PRs and SRs are powered by reliable energy sources.

For the primary network, the PTs independently access the spectrum with probability ρ_p [27]. For the secondary network, the EH-PRA protocol is applied, under which a ST is allowed to transmit only if the battery level is larger than the transmit power P_s and the spatial spectrum hole of the primary network is detected.

Let $\mathbf{B}_s$ denote the battery capacities for STs. Further, let P_p and P_s be the transmit powers of PTs and STs. Then, given $S_t^s(\mathbf{y})$ as the battery level of ST located at positions $\mathbf{y} \in \mathbb{R}^{\mathbf{2}}$ in the t-th slot, it can be obtained that

$$S_t^s(\mathbf{y}) = \min\left(S_{t-1}^s(\mathbf{y}) + Z_t^s(\mathbf{y}) - P_s \cdot \mathcal{G}_t^s, \mathbf{B}_s\right), \tag{3}$$

where

$$\mathcal{G}_t^s = \mathbf{1}_{S_{t-1}^s(\mathbf{y}) \geq P_s} \cdot \mathbf{1}_{M_t^{ra}(\mathbf{y}) \leq N_{ra}}, \tag{4}$$

$\mathbf{1}_{\mathcal{A}}$ denotes the indicator function with respect to event $\mathcal{A}$.

For the primary network, the locations of active PTs/PRs follow a HPPP with density $\mu_p = \mu_0 p_p$. For the secondary network, under the energy harvesting based PRA protocol, the density of the point process formed by the active STs in the t-th time slot is given by $\mu_t^s = \eta_t^s \lambda_0$, where

$$\eta_t^s = \mathbb{E}\left[\mathbf{1}_{S_{t-1}^s(\mathbf{y}) \geq P_s} \cdot \mathbf{1}_{M_t^{ra}(\mathbf{y}) \leq N_{ra}}\right]. \tag{5}$$

The propagation channel is modeled by

$$l(r) = h \cdot r^{-\alpha}, \tag{6}$$

where h denotes the exponentially distributed small-scale Rayleigh fading with unit mean, r denotes the transmission distance, and α denotes the path-loss exponent [30]. The SIR targets for primary and secondary networks are denoted by θ_p and θ_s, respectively.

3 Transmission Probability with Infinite Battery Capacity

In this section, assuming infinite battery capacity for STs, we derive the corresponding transmission probabilities η^s. Particularly, based on (3), by letting $\mathbf{B} \to \infty$, it can be easily obtained that

$$S_t^s(\mathbf{y}) = S_{t-1}^s(\mathbf{y}) + Z_t^s(\mathbf{y}) - P_s \cdot \mathcal{G}_t^s. \tag{7}$$

where $\mathcal{G}_t^s$ are defined in (4), respectively. Then, based on (5), we characterize the transmission probability η^s of STs in the following theorems.

Theorem 1. *For CR network with self-sustained STs, assuming infinite battery capacity and under the EH-PRA protocol, η^s is given by*

$$\eta^s = \min\left(Q_{ra},\ \frac{\nu_e^s}{P_s}\right). \tag{8}$$

where

$$Q_{ra} = \exp\left\{-2\pi\mu_p \frac{\Gamma(\frac{2}{\alpha})(\frac{P_p}{N_{ra}})^{\frac{2}{\alpha}}}{\alpha}\right\}. \tag{9}$$

Proof. The proof is omitted due to space limitation.

Remark 3.1. Based on Theorem 1, the intensity of the point process formed by active STs can be immediately obtained as

$$\lambda_s = \min\left(\lambda_0 Q_{ra},\ \lambda_0 \frac{\nu_e^s}{P_s}\right). \tag{10}$$

4 Coverage Probability in Primary Network with Infinity Battery Capacity

4.1 Conditional Distribution of Active STs

To derive the coverage probability of primary transmission, we focus on a typical PR $\mathbf{R}_p$ at the origin with its associated PT $\mathbf{T}_p$ at a distance of d_p away in random direction. Then, by Slivnyak's theorem [35], it can be easily verified that the rest of the active PRs/PTs follow a HPPP with intensity μ_p. For the secondary network, we denote $\Phi_{ra}^{\mathbf{R}_p}(u)$ as the point process formed by the active STs on a circle of radius u centered at $\mathbf{R}_p$. Then, we derive the conditional distribution of the active STs in the following lemma.

Lemma 1. *For CR network with self-sustained STs, assuming infinite battery capacity and under the EH-PRA protocol, $\Phi_{ra}^{\mathbf{R}_p}(u)$ is isotropic with respect to $\mathbf{R}_p$ and its intensity $\lambda_{ra}^{\mathbf{R}_p}(u)$ is given by*

$$\lambda_{ra}^{\mathbf{R}_p}(u) = \min\left(\lambda_0 Q_{ra}\mathcal{P}(u),\ \lambda_0 \frac{\nu_e^s}{P_s}\right), \tag{11}$$

where

$$\mathcal{P}(u) = \left(1 - e^{-\frac{N_{ra}u^\alpha}{P_p}}\right). \tag{12}$$

Proof. The proof is omitted due to space limitation.

It is worth noting that under the EH-PRA protocol, $\Phi_{ra}^{\mathbf{R}_p}(u)$ does not follow a HPPP. Then, due to the fact that the higher order statistics of $\Phi_{ra}^{\mathbf{R}_p}(u)$ are intractable, the coverage performance of the primary network is difficult to be completely characterized. To address this issue, similar to [13,36–39], we make the following approximation on $\Phi_{ra}^{\mathbf{R}_p}(u)$.

Assumption 1. *$\Phi_{ra}^{\mathbf{R}_p}(u)$ follows a HPPP with intensity given by $\lambda_{ra}^{\mathbf{R}_p}(u)$.*

Under Assumption 1, we then characterize the coverage performance of the primary network in the following subsection.

4.2 Coverage Probability with Energy Harvesting Based PRA Protocol

Theorem 2. *For CR network with self-sustained STs, under Assumption 1, the coverage probability of the primary network is given by*

$$\begin{aligned} \tau_p^{ra} &= \exp\left\{-\frac{2\pi^2}{\alpha \sin\left(\frac{2\pi}{\alpha}\right)}\theta_p^{\frac{2}{\alpha}} d_p^2 \mu_p\right\} \\ &\times \exp\left\{-2\pi\lambda_0 Q_{ra}\int_0^{\zeta}(1-\varrho(u))\,\mathcal{P}(u)udu\right\} \\ &\times \exp\left\{-2\pi\lambda_0\frac{\nu_e^s}{P_s}\int_{\zeta}^{\infty}(1-\varrho(u))\,udu\right\}. \end{aligned} \tag{13}$$

where

$$\zeta = \left(-\frac{P_p}{N_{ra}}\ln\left(1-\frac{\eta^s}{Q_{ra}}\right)\right)^{\frac{1}{\alpha}},$$

and

$$\varrho(u) = \int_0^{\frac{N_{ra}u^{\alpha}}{P_p}} e^{-\frac{\theta_p P_s g u^{-\alpha}}{P_p d_p^{-\alpha}}} \times \frac{e^{-g}}{1-e^{-\frac{-N_{ra}u^{\alpha}}{P_p}}}dg.$$

Proof. See Appendix A.

5 Coverage Probability in Secondary Network with Infinity Battery Capacity

5.1 Conditional Distributions of Active PTs and STs

To derive the coverage probability of the secondary network, we focus on a typical SR $\mathbf{R}_s$ at the origin with its associated ST $\mathbf{T}_s$ at a distance of d_s away in random direction. Let $\Psi_{ra}^{\mathbf{T}_s}(r)$ be the point process formed by the active PRs on a circle of radius r centered at $\mathbf{T}_s$ under the ER-PRA protocol. Then, $\Psi_{ra}^{\mathbf{T}_s}(r)$ is characterized as follows.

Lemma 2. *For CR network with self-sustained STs, under the ER-PRA protocol, $\Psi_{ra}^{\mathbf{T}_s}(r)$ follows a HPPP with intensity $\psi_{ra}^{\mathbf{T}_s}(r)$ given by*

$$\psi_{ra}^{\mathbf{T}_s}(r) = \mu_0\rho_p\mathcal{P}(r), \tag{14}$$

where

$$\mathcal{P}(r) = \left(1-e^{-\frac{N_{ra}r^{\alpha}}{P_p}}\right). \tag{15}$$

Proof. Based on Lemma 5.1 in [13], it can be easily verified that $\Psi_{ra}^{\mathbf{T}_s}(r)$ follows a HPPP with density $\psi_{ra}^{\mathbf{T}_s}(r)$ as given by (14).

Let $\Upsilon_{ra}^{\mathbf{T}_s}(r)$ be the point process formed by the active PTs on a circle of radius r centered at $\mathbf{T}_s$ under the ER-PRA protocol. Then, with Lemma 2, $\Upsilon_{ra}^{\mathbf{T}_s}(r)$ is derived in the following lemma.

Lemma 3. *For CR network with self-sustained STs, under the ER-PRA protocol, $\Upsilon_{ra}^{\mathbf{T}_s}(r)$ follows a HPPP with intensity $\mu_{ra}^{\mathbf{T}_s}(r)$, which is upper-bounded by*

$$\mu_{ra}^{\mathbf{T}_s}(r) \leq \mu_0 \rho_p \mathcal{P}(r + d_p). \tag{16}$$

Proof. Based on Lemma 2, it can be easily verified that $\Upsilon_{ra}^{\mathbf{T}_s}(r)$ follows a HPPP and the upper bound on $\mu_{ra}^{\mathbf{T}_s}(r)$ is given by $\psi_{ra}^{\mathbf{T}_s}(r + d_p)$.

For the secondary network, we denote $\Phi_{ra}^{\mathbf{T}_s}(r)$ as the point process formed by the active STs on a circle of radius r centered at $\mathbf{T}_s$ under the energy harvesting based PRA protocol. Then, with Lemma 2, the conditional distribution of $\Phi_{ra}^{\mathbf{T}_s}(r)$ under the energy harvesting based PRA protocol is characterized as follows.

Lemma 4. *For an overlay CR network with self-sustained STs, under the energy harvesting based PRA protocol, conditioned on a typical SR at the origin, $\Phi_{ra}^{\mathbf{T}_s}(r)$ is isotropic around $\mathbf{T}_s$, and the corresponding density, denoted by $\lambda_{ra}^{\mathbf{T}_s}(r)$, is bounded by*

$$\mathcal{K} \leq \lambda_{ra}^{\mathbf{T}_s}(r) \leq \mathcal{D}, \tag{17}$$

where

$$\mathcal{D} = \min\left(\lambda_0 \beta_{ra},\ \lambda_0 \frac{\nu_e^s}{P_s}\right),$$

$$\mathcal{K} = \min\left(\lambda_0 Q_{ra},\ \lambda_0 \frac{\nu_e^s}{P_s}\right),$$

and

$$\beta_{ra} = \exp\left\{-2\pi \int_0^{\infty} e^{-\frac{N_{ra} r^{\alpha}}{P_p}} \mu_{ra}^{\mathbf{T}_s}(r) r\, dr\right\}. \tag{18}$$

Proof. Based on Lemma 5.3 in [13], (17) is immediately obtained. This thus completes the proof of Lemma 4.

It is worth noting that under the ER-PRA protocol, similar to the primary network case, $\Phi_{ra}^{\mathbf{T}_s}(r)$ or does not follow a HPPP. As such, the coverage probability of the secondary network under the energy harvesting based PRA protocol is difficult to be derived. To tackle this difficulty, we make the following approximation on $\Phi_{ra}^{\mathbf{T}_s}(r)$.

Assumption 2. *Under the ER-PRA protocol, $\Phi_{ra}^{\mathbf{T}_s}(r)$ follows a HPPP with intensity $\lambda_{ra}^{\mathbf{T}_s}(r)$.*

With Assumption 2, we then derive the coverage probability of the secondary network under the ER-PRA protocol in the following subsection.

5.2 Coverage Probability with PRA Protocol

Under the energy harvesting based PRA protocol, we denote $\Upsilon_{ra}^{\mathbf{R}_s}(u)$ as the point process formed by the active PTs on a circle of radius u centered at $\mathbf{R}_s$. Then, based on Lemma 3, it can be easily verified that $\Upsilon_{ra}^{\mathbf{R}_s}(u)$ does not follow a HPPP. Let $\mu_{ra}^{\mathbf{R}_s}(u)$ be the average density of $\Upsilon_{ra}^{\mathbf{R}_s}(u)$. Then, we characterize $\mu_{ra}^{\mathbf{R}_s}(u)$ in the following lemma.

Lemma 5. *Under the ER-PRA protocol, $\mu_{ra}^{\mathbf{R}_s}(u)$ is upper bounded by*

$$\mu_{ra}^{\mathbf{R}_s}(u) \leq \mu_0 \rho_p \mathcal{P}(u + d_p + d_s). \tag{19}$$

Proof. Based on Lemma 3, it can be easily verified that the highest density of $\mu_{ra}^{\mathbf{R}_s}(u)$ is $\mu_{ra}^{\mathbf{T}_s}(u + d_s)$.

Based on Lemma 5, we then derive the coverage probability of the secondary network under the ER-PRA protocol in the following theorem.

Theorem 3. *For CR network with self-sustained STs, under the ER-PRA protocol, based on Assumption 2, the coverage probability of the secondary network is lower-bounded by*

$$\begin{aligned}\tau_s^{ra} \geq \exp&\left\{ -\frac{2\pi^2}{\alpha \sin\left(\frac{2\pi}{\alpha}\right)} \theta_s^{\frac{2}{\alpha}} d_s^2 \mathcal{D} \right\} \\ &\times \exp\left\{ -2\pi\mu_0\rho_p \int_0^\infty \left(\frac{1 - e^{-\frac{N_{ra}(u+d_p+d_s)^\alpha}{P_p}}}{1 + \frac{P_s u^\alpha}{\theta_s P_p d_s^\alpha}} \right) u du \right\},\end{aligned} \tag{20}$$

Proof. By applying Lemmas 4 and 5, (20) is readily obtained.

6 Numerical Results

In this section, simulation results are provided to validate our analytical results. Throughout this section, unless specified otherwise, we set $\mu_p = 0.1$, $\lambda_0 = 0.1$, $P_p = 5$, $P_s = 2$, $d_p = d_s = 1$, $\theta_p = \theta_s = 3$, and $\alpha = 4$.

Figure 1 plots the analytical and simulation results on the transmission probability of the STs versus μ_p under the EH-PRA protocol. It is observed that the transmission probability of STs under the EH-PRA protocol are piecewise functions with μ_p, which are intuitively expected from Theorem 1. It is also observed that the simulation results are in accordance with our analytical results.

Figure 2 shows the coverage probability of primary network under the EH-PRA protocol. It is observed that the simulated values fit closely to our analytical values, which thereby shows that Assumption 1 is valid.

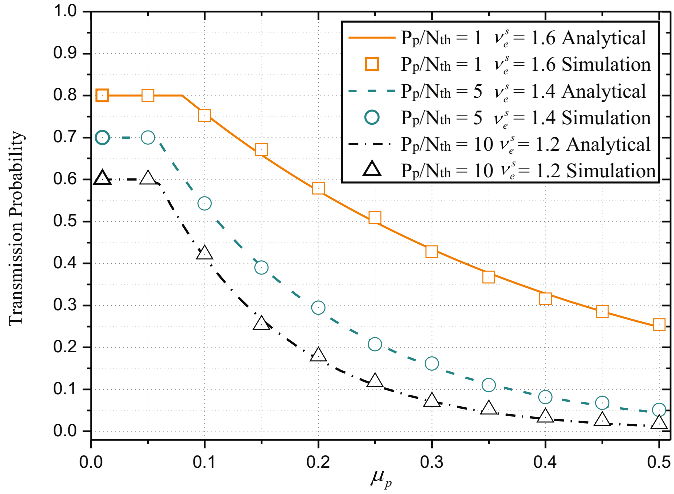

Fig. 1. Transmission probability of STs.

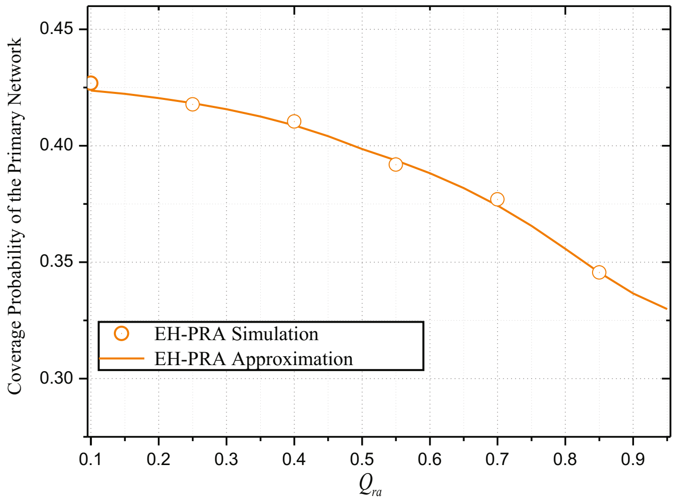

Fig. 2. Coverage probability of primary network.

Figure 3 plots the analytical and simulation results on the coverage probability of the secondary network under the EH-PRA protocol. As observed from Fig. 3, the lower bound on the coverage probability of the secondary network derived in Theorem 3 under Assumption 2 is effective.

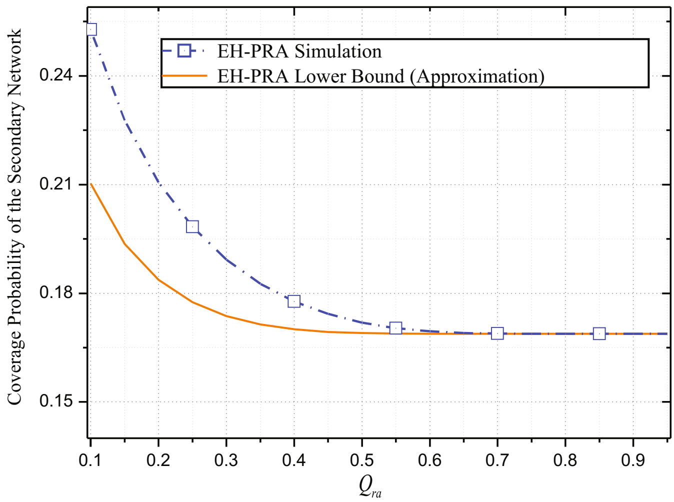

Fig. 3. Coverage probability of secondary network.

7 Conclusions

This paper has studied the performance of CR networks with self-sustained STs. Upon harvesting sufficient energy, the STs opportunistically access the spectrum if the estimated interference at the active PRs is lower than a predefined threshold N_{ra}. Assuming infinite battery capacity, we derived the transmission probability of STs. We then characterized the coverage probabilities of the primary and secondary networks. Simulation results are provided to validate our analysis.

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A Proof of Theorem 2

Proof. With the energy harvesting based PRA protocol, given a typical PR located at the origin, the received SIR is given by

$$\mathrm{SIR}_p = \frac{P_p h_0 d_p^{-\alpha}}{\sum\limits_{i\in\Pi_p^t} P_p h_i |\mathbf{X}_i|^{-\alpha} + \sum\limits_{j\in\Pi_s^{ra}} P_s g_j |\mathbf{Y}_j|^{-\alpha}}. \tag{21}$$

It is worth noting that under the EH-PRA protocol, at the typical PR, the received interference from the j-th active ST is constrained as $P_s g_j |\mathbf{Y}_j|^{-\alpha} \le \frac{P_s N_{ra}}{P_p}$. Therefore, under Assumption 1, the coverage probability of the primary network with the EH-PRA protocol is given by

$$
\begin{aligned}
\tau_p^{ra} &= \Pr\left\{ \mathrm{SIR}_p \geq \theta_p \middle| g_j |\mathbf{Y}_j|^{-\alpha} \leq \frac{N_{ra}}{P_p} \right\} \\
&= \Pr\left\{ \frac{P_p h_0 d_p^{-\alpha}}{\sum\limits_{i \in \Pi_p^t} P_p h_i |\mathbf{X}_i|^{-\alpha} + \sum\limits_{j \in \Pi_s^{ra}} P_s g_j |\mathbf{Y}_j|^{-\alpha}} \geq \theta_p \middle| g_j |\mathbf{Y}_j|^{-\alpha} \leq \frac{N_{ra}}{P_p} \right\} \\
&= \mathbb{E}_{\mathbf{X}} \left[\prod_{i \in \Pi_p^t} \mathbb{E}_h \left[e^{-\frac{\theta_p h_i |\mathbf{X}_i|^{-\alpha}}{d_p^{-\alpha}}} \right] \right] \\
&\quad \times \mathbb{E}_{\mathbf{Y}} \left[\prod_{j \in \Pi_s^{ra}} \mathbb{E}_g \left[e^{-\frac{\theta_p P_s g_j |\mathbf{Y}_j|^{-\alpha}}{P_p d_p^{-\alpha}}} \middle| g_j \leq \frac{N_{ra} |\mathbf{Y}_j|^{\alpha}}{P_p} \right] \right] \\
&\overset{(a)}{=} \exp\left\{ -\frac{2\pi^2}{\alpha \sin\left(\frac{2\pi}{\alpha}\right)} \mu_p \theta_p^{\frac{2}{\alpha}} d_p^2 \right\} \times \exp\left\{ -2\pi \int_0^\infty \mathcal{G} \cdot \lambda_{ra}^{\mathbf{R}}(u) u \mathrm{d}u \right\} \\
&\overset{(b)}{=} \exp\left\{ -\frac{2\pi^2}{\alpha \sin\left(\frac{2\pi}{\alpha}\right)} \theta_p^{\frac{2}{\alpha}} d_p^2 \mu_p \right\} \times \exp\left\{ -2\pi \lambda_0 \frac{\nu_e^s}{P} \int_\zeta^\infty \left(1 - \varrho(u)\right) u du \right\} \\
&\quad \times \exp\left\{ -2\pi \lambda_0 Q_{ra} \int_0^\zeta \left(1 - \varrho(u)\right) \mathcal{P}(u) u du \right\}.
\end{aligned} \tag{22}
$$

where (a) follows from the fact that the probability density function of g conditioned on $g \leq t$ is given by

$$
f(g | g \leq t) = \frac{e^{-g}}{1 - e^{-t}},
$$

$$
\mathcal{G} = 1 - \int_0^{\frac{N_{ra} u^{\alpha}}{P_p}} e^{-\frac{\theta_p P_s g u^{-\alpha}}{P_p d_p^{-\alpha}}} \times \frac{e^{-g}}{1 - e^{-\frac{N_{ra} u^{\alpha}}{P_p}}} dg,
$$

and (b) follows from (8). This thus completes the proof of Theorem 2.

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