IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received October 29, 2017, accepted November 19, 2017, date of publication November 23, 2017,
date of current version February 28, 2018.

Digital Object Identifier 10.1109/ACCESS.2017.2776953

Cognitive Multiuser Energy Harvesting Decode-and-Forward Relaying System With Direct Links

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This work was supported in part by the NSF of China under Grant 61772007, Grant 61372129, and Grant 61501382, in part by the Guangdong Natural Science Funds for Distinguished Young Scholar under Grant 2014A030306027, in part by the Science and Technology Planning Key Project of Guangdong under Grant 2016B010124014), in part by the Innovation Team Project of Guangdong Province University under Grant 2016KCXTD017, in part by the Guangzhou University's 2017 Training Program for Young Top-Notch Personnels under Grant BJ201702, in part by the Open Research Fund of the National Mobile Communications Research Laboratory, Southeast University, under Grant 2017D15, in part by the Sichuan International Science and Technology Cooperation Project under Grant 2017HH0035, and in part by the Fundamental Research Funds for the Central Universities under Grant 2682015RC20 and Grant 2682016CY22.

ABSTRACT In this paper, we study an underlay cognitive energy harvesting decode-and-forward (DF) relaying communications system with multiple secondary users (SUs) and a primary destination. By utilizing power splitting receiver, the relay is capable of harvesting radio frequency energy from SU and retransmitting data with harvested energy. Both direct and relaying links are taken into consideration in selecting the best SU, and furthermore exploited for data transmission by employing selection combining receiver at the secondary destination. To evaluate the system performance, analytical outage probabilities for both selection and fixed DF relaying protocols have been provided under Rayleigh fading channel. Moreover, we further derive their asymptotic expressions of outage probability. With the given asymptotic expressions, we confirm that the system diversity approaches to $N+1$ for selection DF relaying and reaches N for fixed DF relaying. Numerical and simulation results are demonstrated to verify our proposed analysis.

INDEX TERMS Cognitive network, energy harvesting relaying, direct links, decode-and-forward, system diversity.

I. INTRODUCTION

Cognitive radio is an efficient technique to realize the coexistence of primary and secondary networks by utilizing the scarce spectrum in the underlay, overlay or interweave manners, and therefore allow the secondary user to utilize the unlicensed spectrum [1]–[6]. As a result, it has been adopted in various standards such as IEEE 802.22 and IEEE SCC41. To improve the system performance of cognitive networks, incorporating cooperative relaying into cognitive networks has been proposed [7]–[18]. This is due to the fact that cooperative relaying, such as amplify-and-forward (AF) relaying and decode-and-forward relaying, can extend the network coverage and enhance transmission reliability without additional transmit power at the transmitters [19]–[26]. Hence, cognitive relay networks have been extensively studied. Ding *et al.* [7], da Costa *et al.* [8], Duong *et al.* [9], and Jaafar *et al.* [12] studied three-node cognitive relay networks, and [13]–[16] extended to investigate multi-relay scenarios, where relay selection was employed to select the best relay for data retransmitting. In addition, literatures [17], [18] considered scenarios with multiple primary users and analyzed the system performance in terms of ergodic capacity as well as outage probability.

However, the employment of relays requires stable power supply, such as battery or power grid, in the conventional networks. Recently, an architecture that harvesting RF energy and receiving information concurrently has been proposed with two fundamental receivers, namely, power splitting receiver and time switching (TS) receiver [27]. RF energy harvesting is often used for the wireless communications scenarios [5], [28]–[31], particularly for the nodes are hard to be charged by the wire, e.g. wireless nodes placed at the hill or mountain. By utilizing RF energy harvester, relays can enhance system performance without connecting the stable power supply [32]–[38]. As such, the study on cognitive energy harvesting relaying networks has attracted greatly interest. In [39], a three-node underlay cognitive relay network has been studied, where the DF relay is able to harvest the energy from SU and adjust the PS factor to satisfy the decoding conditions at the relay. Moreover, [40] studied a cognitive network with multiple secondary energy harvesting relays, where the TS factor was fixed. Furthermore, [41]–[43] extended to study cognitive relay networks in which both relay and secondary user were able to harvest energy, and investigated scenarios regarding multi-hop relay and multiple primary users respectively.

Although cognitive relay networks deploying energy harvesters have been extensively studied, the bulk of them considered single-SU scenario only. However, multiuser relay networks are capable of exploiting not only the cooperative diversity, but also the inherent multiuser diversity [44]–[50]. For instance, Fan *et al.* [48] and Guimaraes *et al.* [49] investigated the spectrum-sharing cognitive relay networks with multiuser, and [50] investigated a multiuser energy harvesting relaying network. Their results suggested that multiuser diversity enhanced the system performance significantly in term of outage probability. Motivated by the aforementioned researches, we intend to introduce multiuser diversity into cognitive energy harvesting relaying communications system.

In this paper, we consider a cognitive energy harvesting DF relaying communications system, considering both direct and relaying links. In this underlay spectrum-sharing network, multiple SUs convey message to a secondary destination, assisted by a secondary energy harvesting relay. In the meantime, both SUs and relay maintain their interference tolerable to the primary destination. In virtue of maximal received signal-to-noise ratio (SNR) principle, one optimal secondary user is selected to accomplish data transmission. Both direct and relaying links are taken into consideration selecting the best secondary user and exploited for data transmission, attribute to the selection combining receiver at the secondary destination. To evaluate the system performance, analytical outage probabilities for both selection and fixed DF relaying protocols have been provided under Rayleigh fading channel. Moreover, we further derive their asymptotic outage probability in the high peak interference to noise ratio regime. From the given asymptotic expressions, we confirm that selection DF relaying achieves full system diversity order of $N+1$, yet fixed DF relaying system reaches diversity order of N. Numerical and simulation results are demonstrated to verify the proposed analysis.

The rest of this paper are organized as follows. After the introduction, Section II provides a description on the proposed two-hop uplink cognitive multiuser energy harvesting relay network. The detailed transmission process

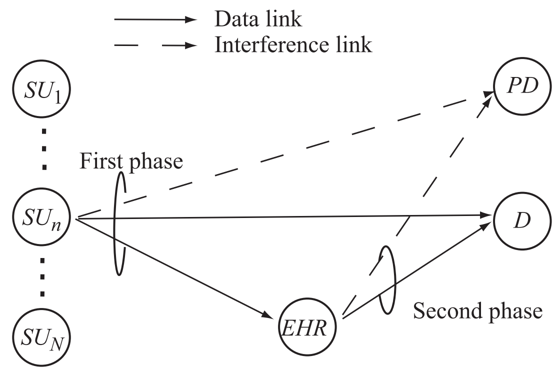

FIGURE 1. Cognitive multiuser energy harvesting relay network with direct links.

and secondary user selection criterion are discussed as well. In Section III, outage probabilitiesč consist of analytical and asymptotic expressions are derived for selection and fixed DF relaying. Then Section IV presents numerical and simulation results to validate our analysis. Desirable insights are provided as well. Conclusions of our works are drawn in Section V.

Notations: $X \sim \mathcal{CN}(0, \sigma^2)$ denotes a zero-mean circularly symmetric complex Gaussian random variable (RV) X with variance σ^2. $\Pr[\cdot]$ denotes the probability. $f_Y(y)$ is the probability density function (PDF) for RV Y.

II. SYSTEM MODEL

As depicted in Fig. 1, we consider a multiuser uplink two-hop communication system composed of N secondary user $\{SU_n|n = 1, \ldots N\}$, a secondary energy harvesting DF relay R, a secondary destination D and a primary destination PD, where the SUs and relay share the same spectrum as primary destination and keep their interference tolerable to the primary destination.[1] By employing power splitting receiver, the relay is capable of harvesting RF energy from SU and forwarding data with harvested energy. We adopt the assumption that all the SUs are close together and share the same distance to relay as well as the distance to PD. At the receiver side, the two-branch signals from direct and relaying links are combined with selection combining (SC) technique for the sake of easy implementation in practice. All links referred in this paper experience flat Rayleigh fading, as the moderate shadowing environments are considered. All terminals are equipped with single antenna and configured in half-duplex mode. The two-phase cooperative information and energy harvesting protocol is illustrated as follows.

Suppose secondary user SU_n is chosen to emit its information and energy. During the first time slot of $\frac{T}{2}$ seconds, SU_n sends the normalized signal x_n to R and D with transmit power P_n. The received signals at relay R and secondary

[1] In practice, AF relaying is easier to be implemented compared with DF relaying. However, AF relaying may yield noise amplification at the relaying process, and hence DF relaying protocol is adopted in this paper.

destination D are respectively given by

$$y_R = \sqrt{(1-\varepsilon)P_n} h_{S_n,R} x_n + n_R \tag{1}$$

$$y_D^{(1)} = \sqrt{P_n} h_{S_n,D} x_n + n_D^{(1)} \tag{2}$$

where ε is the PS factor. $h_{S_n,R} \sim \mathcal{CN}(0,\alpha)$ and $h_{S_n,D} \sim \mathcal{CN}(0,\lambda)$ are the channel parameters of secondary user to relay links and secondary user to secondary destination links, respectively. Besides, $n_R \sim \mathcal{CN}(0,\sigma^2)$ and $n_D^{(1)} \sim \mathcal{CN}(0,\sigma^2)$ are the additive white Gaussian noise (AWGN) at R and D in the first time slot, respectively. We note that the transmit power at each secondary user is decided by $SU_n \to PD$ link, in order to maintain the peak interference level at PD below a given threshold I_P. Accordingly, the transmit power at secondary user S_n is $P_n = \frac{I_P}{|h_{S_n,PD}|^2}$, where $h_{SU_n,PD} \sim \mathcal{CN}(0,\phi)$ is the channel parameter of $SU_n \to PD$ link. In addition, the harvested energy at the relay R can be expressed as

$$E_R = \eta\varepsilon P_n |h_{SU_n,R}|^2 \frac{T}{2} \tag{3}$$

where η is the conversion efficiency of the energy harvester at the relay. Similarly, the transmit power at the relay is under the same constraint as the transmit power at SU_n, which yields the transmit power at the relay $P_{SU_n,R} = \min\left[\eta\varepsilon P_n |h_{SU_n,R}|^2, \frac{I_P}{|h_{R,PD}|^2}\right]$, where $h_{R,PD} \sim CN(0,\psi)$ is the channel parameter of $R \to PD$ link. Moreover, we denote $\omega_n = |h_{SU_n,D}|^2$, $u_n = |h_{SU_n,R}|^2$, $t = |h_{R,PD}|^2$ and $g_n = |h_{SU_n,PD}|^2$ and $\upsilon = |h_{R,D}|^2$ as the channel gains of $SU_n \to D$ $SU_n \to R$, $R \to PD$ and $SU_n \to PD$ and $R \to D$ links, respectively.

In the second time slot, D receives

$$y_D^{(2)} = h_{R,D} P_{SU_n,R} + n_D^{(2)} \tag{4}$$

where $h_{R,D} \sim \mathcal{CN}(0,\beta)$ is the channel parameter of relay to secondary destination link and $n_D^{(2)} \sim \mathcal{CN}(0,\sigma^2)$ is the AWGN at the destination in the second time slot. By employing SC technique, the received SNR at D is given by

$$SNR_n^{DF} = \max\left[\frac{\tilde{I}_P\omega_n}{g_n}, \min\left(\frac{\eta\varepsilon\tilde{I}_P u_n \upsilon}{g_n}, \frac{\tilde{I}_P\upsilon}{t}\right)\right]. \tag{5}$$

where $\tilde{I}_P = \frac{I_P}{\sigma^2}$ is the peak interference to noise ratio and $\upsilon = |h_{R,D}|^2$ is the channel gains of $R \to D$ links.

For selection DF relaying, once the received SNR at R fails to reach a given SNR threshold γ_{th},

$$\frac{(1-\varepsilon)\tilde{I}_P u_n}{g_n} < \gamma_{th} \tag{6}$$

relay R keeps silent and only the direct link is utilized for data transmission. Correspondingly, the SNR at D is

$$SNR_n^{DF} = \frac{\tilde{I}_P\omega_n}{g_n}. \tag{7}$$

Otherwise, when $\frac{(1-\varepsilon)\tilde{I}_P u_n}{g_n} \geq \gamma_{th}$ holds, the relay R will forward D the decoded data during the second time slot. From the above descriptions and [19], the received SNR at destination with selection DF relaying for SU_n can be summarized as

$$SNR_n^{SDF} = \begin{cases} \frac{\tilde{I}_P\omega_n}{g_n}, \text{ If } \frac{(1-\varepsilon)\tilde{I}_P u_n}{g_n} < \gamma_{th} \\ \max\left[\frac{\tilde{I}_P\omega_n}{g_n}, \min\left(\frac{\eta\varepsilon\tilde{I}_P u_n\upsilon}{g_n}, \frac{\tilde{I}_P\upsilon}{t}\right)\right] \\ \text{If } \frac{(1-\varepsilon)\tilde{I}_P u_n}{g_n} \geq \gamma_{th}. \end{cases} \tag{8}$$

For fixed DF relaying, the relay keeps forwarding the received message regardless whether the decoding at the relay succeeds or not. Therefore, to guarantee the success of transmission, the relay is required to fully decode the message from SUs, and the received SNR at destination with fixed DF relaying for SU_n can be summarized as

$$SNR_n^{FDF} = \min\left\{\frac{\tilde{I}_P u_n}{g_n}, \max\left[\frac{\tilde{I}_P\omega_n}{g_n}, \min\left(\frac{\eta\varepsilon\tilde{I}_P u_n\upsilon}{g_n}, \frac{\tilde{I}_P\upsilon}{t}\right)\right]\right\}. \tag{9}$$

We denote the set consists all secondary users as $C = \{1, 2, \ldots N\}$. The best secondary user SU_{n^*} is selected by

$$n^* = \arg\max_{n\in C} SNR_n^{SDF/FDF}. \tag{10}$$

$$P_{out}^{SDF} = \underbrace{\Pr\left\{\max_{n\in C}(\frac{\tilde{I}_P\omega_n}{g_n}) leq\gamma_{th} \max_{n\in C}\frac{(1-\varepsilon)\tilde{I}_P u_n}{g_n} \leq \gamma_{th}\right\}}_{I_1} + \sum_{k=1}^{N}\binom{N}{k}\underbrace{\Pr\left\{\max_{n\in(C/\Omega)}(\frac{\tilde{I}_P\omega_n}{g_n}) \leq \gamma_{th}\right\}}_{I_2}$$
$$\times \underbrace{\Pr\left\{\max_{n\in\Omega}\left\{\max\left[\frac{\tilde{I}_P\omega_n}{g_n}, \min\left(\frac{\eta\varepsilon\tilde{I}_P u_n\upsilon}{g_n}, \frac{\tilde{I}_P\upsilon}{t}\right)\right]\right\} \leq \gamma_{th}, |\Omega| = k\right\}}_{I_3} \tag{12}$$

III. PERFORMANCE ANALYSIS

In this section, we aim to derive the exact outage probabilities for both selection and fixed DF relaying. Moreover, we further derive their asymptotic expressions to obtain some insights into the proposed system in the high peak interference to noise ratio regime.

A. ANALYTICAL OUTAGE PROBABILITY FOR SELECTION DF RELAYING

Outage probability is defined as the probability that the received SNR at the destination falls below the given threshold γ_{th}. Based on [51] and the analysis in (8) and (10), the outage probability for selection DF relaying can be expressed as (12), as shown at the top of the next page.

Here I_1 represents the probability when all the relay can not decode the message from any secondary user with received SNR at D falling below γ_{th}, while I_2 denotes the probability when the relay can correctly decode the message from $k \in C$ secondary users and I_3 denotes the probability when the relay can correctly decode the message from k secondary users with received SNR at D falling below γ_{th}. For simplicity's sake, we define

$$\theta = \frac{\gamma_{th}}{\tilde{I_P}}. \tag{11}$$

By applying the PDF of RVs ω_n, u_n and g_n, we can calculate I_1 and I_2 as

$$\begin{aligned} I_1 &= \Pr\left\{\frac{\omega_n}{g_n} \le \theta, \frac{u_n}{g_n} \le \frac{\theta}{1-\varepsilon}\right\}^N \\ &= \left\{\int_0^\infty \left[\int_0^{g_n\theta} f_{\omega_n}(\omega_n)d\omega_n \int_0^{\frac{g_n\theta}{1-\varepsilon}} f_{u_n}(u_n)du_n\right] \times f_{g_n}(g_n)dg_n\right\}^N \\ &= \left[1 - \frac{\frac{1}{\phi}}{\frac{\theta}{\lambda}+\frac{1}{\phi}} - \frac{\frac{1}{\phi}}{\frac{\theta}{(1-\varepsilon)\alpha}+\frac{1}{\phi}} + \frac{\frac{1}{\phi}}{\frac{\theta}{\lambda}+\frac{\theta}{(1-\varepsilon)\alpha}+\frac{1}{\phi}}\right]^N \end{aligned} \tag{13}$$

$$\begin{aligned} I_2 &= \Pr\left\{\frac{\omega_n}{g_n} \le \theta, \frac{u_n}{g_n} \le \frac{\theta}{1-\varepsilon}\right\}^{N-k} \\ &= \left[1 - \frac{\frac{1}{\phi}}{\frac{\theta}{\lambda}+\frac{1}{\phi}} - \frac{\frac{1}{\phi}}{\frac{\theta}{(1-\varepsilon)\alpha}+\frac{1}{\phi}} + \frac{\frac{1}{\phi}}{\frac{\theta}{\lambda}+\frac{\theta}{(1-\varepsilon)\alpha}+\frac{1}{\phi}}\right]^{N-k}. \end{aligned} \tag{14}$$

Moreover, we can further rewrite the expression of I_3 as

$$I_3 = \int_0^\infty \int_0^\infty F_\theta(\theta|v,t)^k f_\upsilon(\upsilon) f_t(t) d\upsilon dt \tag{15}$$

where

$$F_\theta(\theta|v,t) = \Pr\left\{\frac{\omega_n}{g_n} \le \theta, \min\left(\frac{\eta\varepsilon u_n \upsilon}{g_n}, \frac{v}{t}\right) \le \theta, \frac{u_n}{g_n} \ge \frac{\theta}{1-\varepsilon}\right\}. \tag{16}$$

Theorem 1: The analytical expression of $F_\theta(\theta|v,t)$ can be showed as

$$F_\theta(\theta|\upsilon,t) = \begin{cases} \underbrace{\frac{\frac{1}{\phi}}{\frac{\theta}{(1-\varepsilon)\alpha}+\frac{1}{\phi}} - \frac{\frac{1}{\phi}}{\frac{\theta}{\lambda}+\frac{\theta}{(1-\varepsilon)\alpha}+\frac{1}{\phi}}}_{F_1}, & \upsilon \le t\theta \\ \frac{\frac{1}{\phi}}{\frac{\theta}{(1-\varepsilon)\alpha}+\frac{1}{\phi}} - \frac{\frac{1}{\phi}}{\frac{\theta}{\lambda}+\frac{\theta}{(1-\varepsilon)\alpha}+\frac{1}{\phi}} \underbrace{- \frac{\frac{1}{\phi}}{\frac{\theta}{\eta\varepsilon\upsilon\alpha}+\frac{1}{\phi}} + \frac{\frac{1}{\phi}}{\frac{\theta}{\lambda}+\frac{\theta}{\eta\varepsilon\upsilon\alpha}+\frac{1}{\phi}}}_{F_2}, & t\theta < \upsilon \ \& \ \upsilon \le \frac{1-\varepsilon}{\eta\varepsilon} \\ 0, & t\theta < \upsilon \ \& \ \frac{1-\varepsilon}{\eta\varepsilon} < \upsilon. \end{cases} \tag{17}$$

Proof: See Appendix A.

By applying the given result of $F_\theta(\theta|\upsilon,t)$ into (19), we can further derive that

$$\begin{aligned} I_3 &= \int_o^\infty \int_0^{t\theta} F_1^k \frac{1}{\beta} \exp\left(-\frac{\upsilon}{\beta}\right) d\upsilon \frac{1}{\psi} \exp\left(-\frac{t}{\psi}\right) dt \\ &\quad + \int_0^{\frac{1-\varepsilon}{\eta\varepsilon}} \int_0^{\frac{\upsilon}{\theta}} \frac{1}{\psi} \exp\left(-\frac{t}{\psi}\right) dt \, [F_1+F_2]^k \frac{1}{\beta} \exp\left(-\frac{\upsilon}{\beta}\right) d\upsilon. \end{aligned} \tag{18}$$

Furthermore, by applying the PDFs of υ and t, $f_\upsilon(\upsilon) = \frac{1}{\beta}e^{-\frac{\upsilon}{\beta}}$ and $f_t(t) = \frac{1}{\psi}e^{-\frac{t}{\psi}}$, we can calculate I_3 as

$$I_3 = F_1^k \left(1 - \frac{\frac{1}{\psi}}{\frac{\theta}{\beta}+\frac{1}{\psi}}\right) + \sum_{l=0}^{k} \binom{k}{l} \left(1 - \frac{\frac{1}{\phi}}{\frac{\theta}{\lambda}+\frac{1}{\phi}}\right)^{k-l} \Psi(l) \tag{19}$$

where $\Psi(l)$ is defined as

$$\Psi(l) = \int_0^{\frac{1-\varepsilon}{\eta\varepsilon}} \left[1 - \exp\left(-\frac{\upsilon}{\theta\psi}\right)\right] F_2^l \frac{1}{\beta} \exp\left(-\frac{\upsilon}{\beta}\right) d\upsilon. \tag{20}$$

The close-form solution of $\Psi(l)$ is given by (45) in Appendix B. By substituting the results of (13), (14) and (19) into (12), we get the exact outage probability for selection DF relaying as (21), as shown at the top of the next page, where $\Gamma(d,x)$ is the upper incomplete Gamma function [52, eq. (8.350.2)].

B. ASYMPTOTIC OUTAGE PROBABILITY FOR SELECTION DF RELAYING

We see that

$$\begin{aligned} F_2 &= -\frac{\frac{1}{\phi}}{\frac{\theta}{\eta\varepsilon\upsilon\alpha}+\frac{1}{\phi}} + \frac{\frac{1}{\phi}}{\frac{\theta}{\lambda}+\frac{\theta}{\eta\varepsilon\upsilon\alpha}+\frac{1}{\phi}} \\ &= -\frac{\frac{\theta\phi}{\lambda}}{\left(1+\frac{\theta\phi}{\eta\varepsilon\alpha\upsilon}\right)^2 + \left(1+\frac{\theta\phi}{\eta\varepsilon\alpha\upsilon}\right)\frac{\theta\phi}{\lambda}} \end{aligned}$$

$$P_{out}^{SDF} = \left[1 - \frac{\frac{1}{\phi}}{\frac{\gamma_{th}}{\tilde{I}_P\lambda} + \frac{1}{\phi}} - \frac{\frac{1}{\phi}}{\frac{\gamma_{th}}{(1-\varepsilon)\alpha\tilde{I}_P} + \frac{1}{\phi}} + \frac{\frac{1}{\phi}}{\frac{\gamma_{th}}{\tilde{I}_P\lambda} + \frac{\gamma_{th}}{(1-\varepsilon)\alpha\tilde{I}_P} + \frac{1}{\phi}}\right]^N$$
$$+ \sum_{k=1}^{N}\binom{N}{k}\left[1 - \frac{\frac{1}{\phi}}{\frac{\gamma_{th}}{\tilde{I}_P\lambda} + \frac{1}{\phi}} - \frac{\frac{1}{\phi}}{\frac{\gamma_{th}}{(1-\varepsilon)\alpha\tilde{I}_P} + \frac{1}{\phi}} + \frac{\frac{1}{\phi}}{\frac{\gamma_{th}}{\tilde{I}_P\lambda} + \frac{\gamma_{th}}{(1-\varepsilon)\alpha\tilde{I}_P} + \frac{1}{\phi}}\right]^{N-k}$$
$$\times \left\{\left[\frac{\frac{1}{\phi}}{\frac{\gamma_{th}}{(1-\varepsilon)\alpha\tilde{I}_P} + \frac{1}{\phi}} - \frac{\frac{1}{\phi}}{\frac{\gamma_{th}}{\tilde{I}_P\lambda} + \frac{\gamma_{th}}{(1-\varepsilon)\alpha\tilde{I}_P} + \frac{1}{\phi}}\right]^k \left(1 - \frac{\frac{1}{\psi}}{\frac{\gamma_{th}}{\tilde{I}_P\beta} + \frac{1}{\psi}}\right) + \sum_{l=0}^{k}\binom{k}{l}\Psi(l)\left[1 - \frac{\frac{1}{\phi}}{\frac{\gamma_{th}}{\tilde{I}_P\lambda} + \frac{1}{\phi}}\right]^{k-l}\right\} \quad (21)$$

$$\simeq -\frac{\frac{\theta\phi}{\lambda}(\eta\varepsilon\alpha\upsilon)^2}{(\theta\phi + \eta\varepsilon\alpha\upsilon)^2}. \quad (22)$$

This approximation holds well in the high peak interference to noise ratio region as $\tilde{I}_P$ approaches to $+\infty$. Furthermore, by applying the proposed approximation, then using the Taylor expansion and omitting the higher order terms, we can obtain the asymptotic expression for P_{out}^{SDF} in a compact form as

$$P_{out}^{DF} \cong \begin{cases} \left(\frac{\gamma_{th}}{\tilde{I}_P}\right)^2 \rho_1, & N = 1 \\ \left(\frac{\gamma_{th}}{\tilde{I}_P}\right)^{N+1} \rho_2, & N \geq 2 \end{cases} \quad (23)$$

where

$$\rho_1 = -\left(\frac{\phi}{\lambda}\right)^2\left[1 - \exp\left(\frac{\varepsilon - 1}{\eta\varepsilon\beta}\right)\right]$$
$$- \frac{\phi^2}{\eta\varepsilon\alpha\beta\lambda}\left[2\mathbf{C} + 2\ln\left(\frac{\gamma_{th}\phi}{\tilde{I}_P\eta\varepsilon\alpha\beta}\right) + 1\right]$$
$$- \frac{\phi\psi}{\lambda\beta}\exp\left(\frac{\phi}{\eta\varepsilon\alpha\psi}\right)\left[-\frac{2\phi}{\eta\varepsilon\alpha\psi}\Gamma\left(0, \frac{\phi}{\eta\varepsilon\alpha\psi}\right)\right.$$
$$\left. + \left(\frac{\phi}{\eta\varepsilon\alpha\psi}\right)^2\Gamma\left(-1, \frac{\phi}{\eta\varepsilon\alpha\psi}\right)\right] \quad (24)$$

$$\rho_2 = \left(\frac{\phi}{\lambda}\right)^N \sum_{k=1}^{N}\binom{N}{k}(-1)^k\left[\frac{\phi}{\eta\varepsilon\alpha\beta}\sum_{m=2}^{2k}\binom{2k}{m}\frac{(-1)^m}{m-1}\right.$$
$$- \frac{\psi}{\beta}\exp\left(\frac{\phi}{\eta\varepsilon\alpha\psi}\right)\sum_{m=0}^{2k}\binom{2k}{m}\left(-\frac{\phi}{\eta\varepsilon\alpha\psi}\right)^m$$
$$\left.\times\ \Gamma\left(-m+1, \frac{\phi}{\eta\varepsilon\alpha\psi}\right)\right]. \quad (25)$$

Here $\mathbf{C}$ is the Euler's constant [52]. According to the given asymptotic expression, we confirm that the proposed system with selection DF relaying is able to exploit full diversity of $N + 1$.

C. ANALYTICAL OUTAGE PROBABILITY FOR FIXED DF RELAYING

From (9) and (10), the outage probability for fixed DF relaying can be written as

$$P_{out}^{FDF} = \Pr\left\{\max_{n\in C}\left\{\min\left\{\frac{\tilde{I}_P u_n(1-\varepsilon)}{g_n},\right.\right.\right.$$
$$\left.\left.\left.\max\left[\frac{\tilde{I}_P\omega_n}{g_n}, \min\left(\frac{\eta\varepsilon\tilde{I}_P u_n\upsilon}{g_n}, \frac{\tilde{I}_P\upsilon}{t}\right)\right]\right\}\right\} \leq \gamma_{th}\right\}$$
$$= \int_0^\infty\int_0^\infty G_\theta(\theta|v,t)^N f_\upsilon(\upsilon) f_t(t)\, d\upsilon\, dt \quad (26)$$

where

$$G_\theta(\theta|v,t) = \Pr\left\{\min\left\{\frac{u_n(1-\varepsilon)}{g_n},\right.\right.$$
$$\left.\left.\max\left[\frac{\omega_n}{g_n}, \min\left(\frac{\eta\varepsilon u_n\upsilon}{g_n}, \frac{\upsilon}{t}\right)\right]\right\} \leq \theta\right\}$$
$$= \underbrace{\Pr\left\{\frac{u_n}{g_n} \leq \frac{\theta}{1-\varepsilon}\right\}}_{G_1} + F_\theta(\theta|v,t). \quad (27)$$

By applying the PDFs of u_n and g_n, we can compute G_1 as

$$G_1 = \int_0^\infty\int_0^{\frac{g_n\theta}{1-\varepsilon}} f_{u_n}(u_n)du_n f_{g_n}(g_n)dg_n$$
$$= \int_0^\infty\left[1 - \exp\left(-\frac{g_n\theta}{\alpha(1-\varepsilon)}\right)\right] f_{g_n}(g_n)dg_n$$
$$= 1 - \frac{\frac{1}{\phi}}{\frac{1}{\phi} + \frac{\theta}{\alpha(1-\varepsilon)}}. \quad (28)$$

Moreover, by substituting the results of G_1 in (28) and $F_\theta(\theta|v,t)$ into (17), we can summarize that

$$G_\theta(\theta|\upsilon,t) = \begin{cases} \underbrace{1-\frac{\frac{1}{\phi}}{\frac{\theta}{\lambda}+\frac{\theta}{(1-\varepsilon)\alpha}+\frac{1}{\phi}}}_{G_2}, & \upsilon \le t\theta \\ 1-\frac{\frac{1}{\phi}}{\frac{\theta}{\lambda}+\frac{\theta}{(1-\varepsilon)\alpha}+\frac{1}{\phi}}+F_2, & t\theta \le \upsilon \ \& \ \upsilon \le \frac{1-\varepsilon}{\eta\varepsilon} \\ 1-\frac{\frac{1}{\phi}}{\frac{1}{\phi}+\frac{\theta}{(1-\varepsilon)\alpha}}, & t\theta \le \upsilon \ \& \ \frac{1-\varepsilon}{\eta\varepsilon} \le \upsilon. \end{cases} \tag{29}$$

We substitute $G_\theta(\theta|\upsilon,t)$ into (26) and calculate P_{out}^{Fixed} as (30), as shown at the bottom of this page, Finally, by using the above results and substituting the close-form result of $\Psi(l)$ in Appendix B, we are able to compute the outage probability for fixed DF relaying.

D. ASYMPTOTIC OUTAGE PROBABILITY FOR FIXED DF RELAYING

By using the same approach in Section III-B, we can summarize the asymptotic expression for P_{out}^{FDF} as

$$P_{out}^{FDF} \cong \left[\frac{\gamma_{th}\phi}{\tilde{I_P}\alpha(1-\varepsilon)}\right]^N \tag{31}$$

From the asymptotic expression of P_{out}^{FDF}, we see that the system diversity order is equal to N, which indicates that fixed DF relaying can not gain full system diversity. This is because that the system requires the relay to fully decode the information from the secondary users, which makes the first hop of relaying links the bottleneck of the system. As a result, the outage probability is reversely proportional to power split factor ε in the high peak interference to noise ratio region as smaller value of ε means greater received SNR at the relay, which is consistent to the asymptotic results.

IV. NUMERICAL RESULTS

In this section, numerical and simulation results are provided to verify the proposed analysis and evaluate the impact of several important network parameters on the system performance. Without exception, it is assumed that all links in the proposed system experience flat Rayleigh fading. Generally, we set the distance from each secondary users to the secondary destination a unity, and the same configuration is applied for the distance from each secondary users to the primary destination as well as the distance from relay to primary destination. The relay is placed between the secondary users and the secondary destination, and d represents the distance from relay to the secondary users. A path loss model with path loss factor of 3 is adopted for the simulation. Accordingly, we set the channel gains of $SU_n \to R$, $R \to D$, $SU_n \to D$, $SU_n \to PD$ and $R \to PD$ links as $\alpha = (1-d)^{-3}$, $\beta = d^{-3}$ and $\lambda = \phi = \psi = 1$, respectively. Normalized as benchmark, the variance of AWGN at R and D are set to 1. The conversion efficiency of energy harvester at the relay η is set to 20%. In addition, SNR threshold γ_{th} is set to 3, corresponding to the transmission rate R_S of 1 bit per second per Hz (bps/Hz).

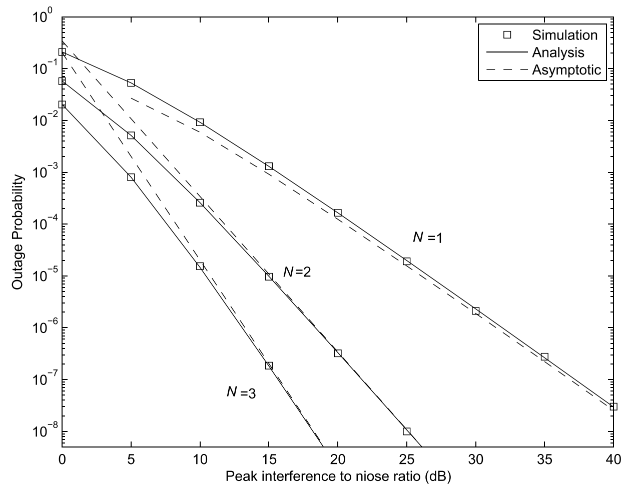

FIGURE 2. Outage probabilities versus peak interference to noise ratio $\tilde{I_P}$.

Figs. 2 and 3 plot how the outage probabilities vary with peak interference to noise ratio $\tilde{I_P}$ for $\varepsilon = 0.5$ and $d = 0.5$, for selection and fixed DF relaying respectively. It can be observed from these two figures that analytical results perfectly match the related simulation results for different values of N. Furthermore, the asymptotic results for each DF relaying protocols are consistent to the related

$$\begin{aligned} P_{out}^{FDF} &= G_2^N\int_0^\infty\int_0^{t\theta} f_\upsilon(\upsilon)d\upsilon f_t(t)dt + G_1^N\int_{\frac{1-\varepsilon}{\eta\varepsilon}}^\infty\int_0^{\frac{\upsilon}{\theta}} f_t(t)dtf_\upsilon(\upsilon)d\upsilon + \int_0^{\frac{1-\varepsilon}{\eta\varepsilon}}\int_0^{\frac{\upsilon}{\theta}} [G_2+F_2]^N f_t(t)dtf_\upsilon(\upsilon)d\upsilon \\ &= \left[1-\frac{\frac{1}{\phi}}{\frac{\gamma_{th}}{\tilde{I_P}\lambda}+\frac{\gamma_{th}}{(1-\varepsilon)\alpha\tilde{I_P}}+\frac{1}{\phi}}\right]^N\left(1-\frac{\frac{1}{\psi}}{\frac{\gamma_{th}}{\tilde{I_P}\beta}+\frac{1}{\psi}}\right)+\sum_{k=0}^N\binom{N}{k}\Psi(k)\left[1-\frac{\frac{1}{\phi}}{\frac{\gamma_{th}}{\tilde{I_P}\lambda}+\frac{\gamma_{th}}{(1-\varepsilon)\alpha\tilde{I_P}}+\frac{1}{\phi}}\right]^{N-k} \\ &\quad + \left[1-\frac{\frac{1}{\phi}}{\frac{1}{\phi}+\frac{\gamma_{th}}{\tilde{I_P}\alpha(1-\varepsilon)}}\right]^N \times \left\{\exp\left(-\frac{1-\varepsilon}{\eta\varepsilon\beta}\right)-\frac{\frac{1}{\beta}}{\frac{\tilde{I_P}}{\gamma_{th}\psi}+\frac{1}{\beta}}\exp\left[-\frac{1-\varepsilon}{\eta\varepsilon}\left(\frac{\tilde{I_P}}{\gamma_{th}\psi}+\frac{1}{\beta}\right)\right]\right\} \end{aligned} \tag{30}$$

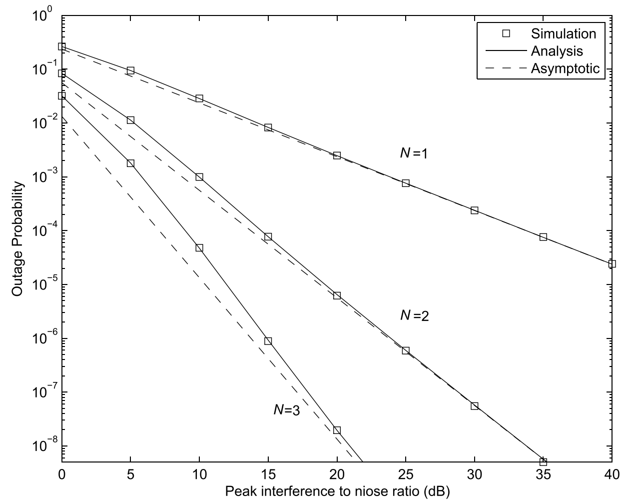

FIGURE 3. Outage probabilities versus peak interference to noise ratio $\tilde{I}_P$.

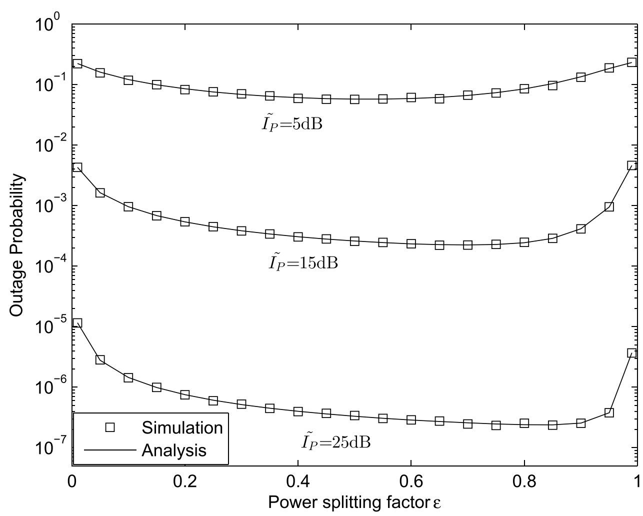

FIGURE 4. Outage probabilities versus power split factor ε.

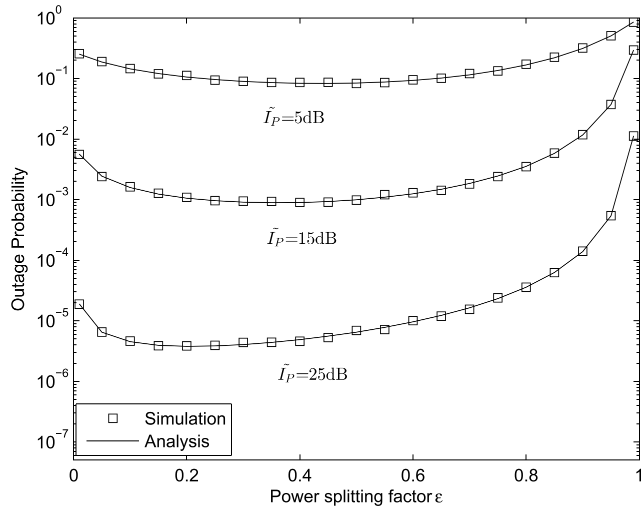

FIGURE 5. Outage probabilities versus power split factor ε.

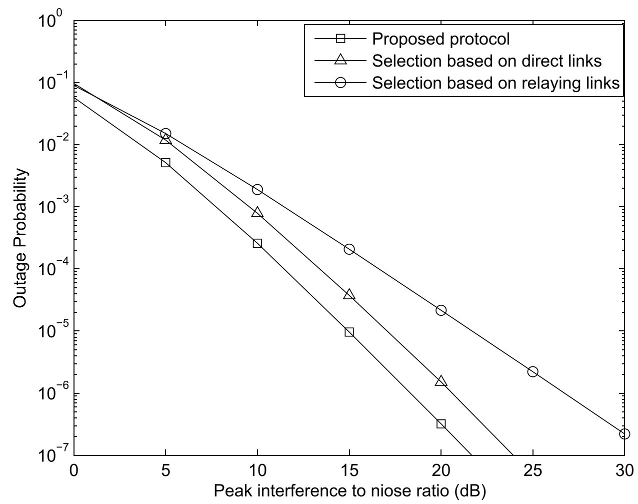

FIGURE 6. Outage probabilities versus peak interference to noise ratio $\tilde{I}_P$.

simulation results in the high peak interference to noise ratio regime, which confirms the derived analysis results for selection and fixed DF relaying. In addition, the diversity order increases with N for both selection and fixed DF relaying. This suggests that increasing secondary users number can remarkably enhance the system performance, particularly in the high peak interference to noise ratio region. Moreover, fixed DF relaying is unable to fully exploit the system diversity. This is due to the fact that requiring the relay to fully decode the source message limits the performance of system to the transmission of the first hop in the relaying links, as [19] suggested.

Figs. 4 and 5 plot the variation of outage probabilities with power splitting factor ε for $d = 0.5$ and $N = 2$, for selection DF relaying and fixed DF relaying respectively. We see that,in high peak interference to noise ratio regime, the outage probabilities for selection DF relaying vary reversely with power split factor ε, however, the results for fixed DF relaying act in the opposite way. This is because, for selection DF relaying, the first hop of relaying links gains more diversity than the second hop, multiuser diversity in this case, which makes the second hop the weaker hop as to the relaying links, hence increasing η can enhance the system performance. However, for fixed DF relaying, the first hop is the bottleneck regarding the whole system, hence splitting more power for received signal is able to guarantee the transmission of the first hop in the relaying link, and therefore decrease the outage probabilities. In addition, as ε approaches to 0 or 1, which means the received SNR or harvested energy at the relay tend to zero, the relaying links are unable to maintain and the transmission proceeds through the direct links only, hence the outage probabilities increase promptly. The system becomes becomes worse in the case of ε approaching to 1 for fixed relaying, since the relay conveys little information but false message when the relay can not successfully decode the message from the source.

To compare the proposed protocols with other scehmes, such as, selection based on relaying links and selection based

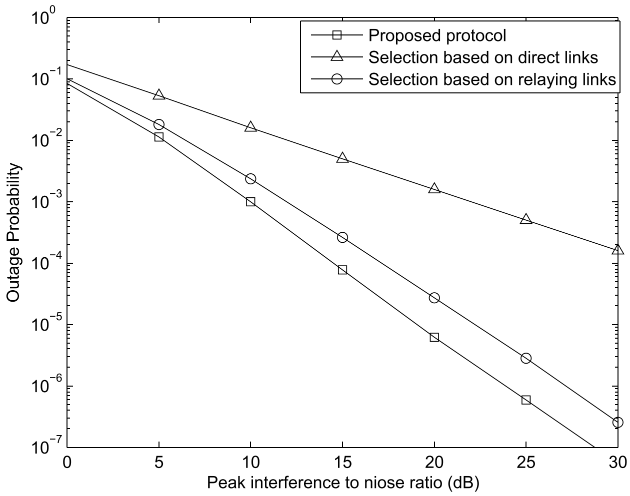

FIGURE 7. Outage probabilities versus peak interference to noise ratio $\tilde{I_P}$.

on direct links, Figs. 6 and 7 plot the outage probabilities for the aforementioned protocols versus peak interference to noise ratio $\tilde{I_P}$ with $d = 0.5$, $\varepsilon = 0.5$, $N = 2$ and $\eta = 20\%$ for selection DF relaying and fixed DF relaying respectively. From the simulation results, we see that the proposed protocols has outperformed the other protocols. This is because the joint impact of direct and relaying links are exploited for data transmission in the proposed protocols.

V. CONCLUSIONS

In this works, we analyzed a spectrum-sharing cognitive multiuser energy harvesting relaying communications system regarding the joint impact of direct and relaying links. Both exact and asymptotic expressions of outage probabilities for selection and fixed DF relaying have been provided under Rayleigh fading channel. Furthermore, we concluded that the system adopting selection DF relaying achieved full diversity of $N + 1$, yet the system regarding fixed DF relaying failed. In addition, the PS factor plays opposite roles on the system performance for selection and fixed DF relaying. The numerical and simulations results validated the proposed analysis and brought some meaningful insights as well.

APPENDIX

A. PROOF OF THEOREM 1

We can rewrite $F_\theta(\theta|v, t)$ as

$$F_\theta(\theta|v,t) = \underbrace{\Pr\left\{\frac{\omega_n}{g_n} \le \theta, \frac{u_n}{g_n} < \frac{\theta}{\eta\varepsilon\upsilon}, \frac{u_n}{g_n} \ge \frac{\theta}{1-\varepsilon}\right\}}_{J_1} + \underbrace{\Pr\left\{\frac{\omega_n}{g_n} \le \theta, \frac{v}{t} < \theta, \frac{u_n}{g_n} \ge \frac{\theta}{\eta\varepsilon\upsilon}, \frac{u_n}{g_n} \ge \frac{\theta}{1-\varepsilon}\right\}}_{J_2}. \tag{32}$$

In the following, we discuss $F_\theta(\theta|\upsilon, t)$ with different conditions based on the relations among υ, $t\theta$ and $\frac{1-\varepsilon}{\eta\varepsilon}$.

A) When $\upsilon \le t\theta$ & $\upsilon \le \frac{1-\varepsilon}{\eta\varepsilon}$: In this case, J_1 and J_2 can be derived as

$$\begin{aligned} J_1 &= \Pr\left\{\frac{\omega_n}{g_n} \le \theta, \frac{\theta}{1-\varepsilon} \le \frac{u_n}{g_n} < \frac{\theta}{\eta\varepsilon\upsilon}\right\} \\ &= \int_0^\infty \left[\int_0^{g_n\theta} f_{\omega_n}(\omega_n)d\omega_n \int_{\frac{g_n\theta}{1-\varepsilon}}^{\frac{g_n\theta}{\eta\varepsilon\upsilon}} f_{u_n}(u_n)du_n\right] f_{g_n}(g_n)dg_n \\ &= \frac{\frac{1}{\phi}}{\frac{\theta}{(1-\varepsilon)\alpha} + \frac{1}{\phi}} - \frac{\frac{1}{\phi}}{\frac{\theta}{\eta\varepsilon\upsilon\alpha} + \frac{1}{\phi}} \\ &\quad - \frac{\frac{1}{\phi}}{\frac{\theta}{\lambda} + \frac{\theta}{(1-\varepsilon)\alpha} + \frac{1}{\phi}} + \frac{\frac{1}{\phi}}{\frac{\theta}{\lambda} + \frac{\theta}{\eta\varepsilon\upsilon\alpha} + \frac{1}{\phi}} \end{aligned} \tag{33}$$

$$\begin{aligned} J_2 &= \Pr\left\{\frac{\omega_n}{g_n} \le \theta, \frac{u_n}{g_n} \ge \frac{\theta}{\eta\varepsilon\upsilon}\right\} \\ &= \int_0^\infty \left[\int_0^{g_n\theta} f_{\omega_n}(\omega_n)d\omega_n \int_{\frac{g_n\theta}{\eta\varepsilon\upsilon}}^{\infty} f_{u_n}(u_n)du_n\right] f_{g_n}(g_n)dg_n \\ &= \frac{\frac{1}{\phi}}{\frac{\theta}{\eta\varepsilon\upsilon\alpha} + \frac{1}{\phi}} - \frac{\frac{1}{\phi}}{\frac{\theta}{\lambda} + \frac{\theta}{\eta\varepsilon\upsilon\alpha} + \frac{1}{\phi}}. \end{aligned} \tag{34}$$

B) When $\upsilon \le t\theta$ & $\upsilon \ge \frac{1-\varepsilon}{\eta\varepsilon}$: In this case, J_1 and J_2 become

$$J_1 = 0, \tag{35}$$

$$\begin{aligned} J_2 &= \Pr\left\{\frac{\omega_n}{g_n} \le \theta, \frac{u_n}{g_n} \ge \frac{\theta}{1-\varepsilon}\right\} \\ &= \int_0^\infty \left[\int_0^{g_n\theta} f_{\omega_n}(\omega_n)d\omega_n \int_{\frac{g_n\theta}{1-\varepsilon}}^{\infty} f_{u_n}(u_n)du_n\right] f_{g_n}(g_n)dg_n \\ &= \frac{\frac{1}{\phi}}{\frac{\theta}{(1-\varepsilon)\alpha} + \frac{1}{\phi}} - \frac{\frac{1}{\phi}}{\frac{\theta}{\lambda} + \frac{\theta}{(1-\varepsilon)\alpha} + \frac{1}{\phi}}. \end{aligned} \tag{36}$$

C) When $\upsilon \ge t\theta$ & $\upsilon \le \frac{1-\varepsilon}{\eta\varepsilon}$: In this case, J_1 and J_2 are showed as

$$\begin{aligned} J_1 &= \Pr\left\{\frac{\omega_n}{g_n} \le \theta, \frac{\theta}{1-\varepsilon} \le \frac{u_n}{g_n} < \frac{\theta}{\eta\varepsilon\upsilon}\right\} \\ &= \frac{\frac{1}{\phi}}{\frac{\theta}{(1-\varepsilon)\alpha} + \frac{1}{\phi}} - \frac{\frac{1}{\phi}}{\frac{\theta}{\eta\varepsilon\upsilon\alpha} + \frac{1}{\phi}} \\ &\quad - \frac{\frac{1}{\phi}}{\frac{\theta}{\lambda} + \frac{\theta}{(1-\varepsilon)\alpha} + \frac{1}{\phi}} + \frac{\frac{1}{\phi}}{\frac{\theta}{\lambda} + \frac{\theta}{\eta\varepsilon\upsilon\alpha} + \frac{1}{\phi}} \end{aligned} \tag{37}$$

$$J_2 = 0. \tag{38}$$

D) When $\upsilon \ge t\theta$ & $\upsilon \ge \frac{1-\varepsilon}{\eta\varepsilon}$: In this case, J_1 and J_2 become

$$J_1 = 0 \tag{39}$$

$$J_2 = 0. \tag{40}$$

Bring the above results together, we can obtain the analytical expression of $F_\theta(\theta|v, t)$ in (17).

B. CLOSE-FORM SOLUTION OF $\Psi(l)$

Ψ_k can be further expanded as

$$\Psi(l) = \sum_{m=0}^{l} \binom{l}{m} (-1)^m \int_0^{\frac{1-\varepsilon}{\eta\varepsilon}} \left[1 - \exp\left(-\frac{\upsilon}{\theta\psi}\right)\right] \times \left(\frac{1}{\frac{\theta\phi}{\lambda} + \frac{\theta\phi}{\eta\varepsilon\upsilon\alpha} + 1}\right)^{l-m} \left(\frac{1}{\frac{\theta\phi}{\eta\varepsilon\upsilon\alpha} + 1}\right)^{m} \times \frac{1}{\beta} \exp\left(-\frac{\upsilon}{\beta}\right) d\upsilon. \quad (41)$$

We see that

$$\frac{1}{\frac{\theta\phi}{\lambda} + \frac{\theta\phi}{\eta\varepsilon\upsilon\alpha} + 1} \times \frac{1}{\frac{\theta\phi}{\eta\varepsilon\upsilon\alpha} + 1} = \left(\frac{1}{\frac{\theta\phi}{\eta\varepsilon\upsilon\alpha} + 1} - \frac{1}{\frac{\theta\phi}{\lambda} + \frac{\theta\phi}{\eta\varepsilon\upsilon\alpha} + 1}\right) \times \left(\frac{\theta\phi}{\lambda}\right)^{-1}. \quad (42)$$

By the way of recurrent relation of (42), we can obtain the following equality

$$\left(\frac{1}{\frac{\theta\phi}{\lambda} + \frac{\theta\phi}{\eta\varepsilon\upsilon\alpha} + 1}\right)^{l} \left(\frac{1}{\frac{\theta\phi}{\eta\varepsilon\upsilon\alpha} + 1}\right)^{m} = \sum_{t=1}^{m} \left(\frac{1}{\frac{\theta\phi}{\eta\varepsilon\upsilon\alpha} + 1}\right)^{m-t+1} (-1)^{t-1} \times \underbrace{\sum_{i_1=1}^{l} \sum_{i_2=1}^{i_1} \cdots \sum_{i_{t-1}=1}^{i_{t-2}}}_{(t-1)\ terms} \left(\frac{\theta\phi}{\lambda}\right)^{-(l+t-1)} + (-1)^m \underbrace{\sum_{i_1=1}^{l} \sum_{i_2=1}^{i_1} \cdots \sum_{i_m=1}^{i_{m-1}}}_{m\ terms} \left(\frac{\theta\phi}{\lambda}\right)^{-(l+m-i_m)} \times \left(\frac{1}{\frac{\theta\phi}{\lambda} + \frac{\theta\phi}{\eta\varepsilon\upsilon\alpha} + 1}\right)^{i_m}. \quad (43)$$

Moreover, we define

$$\Delta(l, t, x) = \sum_{i_1=1}^{l} \sum_{i_2=1}^{i_1} \cdots \sum_{i_{t-1}=1}^{i_{t-2}} x^{-(l+t-1)}. \quad (44)$$

Therefore, by substituting the results in (43) and (44) into (41), we can obtain the close-form expression of $\Psi(l)$ as

$$\Psi(l) = \sum_{m=0}^{l} \binom{l}{m} \sum_{t=1}^{m} (-1)^{m+t-1} \Delta(l-m, t, \frac{\theta\phi}{\lambda}) \times \left[\Xi\left(\frac{1-\varepsilon}{\eta\varepsilon}, \eta\varepsilon\alpha, \theta\phi, 1, \frac{1}{\beta}, 0, m-t\right) - \Xi\left(\frac{1-\varepsilon}{\eta\varepsilon}, \eta\varepsilon\alpha, \theta\phi, 1, \frac{1}{\beta}, \frac{1}{\theta\psi}, m-t\right)\right] + \sum_{m=0}^{l} \binom{l}{m} \sum_{i_1=1}^{l-m} \sum_{i_2=1}^{i_1} \cdots \sum_{i_m=1}^{i_{m-1}} \left(\frac{\theta\phi}{\lambda}\right)^{-(l-i_m)} \times \left[\Xi\left(\frac{1-\varepsilon}{\eta\varepsilon}, \eta\varepsilon\alpha, \theta\phi, 1 + \frac{\theta\phi}{\lambda}, \frac{1}{\beta}, 0, i_m\right) - \Xi\left(\frac{1-\varepsilon}{\eta\varepsilon}, \eta\varepsilon\alpha, \theta\phi, 1 + \frac{\theta\phi}{\lambda}, \frac{1}{\beta}, \frac{1}{\theta\psi}, i_m\right)\right] \quad (45)$$

where $\Xi(h_1, h_2, h_3, h_4, h_5, h_6, d)$ is defined as

$$\Xi(h_1, h_2, h_3, h_4, h_5, h_6, d) = \int_0^{h_1} \left(\frac{h_2\upsilon}{h_2h_4\upsilon + h_3}\right)^d h_5 \exp\left[-\upsilon\left(h_5 + h_6\right)\right] d\upsilon = \exp\left[\frac{h_3}{h_2h_4}\left(h_5 + h_6\right)\right] \times (h_4)^{-d} \frac{h_5}{h_5 + h_6} \sum_{n=0}^{d} \binom{d}{n} \left[-\frac{h_3}{h_2h_4}\left(h_5 + h_6\right)\right]^n \times \left\{\Gamma\left[-n+1, \frac{h_3}{h_2h_4}\left(h_5 + h_6\right)\right] - \Gamma\left[-n+1, \left(h_1 + \frac{h_3}{h_2h_4}\right)\left(h_5 + h_6\right)\right]\right\} \quad (46)$$

and $\Gamma(d, x)$ is the upper incomplete Gamma function [52, eq. (8.350.2)], which can be calculated promptly with mathematical tool such as Matlab.

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