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Performance Analysis of Piece-Wise Linear Model of Energy Harvesting-Based Multiuser Overlay Spectrum Sharing Networks

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ABSTRACT In this article, we investigate the performance of a piece-wise linear model of energy harvesting-based multiuser overlay spectrum sharing system. Herein, an energy-constrained secondary node acts as a cooperative relay to assist the information transmission between a primary transmitter and multiple primary receivers. In return for the cooperation, the secondary node enjoys access to the primary user's spectrum for its own information transfer. Specifically, by employing a time-switching based receiver, the secondary node harvests energy from the received radio-frequency signal of primary transmitter during a dedicated energy harvesting phase. In the subsequent information transfer phase, the secondary node splits the harvested power to forward the primary data as well as its own information intended for another secondary user. We analyze the impact of decoding primary's information at the secondary receiver on the performance of secondary network. Importantly, we propose an improved energy harvesting-based relaying scheme which makes an efficient use of available degrees of freedom and thereby enhances the performance of both primary and secondary networks significantly. For this analytical framework, we derive the expressions of outage probability for primary and secondary networks. Numerical and simulation results are obtained to extract various useful insights and to validate our theoretical developments.

INDEX TERMS Cooperative relaying, non-linear energy harvesting, outage probability, performance analysis, spectrum sharing, simultaneous wireless information and power transfer (SWIPT).

I. INTRODUCTION

ENERGY efficiency and spectrum efficiency are two important design objectives for future wireless networks, i.e., fifth-generation (5G) and beyond [2]. In this regard, energy harvesting (EH) has emerged as a promising technology for the design of energy-efficient systems. The key idea is to efficiently power the network nodes without having to replace the batteries periodically. This will significantly bring down the operational cost for future ultra-dense networks and Internet-of-Things (IoT). As such, energy can be harvested from the surrounding environment using the various traditional sources viz., wind, solar, thermal, etc. However, EH from these traditional sources primarily depends on environment and weather conditions and, therefore, harvesting from them is not suitable for the continuous energy supply. To this end, the simultaneous wireless information and power transfer (SWIPT) scheme has been regarded as an effective approach to scavenge the energy from the ambient radio-frequency (RF) signals [3]. The SWIPT scheme is based on the fact that energy and information can be simultaneously carried through RF signals. In this, the EH node gathers the transmitted energy (RF radiation) and stores it in a battery by converting it into the direct current (DC) using appropriate circuitry. However, it is difficult for a receiver to concurrently process the information and harvest the energy. For this, two practical receiver architectures viz., time-switching (TS) and power-splitting (PS), have been introduced in [4] and [5]. In the TS-based receiver architecture, time is switched between information processing (IP) and EH. Whereas, in the PS-based architecture, a part of the received power is used for the EH and the remaining one for the IP. Note that, amongst TS and PS protocols, there is no explicit answer about which protocol is better. For instance, TS protocol performs better than the PS protocol in low signal-to-noise-ratio (SNR) regime while PS protocol outperforms its TS counterpart in high-SNR region [6]. An antenna switching based scheme has also been proposed in [7] for the multiple-antenna systems.

On another front, to accommodate the larger number of users in the ultra-dense networks and to interconnect various IoT devices, the efficient use of available scarce spectrum is crucial. In this context, cognitive radio technology has been envisioned as a potential candidate to dramatically improve the spectrum efficiency. This dynamic spectrum access technique allows the secondary users (SUs) to share the spectrum with the primary users (PUs). Mainly, three paradigms have been proposed to facilitate the spectrum sharing amongst PUs and SUs viz., overlay, underlay, and interweave [8].

More recently, RF-EH and cognitive radio technologies have been integrated with each other for an energy- and spectrum-efficient system design. Various research works have incorporated the EH concept in cognitive radio networks to cater for the demands of future wireless networks [9]. For instance, researches in [10]–[18] have focused on the use of EH techniques in underlay spectrum sharing networks. Note that, in underlay cognitive radio networks, SUs have to limit their transmit power in anticipation for the interference temperature limit stipulated by the PUs. Consequently, the performance of the secondary system is significantly affected. On the contrary, in the overlay cognitive radio, spectrum sharing can be facilitated by incentivizing PUs through the cooperation of SUs [19]. In fact, the authors in [20] have compared the sum throughput of both overlay and underlay models in RF-EH networks. In such a study, they have shown that the overlay approach outperforms the underlay approach. This was primarily due to the imposition of stringent restrictions over the maximum transmit powers of the SUs in the underlay model. Owing to the potential benefits of the overlay model, some researches [21]–[28] have focused on this paradigm of spectrum sharing. For instance, the authors in [21] investigated the cooperation between primary and secondary networks. Here, the secondary transmitter was assumed to be an energy-constrained source that harvests energy from the primary transmission. In [22], Yin *et al.* studied the optimized cooperation strategy of the SUs to assist the PUs and to decide the EH time. The authors in [23] considered the selection of the best secondary transmitter to relay the PU's data. In [24], a PU was assumed to be an energy-constrained node which harvests energy from a SU as well as from an access point and then transfers the data using the cooperation from a SU. In a similar way, the authors in [25] considered the EH scheme at a cooperative SU node using a PU's signal and a dedicated hybrid access point. In [26], the authors studied the joint power allocation and route selection to minimize the outage probability of the EH-based multihop cognitive radio networks. The authors in [27] investigated the security and efficiency of data transmission for overlay cognitive radio networks. In [28], the authors provided a comprehensive performance analysis of SWIPT for cooperative spectrum sharing networks with different relaying schemes.

Common to all the aforementioned works is that they have considered a linear EH model, i.e., the harvested energy at the node linearly varies with the received power. However, since the EH circuit consists of various non-linear elements viz., capacitors, inductors, and diodes, the conventional linear model of EH is not practical. In fact, an experimental study in [29] established the non-linear behavior of the energy harvesting circuit which has been also verified in [30]. And it is popularly known that the non-linear characteristics can be well approximated using the piece-wise linear model [31]. Further, most of these works considered the conventional fixed relaying scheme which requires the relay to transmit all the time and thus it is deemed inefficient from a system performance perspective. On the contrary, in cooperative hybrid automatic-repeat-request (ARQ)-based incremental relaying [32], the relay operation is invoked only when the direct transmission is declared unsuccessful using a limited feedback mechanism. Motivated by the preceding discussion, in this article, we examine the outage performance of a piece-wise linear EH-based multiuser overlay spectrum sharing (EHMOSS) system. Relying upon the principle of incremental relaying, we propose an improved relaying scheme which efficiently exploits the available degrees of freedom to enhance the performance. Herein, a battery-enabled secondary node harvests energy from an RF signal of the PU and then utilizes this energy to relay the PU's data along with its own information. The main contributions of this article can be summarized as follows.

- We comprehensively investigate the performance of piece-wise linear EHMOSS system over Rayleigh fading channels. In the considered analytical framework, we attempt to harness the combined advantages of multiuser diversity and cooperative diversity to improve the performance of primary network.
- An improved EH-based relaying scheme is proposed, based on which expressions for the outage probability of both primary and secondary networks are derived. It is observed that the proposed scheme substantially enhances the overall performance of the considered EHMOSS system.
- We highlight the importance of cooperative transmission over direct transmission and subsequently obtain the spectrum sharing condition. Such condition enables the seamless co-existence between primary and secondary networks without compromising the performance of the primary network.
- The significance of direct link for the performance of primary network in the EHMOSS system is highlighted. In addition to the inherent benefit of cooperative diversity, we identify that when the cooperation from the secondary node ceases to exist beyond a certain rate, the primary network can rely on the potential direct links for its information transmission.
- To simplify the obtained analytical results and to verify their accuracy, the asymptotic analysis for the outage probability of both primary and secondary networks is also performed.

The remainder of this article is structured as follows. In Section II, detailed descriptions of the considered EHMOSS system are presented along with discussions of the adopted EH and IP strategies. In Section III, the performance of EHMOSS system is investigated by deriving the outage probability for the primary network while, in Section IV, the outage probability of secondary network is examined. Section V proposes an improved EH-based relaying scheme and then analyze its outage performance for both primary and secondary networks. In Section VI, spectrum sharing condition to enable the cooperative transmission is discussed. Numerical and simulation results are provided in Section VII and, finally, conclusions are presented in Section VIII.

Notations: Throughout the article, we use $\mathbb{E}\{\cdot\}$ to denote expectation and $\mathcal{CN}(0, \sigma^2)$ to denote complex normal distribution with mean zero and variance σ^2. $\mathcal{W}_{u,v}(\cdot)$ represents the Whittaker function [33, eq. (9.222)] and $\mathrm{Ei}(\cdot)$ represents the exponential integral function [33, eq. (8.211.1)]. $f_X(\cdot)$ and $F_X(\cdot)$ denote the probability density function (PDF) and the cumulative distribution function (CDF) of a random variable X, respectively, and $\Pr[\,\cdot\,]$ represents probability.

II. SYSTEM MODEL

A. SYSTEM DESCRIPTION

As shown in Fig. 1, we consider an EHMOSS system consisting of primary and secondary networks. The primary network includes a transmitter T_c and the corresponding multiple receivers $\{T_{p_n}\}_{n=1}^{N}$. On the other hand, the secondary network comprises an energy-constrained transmitter S and a receiver D. Hereby, the primary transmitter T_c intends to establish a communication with one out of T_{p_n} receivers. Though the direct links are assumed to exist between T_c and T_{p_n}, the primary transmitter may still seek cooperation from the nearby secondary transmitter S to harness the benefits of diversity. As a reward for the benign cooperation towards the primary network, the secondary network gets access to primary's licensed spectrum. However, being an energy-constrained node, the secondary transmitter S first harvests energy from the received RF signal of T_c and then splits the harvested power to relay the primary data and to transmit its own data intended for its corresponding secondary receiver D. Hereby, we employ an amplify-and-forward[1] (AF) based processing at S to relay the primary's signal. Further, to harvest energy at the node S, we adopt a TS-based receiver architecture. In contrast to PS, the receiver architecture of TS protocol is less complex which motivates us to adopt this protocol of EH. In our considered TS-based EH approach, a transmission block duration is split into two time phases. The first phase is an EH phase wherein S harvests energy using the received signal from T_c and then utilizes this energy for broadcasting the combined signal (primary and secondary data) in the second phase. The second phase is further subdivided into two IP phases to realize the overall communication between T_c & T_{p_n} and S & D. The EH and IP will be discussed in detail in the next subsections. In the considered analytical framework, we assume that all the network nodes are half-duplex and single-antenna devices. We also assume that all the channels follow the block fading so that they remain constant for a block duration (EH and IP phases) but changes independently in the next block transmission. Thermal noise at each receiver is modeled as additive white Gaussian noise (AWGN) variable with $\mathcal{CN}(0, \sigma^2)$. We denote the channel coefficients for

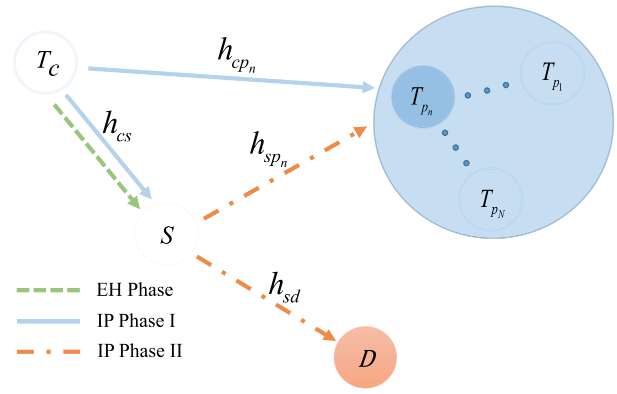

FIGURE 1. System model for EHMOSS.

1. The reason for adopting AF relaying is its simplicity and low-complexity over its decode-and-forward (DF) counterpart. Note that, in AF relaying, baseband processing including front end processing, demodulation, and decoding are not required after the analog-to-digital converter, which makes it less complex than DF relaying [34].

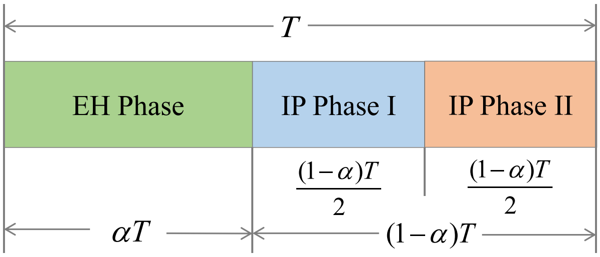

FIGURE 2. An illustration for TS-based EH.

the links $T_c - T_{p_n}$, $T_c - S$, $S - T_{p_n}$, and $S - D$ as h_{cp_n}, h_{cs}, h_{sp_n}, and h_{sd}, respectively. Further, we assume that all the channels experience Rayleigh flat fading such that the channel gains $|h_{\imath\jmath}|^2$ follow exponential distribution, where $\imath \in \{c, s\}$, $\jmath \in \{s, p_n, d\}$, and $\imath \neq \jmath$. We also assume that multiple links over the same hop are independent but not necessarily identically distributed by considering a cluster-based placement of multiple nodes. The channels h_{cp_n}, h_{cs}, h_{sp_n}, and h_{sd} have average powers Ω_{cp_n}, Ω_{cs}, Ω_{sp}, and Ω_{sd}, respectively. In general, the CDF and the PDF for an exponentially distributed random variable W with mean $\Omega_{\imath\jmath}$ are given by $F_W(w) = 1 - \exp(-\frac{w}{\Omega_{\imath\jmath}})$ and $f_W(w) = \frac{1}{\Omega_{\imath\jmath}}\exp(-\frac{w}{\Omega_{\imath\jmath}})$, respectively, where $w \geq 0$ [35].

B. EH ARCHITECTURE

In the secondary network, the source S is an energy-constrained node and is equipped with a rechargeable battery. As shown in Fig. 2, the node S employs a harvest-then-transmit strategy. More specifically, we adopt a TS approach for the EH procedure [5] wherein a transmission block of duration T is split into two time phases, i.e., αT and $(1-\alpha)T$. Here, α represents the fraction of time for which the node S harvests the energy, with $0 < \alpha < 1$. In the first phase, S harvests energy[2] from the RF signal transmitted by T_c for a duration of αT. In the second phase, the remaining $(1-\alpha)T$ is utilized for the IP and signaling which is further subdivided into two equal phases. To harvest energy, two EH models have been studied in the literature, i.e., linear [5] and non-linear [30], [36]–[37]. As the EH circuit, in general, comprises various non-linear electronic devices, the traditional linear model may not comprehend the actual harvested energy and, therefore, the non-linear model of EH is deemed more practical. In fact, as we shall observe later in Section VII, the linear model may provide very misleading results for the design of future networks. However, dealing with the accurate non-linear model is rather complex for analytical purposes. Consequently, we hereby adopt a simplified piece-wise linear model [38]–[41] which closely follows the true behavior of the practical EH circuits. Following this, the transmit power at node S can be expressed as

$$P_{H,s} = \begin{cases} \frac{2\eta\alpha P_{E,R}}{1-\alpha}, & \text{if } P_c|h_{cs}|^2 \leq \zeta_{\text{th}}, \\ \frac{2\eta\alpha\zeta_{\text{th}}}{1-\alpha}, & \text{if } P_c|h_{cs}|^2 > \zeta_{\text{th}}, \end{cases} \tag{1}$$

where $P_{E,R} = P_c|h_{cs}|^2$, $0 < \eta \leq 1$ is the energy conversion efficiency, P_c is the transmit power at the node T_c, and ζ_{th} is the saturation threshold. In (1), the linear term ($P_{H,s} \propto P_{E,R}$) stands for the linear-regime operation of the RF-DC (direct current) conversion curves of the EH circuit, whereas, the constant term corresponds to the saturation-regime operation.

C. INFORMATION PROCESSING

After the EH phase, the overall communication in the considered EHMOSS system takes place in two IP phases. In the first IP phase, the primary transmitter T_c transmits its unit energy symbol x_c, such that $\mathbb{E}\{|x_c|^2\} = 1$, to T_{p_n} and to the cooperative secondary node S. Consequently, the signals received at T_{p_n} and S can be expressed, respectively, as

$$y_{p_n,1} = \sqrt{P_c} h_{cp_n} x_c + n_{p_n,1} \tag{2}$$

and

$$y_{s,1} = \sqrt{P_c} h_{cs} x_c + n_{s,1}, \tag{3}$$

where $n_{p_n,1}$ and $n_{s,1}$ denote AWGN terms at T_{p_n} and S, respectively. As such, the resulting SNR at T_{p_n} via direct link in the first phase can be written, using (2), as

$$\Lambda_{p_n,1} = \frac{P_c|h_{cp_n}|^2}{\sigma^2}. \tag{4}$$

In the second IP phase, the node S superimposes the received primary signal along with its own information symbol x_s to obtain a combined signal as $x_{c,s} = \mathcal{G} y_{s,1} + \sqrt{(1-\xi)P_{H,s}} x_s$, where $\mathcal{G} = \sqrt{\frac{\xi P_{H,s}}{P_c|h_{cs}|^2 + \sigma^2}} \approx \sqrt{\frac{\xi P_{H,s}}{P_c|h_{cs}|^2}}$ [42], with $\mathcal{G}$ be the amplification gain. This approximation is found to yield tight results over the entire SNR regime. Note that the secondary cooperative node S utilizes a fraction of the harvested power, denoted by $\xi P_{H,s}$, to transmit the primary's data and the remaining $(1-\xi)P_{H,s}$ for its own transmission, where $\xi \in [0, 1]$ is referred to as a spectrum sharing factor since it facilitates the spectrum sharing between PUs and SUs. Consequently, after the second IP phase, the received signals at nodes T_{p_n} and D can be expressed, respectively, as

$$y_{p_n,2} = h_{sp_n}\left(\mathcal{G} y_{s,1} + \sqrt{(1-\xi)P_{H,s}} x_s\right) + n_{p_n,2} \tag{5}$$

and

$$y_{d,2} = h_{sd}\left(\mathcal{G} y_{s,1} + \sqrt{(1-\xi)P_{H,s}} x_s\right) + n_{d,2}, \tag{6}$$

where $n_{p_n,2}$ and $n_{d,2}$ denote AWGN terms at T_{p_n} and D, respectively, in the second IP phase. By substituting $\mathcal{G}$ along with $y_{s,1}$ from (3) in (5), the resulting signal-to-interference-noise ratio (SINR) at node T_{p_n}, after the second phase, can

2. Hereby, cooperative spectrum sharing starts once the secondary transmitter has harvested its energy (during EH phase) to assist the primary transmission (in IP phase). Meanwhile, primary transmitter can transmit its signal continuously and non-cooperatively till the time spectrum sharing begins.

be written as

$$\Lambda_{p_n,2} = \frac{\xi P_{H,s}P_c|h_{cs}|^2|h_{sp_n}|^2}{\xi P_{H,s}|h_{sp_n}|^2\sigma^2 + (1-\xi)P_{H,s}P_c|h_{cs}|^2|h_{sp_n}|^2 + P_c|h_{cs}|^2\sigma^2}. \quad (7)$$

Similarly, the SINR at D, after the second phase, can be expressed as

$$\Lambda_{d,2} = \frac{(1-\xi)P_{H,s}P_c|h_{cs}|^2|h_{sd}|^2}{\xi P_{H,s}P_c|h_{cs}|^2|h_{sd}|^2 + \xi P_{H,s}|h_{sd}|^2\sigma^2 + P_c|h_{cs}|^2\sigma^2}. \quad (8)$$

D. BEST USER SELECTION POLICY

As discussed, the primary transmitter T_c intends to establish a communication link with one out of T_{p_n} receivers. As such, the best user amongst multiple N receivers can be opportunistically selected as

$$n^* = \arg\max_{n=1,\ldots,N}\left(\Lambda_{p_n,1}\right). \quad (9)$$

Herein, we assume that the user selection process is executed using a distributed timer technique [43] based on the channel state information of the direct links. The application for such a multiuser scenario includes heterogeneous networks to offload the traffic of the macro base station to a selected small base station. Another application can be found in the context of multi-hop transmissions, such as coordinated multipoint, wherein the best available base station can be selected based on the multiuser scheduling to transfer the data forward in subsequent hops.

In the subsequent sections, we present the performance analysis for the primary and secondary networks.

III. PERFORMANCE ANALYSIS OF PRIMARY NETWORK

A. OUTAGE PROBABILITY

The primary system is said to be in outage if the instantaneous SINR at T_{p_n} falls below a fixed SNR threshold γ_{th}. As such, the outage probability, with the application of selection combining[3] (SC), can be formulated as

$$\mathcal{P}_{\text{out}}^{\text{Pri}}(\gamma_{\text{th}}) = \Pr\left[\max\left(\max_n\left(\Lambda_{p_n,1}\right), \Lambda_{p_{n^*},2}\right) < \gamma_{\text{th}}\right], \quad (10)$$

where $\gamma_{\text{th}} = 2^{\frac{2r_{\text{th}}}{1-\alpha}} - 1$ and r_{th} is a target rate. Since the direct links and relaying links are independent, the outage expression in (10) can be reformulated as

$$\mathcal{P}_{\text{out}}^{\text{Pri}}(\gamma_{\text{th}}) = \underbrace{\Pr\left[\max_n\left(\Lambda_{p_n,1}\right) < \gamma_{\text{th}}\right]}_{\mathcal{P}_1}\underbrace{\Pr\left[\Lambda_{p_{n^*},2} < \gamma_{\text{th}}\right]}_{\mathcal{P}_2}, \quad (11)$$

3. Although the maximum ratio combining (MRC) scheme achieves better performance, SC has been popularly used due to its simplicity and lower implementation cost. In addition, it is worth remarking that SC offers the same diversity gain as MRC.

where the probability term $\mathcal{P}_1$ can be obtained as

$$\mathcal{P}_1 = \prod_{n=1}^{N}\Pr\left[\Lambda_{p_n,1} < \gamma_{\text{th}}\right] = \prod_{n=1}^{N}\left(1 - \exp\left(-\frac{\gamma_{\text{th}}}{\varrho\Omega_{cp_n}}\right)\right), \quad (12)$$

with $\varrho = \frac{P_c}{\sigma^2}$. By utilizing the concepts of total probability theorem [44], the other probability term $\mathcal{P}_2$ in (11) can be obtained, using (7), as

$$\mathcal{P}_2 = \Pr\left[\Lambda_{p_{n^*},2} < \gamma_{\text{th}}\right] = \sum_{n=1}^{N}\Pr\left[n^* = n\right] \times \Pr\left[\frac{\xi P_{H,s}\varrho|h_{cs}|^2|h_{sp_n}|^2}{\xi P_{H,s}|h_{sp_n}|^2 + (1-\xi)P_{H,s}\varrho|h_{cs}|^2|h_{sp_n}|^2 + P_c|h_{cs}|^2} < \gamma_{\text{th}}\right]. \quad (13)$$

By substituting $P_{H,s}$ from (1) into (13), we can express $\mathcal{P}_2$ as given in (14), shown at the bottom of the next page. Hereby, firstly, $\mathcal{P}_{21}$ in (14) is derived in the following lemma.

Lemma 1: The probability $\mathcal{P}_{21}$ in (14) can be expressed as

$$\mathcal{P}_{21} = \begin{cases} 1 - \exp\left(\frac{-\zeta_{\text{th}}}{P_c\Omega_{cs}}\right), & \text{for } \gamma_{\text{th}} \geq \frac{\xi}{1-\xi}, \\ 1 - \exp\left(\frac{-\zeta_{\text{th}}}{P_c\Omega_{cs}}\right), & \text{for } \gamma_{\text{th}} < \frac{\xi}{1-\xi} \ \& \ \frac{\zeta_{\text{th}}}{P_c} \leq \frac{\xi\gamma_{\text{th}}}{\mathcal{B}}, \\ \Psi(\gamma_{\text{th}}), & \text{for } \gamma_{\text{th}} < \frac{\xi}{1-\xi} \ \& \ \frac{\zeta_{\text{th}}}{P_c} > \frac{\xi\gamma_{\text{th}}}{\mathcal{B}}, \end{cases} \quad (15)$$

where $\Psi(\gamma_{\text{th}})$ is given by

$$\Psi(\gamma_{\text{th}}) = \sum_{\ell=0}^{1}(-1)^{\ell}\exp\left(\frac{-\ell\xi\gamma_{\text{th}}}{\mathcal{B}\Omega_{cs}}\right) + \exp\left(\frac{-\gamma_{\text{th}}\xi}{\mathcal{B}\Omega_{cs}}\right) - \exp\left(\frac{-\zeta_{\text{th}}}{P_c\Omega_{cs}}\right) - \sum_{k=0}^{\infty}\frac{(-1)^k}{k!} \times \exp\left(\frac{-\psi}{2}\right)\left(\frac{\mathcal{A}}{\mathcal{B}\Omega_{cs}\Omega_{sp}}\right)^{k+1} \times \exp\left(\frac{-\gamma_{\text{th}}\xi}{\mathcal{B}\Omega_{cs}}\right)\psi^{-\frac{k+2}{2}}\mathcal{W}_{-\frac{k+2}{2},-\frac{k+1}{2}}(\psi), \quad (16)$$

with $\mathcal{A} = \frac{\gamma_{\text{th}}(1-\alpha)}{2\eta\alpha}$, $\mathcal{B} = (\xi - \gamma_{\text{th}}(1-\xi))\varrho$, and $\psi = \mathcal{A}/\Omega_{sp}(\frac{\mathcal{B}\zeta_{\text{th}}}{P_c} - \gamma_{\text{th}}\xi)$.

Proof: See Appendix A. ■

Following the same lines of derivation used for obtaining $\mathcal{P}_{21}$, we can derive $\mathcal{P}_{22}$ in (14) as

$$\mathcal{P}_{22} = \begin{cases} \exp\left(\frac{-\zeta_{\text{th}}}{P_c\Omega_{cs}}\right), & \text{for } \gamma_{\text{th}} \geq \frac{\xi}{1-\xi}, \\ \mathcal{I}_1 + \Phi(\gamma_{\text{th}}), & \text{for } \gamma_{\text{th}} < \frac{\xi}{1-\xi} \ \& \ \frac{\zeta_{\text{th}}}{P_c} < \frac{\xi\gamma_{\text{th}}}{\mathcal{B}}, \\ \Phi(\gamma_{\text{th}}), & \text{for } \gamma_{\text{th}} < \frac{\xi}{1-\xi} \ \& \ \frac{\zeta_{\text{th}}}{P_c} \geq \frac{\xi\gamma_{\text{th}}}{\mathcal{B}}, \end{cases} \quad (17)$$

where $\mathcal{I}_1 = \exp(\frac{-\zeta_{\text{th}}}{P_c\Omega_{cs}}) - \exp(\frac{-\xi\gamma_{\text{th}}}{\mathcal{B}\Omega_{cs}})$ and $\Phi(\gamma_{\text{th}})$ is given by

$$\Phi(\gamma_{\text{th}}) = \exp\left(\frac{-1}{\Omega_{cs}}\max\left(\frac{\xi\gamma_{\text{th}}}{\mathcal{B}}, \frac{\zeta_{\text{th}}}{P_c}\right)\right) - \sum_{m=0}^{\infty}\frac{(-1)^m}{m!}\left(\frac{1}{\mathcal{B}\Omega_{cs}}\right)^m$$

$$\times \exp\left(\frac{-\mathcal{A}P_c}{\mathcal{B}\zeta_{\rm th}\Omega_{sp}} - \frac{\gamma_{\rm th}\xi}{\mathcal{B}\Omega_{cs}}\right)\left(\frac{\gamma_{\rm th}\xi\mathcal{A}P_c}{\mathcal{B}\Omega_{sp}\zeta_{\rm th}}\right)^m\left(\frac{\phi}{\mathcal{B}\Omega_{cs}}\right)^{-\frac{m}{2}}$$
$$\times \exp\left(\frac{-\phi}{2\mathcal{B}\Omega_{cs}}\right)\mathcal{W}_{-\frac{m}{2},\frac{1-m}{2}}\left(\frac{\phi}{\mathcal{B}\Omega_{cs}}\right), \tag{18}$$

with $\phi = \mathcal{B}\max(\frac{\xi\gamma_{\rm th}}{\mathcal{B}}, \frac{\zeta_{\rm th}}{P_c})$. Next, the probability $\Pr[n^* = n]$ in (14) can be obtained as

$$\begin{aligned}\Pr[n^* = n] &= \Pr\left[\bigcap_{\substack{m=1\\ m\neq n}}^{N}(\Lambda_{p_n,1} > \Lambda_{p_m,1})\right]\\ &= \int_0^\infty \prod_{\substack{m=1\\ m\neq n}}^{N}\Pr\left[\Lambda_{p_m,1} < y\right]f_{\Lambda_{p_n,1}}(y)dy\\ &\overset{a}{=} 1 + \sum_{k=1}^{N-1}\sum_{\substack{A_k\subseteq\{1,2,\ldots,m-1,m+1,\ldots,N\}\\ |A_k|=k}}(-1)^k\\ &\quad\times \frac{\frac{1}{\Omega_{cp_n}}}{\frac{1}{\Omega_{cp_n}} + \sum_{j\in A_k}\frac{1}{\Omega_{cp_j}}},\end{aligned} \tag{19}$$

where equality a is obtained using the multinomial expansion [17]. For the independent and identically distributed links, the expression in (19) can be simplified as $\Pr[n^* = n] = 1/N$. By substituting (19) in (14) and the resultant expression along with (12) in (11), we can obtain the outage probability of primary network as

$$\begin{aligned}\mathcal{P}_{\rm out}^{\rm Pri}(\gamma_{\rm th}) &= \prod_{n=1}^{N}\left(1 - \exp\left(-\frac{\gamma_{\rm th}}{\varrho\Omega_{cp_n}}\right)\right)\\ &\quad\times\sum_{n=1}^{N}\Pr[n^* = n](\mathcal{P}_{21} + \mathcal{P}_{22}),\end{aligned} \tag{20}$$

where $\mathcal{P}_{21}$ and $\mathcal{P}_{22}$ are given in (15) and (17), respectively.

Remark 1: From (15) and (17), it can be observed that, for the condition $\gamma_{\rm th} \geq \frac{\xi}{1-\xi}$, the cooperative transmission via secondary node ceases to exist, since $\mathcal{P}_{21} + \mathcal{P}_{22}$ becomes unity. Nevertheless, the primary network still has the availability of potential direct links to carry out the information transmission. From this observation, it is worth remarking that the value of spectrum sharing factor ξ is crucial and should be appropriately chosen for harnessing the benefits of cooperative diversity.

B. ASYMPTOTIC ANALYSIS

In this subsection, we present the simplified expression for the outage probability of primary network at the high SNR, i.e., $\varrho \to \infty$. For this, we make use of the approximation $\exp(-x) \underset{x\to 0}{\simeq} 1 - x$. Based on this approximation, we first simplify $\mathcal{P}_1$ in (12) at asymptotic limit as

$$\mathcal{P}_1^{\rm asy} \underset{\varrho\to\infty}{\simeq} \prod_{n=1}^{N}\left(\frac{\gamma_{\rm th}}{\varrho\Omega_{cp_n}}\right). \tag{21}$$

Next, $\mathcal{P}_2$ can be represented at high SNR, using (14), as

$$\mathcal{P}_2^{\rm asy} \underset{\varrho\to\infty}{\simeq} \sum_{n=1}^{N}\Pr\left[n^* = n\right](\mathcal{P}_{21}^{\rm asy} + \mathcal{P}_{22}^{\rm asy}), \tag{22}$$

where the probability $\Pr[n^* = n]$ is same as given in (19). In (22), $\mathcal{P}_{21}^{\rm asy}$ can be given, after using some approximations in (15), by

$$\mathcal{P}_{21}^{\rm asy} \underset{\varrho\to\infty}{\simeq} \begin{cases}\frac{\zeta_{\rm th}}{\varrho\sigma^2\Omega_{cs}}, & \text{for } \gamma_{\rm th} \geq \frac{\xi}{1-\xi},\\ \frac{\zeta_{\rm th}}{\varrho\sigma^2\Omega_{cs}}, & \text{for } \gamma_{\rm th} < \frac{\xi}{1-\xi} \ \&\ \frac{\zeta_{\rm th}}{P_c} \leq \frac{\xi\gamma_{\rm th}}{\mathcal{B}},\\ \Psi^{\rm asy}(\gamma_{\rm th}), & \text{for } \gamma_{\rm th} < \frac{\xi}{1-\xi} \ \&\ \frac{\zeta_{\rm th}}{P_c} > \frac{\xi\gamma_{\rm th}}{\mathcal{B}},\end{cases} \tag{23}$$

where $\Psi^{\rm asy}(\gamma_{\rm th})$ is derived as follows. Hereby, we first simplify (65) at high SNR to obtain $\Psi^{\rm asy}(\gamma_{\rm th})$ as

$$\Psi^{\rm asy}(\gamma_{\rm th}) = \frac{\zeta_{\rm th}}{P_c\Omega_{cs}} - \frac{1}{\mathcal{B}\Omega_{cs}}\int_{t=0}^{\frac{\mathcal{B}\zeta_{\rm th}}{P_c} - \gamma_{\rm th}\xi}\exp\left(-\frac{\mathcal{A}}{\Omega_{sp}t}\right)dt, \tag{24}$$

after some manipulations and then by evaluating the resultant integral using [33, eq. (3.351.4)] in (24), we obtain

$$\Psi^{\rm asy}(\gamma_{\rm th}) \simeq \frac{\zeta_{\rm th}}{\varrho\sigma^2\Omega_{cs}} - \frac{1}{\mathcal{B}\Omega_{cs}}\left(\frac{\mathcal{A}}{\Omega_{sp}}{\rm Ei}\left(\frac{-\mathcal{A}U}{\Omega_{sp}}\right) + \frac{\exp\left(\frac{-\mathcal{A}U}{\Omega_{sp}}\right)}{U}\right), \tag{25}$$

$$\begin{aligned}\mathcal{P}_2 = \sum_{n=1}^{N}\Pr[n^* = n]\Bigg\{&\underbrace{\Pr\left[\frac{\xi\varrho|h_{cs}|^2|h_{sp_n}|^2}{\xi|h_{sp_n}|^2 + (1-\xi)\varrho|h_{cs}|^2|h_{sp_n}|^2 + \frac{1-\alpha}{2\eta\alpha}} < \gamma_{\rm th},\ P_c|h_{cs}|^2 \leq \zeta_{\rm th}\right]}_{\mathcal{P}_{21}}\\ &+ \underbrace{\Pr\left[\frac{\xi\varrho|h_{cs}|^2|h_{sp_n}|^2}{\xi|h_{sp_n}|^2 + (1-\xi)\varrho|h_{cs}|^2|h_{sp_n}|^2 + \frac{1-\alpha}{2\eta\alpha\zeta_{\rm th}}P_c|h_{cs}|^2} < \gamma_{\rm th},\ P_c|h_{cs}|^2 > \zeta_{\rm th}\right]}_{\mathcal{P}_{22}}\Bigg\}\end{aligned} \tag{14}$$

where $U = \frac{1}{\frac{\zeta_{\text{th}}}{\sigma^2}\mathcal{U} - \gamma_{\text{th}}\xi}$ and $\mathcal{U} = \xi - \gamma_{\text{th}}(1-\xi)$. In a similar way, $\mathcal{P}_{22}^{\text{asy}}$ in (22) can be expressed, using (17), as

$$\mathcal{P}_{22}^{\text{asy}} \underset{\varrho\to\infty}{\simeq} \begin{cases} 1, & \text{for } \gamma_{\text{th}} \geq \frac{\xi}{1-\xi}, \\ \mathcal{I}_1^{\text{asy}} + \Phi^{\text{asy}}(\gamma_{\text{th}}), & \text{for } \gamma_{\text{th}} < \frac{\xi}{1-\xi} \ \& \ \frac{\zeta_{\text{th}}}{P_c} < \frac{\xi\gamma_{\text{th}}}{\mathcal{B}}, \\ \Phi^{\text{asy}}(\gamma_{\text{th}}), & \text{for } \gamma_{\text{th}} < \frac{\xi}{1-\xi} \ \& \ \frac{\zeta_{\text{th}}}{P_c} \geq \frac{\xi\gamma_{\text{th}}}{\mathcal{B}}, \end{cases} \tag{26}$$

where $\mathcal{I}_1^{\text{asy}} \simeq \frac{\xi\gamma_{\text{th}}}{\mathcal{B}\Omega_{cs}} - \frac{\zeta_{\text{th}}}{\varrho\sigma^2\Omega_{cs}}$ and $\Phi^{\text{asy}}(\gamma_{\text{th}})$ is given by

$$\Phi^{\text{asy}}(\gamma_{\text{th}}) \simeq \left(1 - \exp\left(\frac{-\mathcal{A}\sigma^2}{\Omega_{sp}\zeta_{\text{th}}\mathcal{U}}\right)\right). \tag{27}$$

Finally, substituting (23) and (26) in (22), and the resulting expression along with (21) in to (11), one can obtain the asymptotic expression of the outage probability for the primary network. Note that the obtained asymptotic results are useful for verifying the analytical expressions in the high SNR regime in addition to the simulation results. Moreover, the diversity order can also be observed from the numerical plots by analyzing the slope of the curves at high SNR.

IV. PERFORMANCE ANALYSIS OF SECONDARY NETWORK

In this section, we assess the performance of the secondary network in the considered EHMOSS system. In the considered protocol, when the primary transmitter T_c broadcasts the information in the first IP phase, it can be overheard by the secondary receiver D. Using this prior observation of primary signal, the secondary receiver can cancel out the interference from T_c to retrieve its own information in the second IP phase. Hereby, we consider two different cases, i.e., when the SU node D is either able or unable to successfully decode the PU's signal received in the first IP phase.

A. WHEN SU IS UNABLE TO DECODE THE PU'S SIGNAL

Firstly, we consider the case when the secondary node D is unable to decode the PU's signal in the first IP phase.

1) OUTAGE PROBABILITY

The outage probability of secondary network is obtained in the following lemma.

Lemma 2: When SU is unable to decode the PU's signal, the outage probability can be given by

$$\mathcal{P}_{\text{out}}^{\text{Sec}}(\gamma_{\text{th}}) = \mathcal{S}_1 + \mathcal{S}_2, \tag{28}$$

where $\mathcal{S}_1$ is given by

$$\mathcal{S}_1 = \begin{cases} 1 - \exp\left(\frac{-\zeta_{\text{th}}}{P_c\Omega_{cs}}\right), & \text{for } \gamma_{\text{th}} \geq \frac{\xi}{1-\xi}, \\ 1 - \exp\left(\frac{-\zeta_{\text{th}}}{P_c\Omega_{cs}}\right), & \text{for } \gamma_{\text{th}} < \frac{\xi}{1-\xi} \ \& \ \frac{\zeta_{\text{th}}}{P_c} \leq \frac{\xi\gamma_{\text{th}}}{\mathcal{C}}, \\ \Xi(\gamma_{\text{th}}), & \text{for } \gamma_{\text{th}} < \frac{\xi}{1-\xi} \ \& \ \frac{\zeta_{\text{th}}}{P_c} > \frac{\xi\gamma_{\text{th}}}{\mathcal{C}}, \end{cases} \tag{29}$$

where $\Xi(\gamma_{\text{th}})$ can be obtained as

$$\begin{aligned} \Xi(\gamma_{\text{th}}) = & \sum_{p=0}^{1}(-1)^p \exp\left(\frac{-p\xi\gamma_{\text{th}}}{\mathcal{C}\Omega_{cs}}\right) + \exp\left(\frac{-\gamma_{\text{th}}\xi}{\mathcal{C}\Omega_{cs}}\right) \\ & - \exp\left(\frac{-\zeta_{\text{th}}}{P_c\Omega_{cs}}\right) - \sum_{q=0}^{\infty}\frac{(-1)^q}{q!}\left(\frac{\mathcal{A}}{\mathcal{C}\Omega_{cs}\Omega_{sd}}\right)^{q+1} \\ & \times \exp\left(\frac{-\gamma_{\text{th}}\xi}{\mathcal{C}\Omega_{cs}}\right) \\ & \times \varphi^{-\frac{q+2}{2}} \exp\left(\frac{-\varphi}{2}\right)\mathcal{W}_{-\frac{q+2}{2},-\frac{q+1}{2}}(\varphi), \end{aligned} \tag{30}$$

with $\varphi = \mathcal{A}/\Omega_{sd}(\frac{\mathcal{C}\zeta_{\text{th}}}{P_c} - \gamma_{\text{th}}\xi)$. Further, $\mathcal{S}_2$ can be expressed as

$$\mathcal{S}_2 = \begin{cases} \exp\left(\frac{-\zeta_{\text{th}}}{P_c\Omega_{cs}}\right), & \text{for } \gamma_{\text{th}} \geq \frac{\xi}{1-\xi}, \\ \mathcal{I}_2 + \Theta(\gamma_{\text{th}}), & \text{for } \gamma_{\text{th}} < \frac{\xi}{1-\xi} \ \& \ \frac{\zeta_{\text{th}}}{P_c} < \frac{\xi\gamma_{\text{th}}}{\mathcal{C}}, \\ \Theta(\gamma_{\text{th}}), & \text{for } \gamma_{\text{th}} < \frac{\xi}{1-\xi} \ \& \ \frac{\zeta_{\text{th}}}{P_c} \geq \frac{\xi\gamma_{\text{th}}}{\mathcal{C}}, \end{cases} \tag{31}$$

where $\mathcal{I}_2 = \exp(\frac{-\zeta_{\text{th}}}{P_c\Omega_{cs}}) - \exp(\frac{-\xi\gamma_{\text{th}}}{\mathcal{C}\Omega_{cs}})$ and $\Theta(\gamma_{\text{th}})$ is given by

$$\begin{aligned} \Theta(\gamma_{\text{th}}) = & \exp\left(\frac{-\chi}{\mathcal{C}\Omega_{cs}}\right) - \sum_{r=0}^{\infty}\frac{(-1)^r}{r!}\left(\frac{1}{\mathcal{C}\Omega_{cs}}\right)^r\left(\frac{\chi}{\mathcal{C}\Omega_{cs}}\right)^{-\frac{r}{2}} \\ & \times \exp\left(\frac{-\mathcal{A}P_c}{\mathcal{C}\zeta_{\text{th}}\Omega_{sd}} - \frac{\gamma_{\text{th}}\xi}{\mathcal{C}\Omega_{cs}}\right)\left(\frac{\gamma_{\text{th}}\xi\mathcal{A}P_c}{\mathcal{C}\Omega_{sd}\zeta_{\text{th}}}\right)^r \\ & \times \exp\left(\frac{-\chi}{2\mathcal{C}\Omega_{cs}}\right)\mathcal{W}_{-\frac{r}{2},\frac{1-r}{2}}\left(\frac{\chi}{\mathcal{C}\Omega_{cs}}\right), \end{aligned} \tag{32}$$

with $\chi = \mathcal{C}\max(\frac{\xi\gamma_{\text{th}}}{\mathcal{C}}, \frac{\zeta_{\text{th}}}{P_c})$.

Proof: See Appendix B. ■

By carefully observing $\mathcal{S}_1$ and $\mathcal{S}_2$ from (29) and (31), respectively, in Lemma 2, one can note that $\mathcal{P}_{\text{out}}^{\text{Sec}}(\gamma_{\text{th}})$ becomes unity for $\gamma_{\text{th}} \geq \frac{\xi}{1-\xi}$. This condition resonates with the one obtained in Section III-A for the primary network since secondary link cooperates with the transmission of PU. Thus, the values of spectrum sharing factor ξ should be judiciously chosen to avoid the outage of secondary network and thereby to facilitate the cooperative transmission.

2) ASYMPTOTIC ANALYSIS

At high SNR, we can express the outage probability of secondary network, from (68) as

$$\mathcal{P}_{\text{out}}^{\text{Sec,asy}}(\gamma_{\text{th}}) \underset{\varrho\to\infty}{\simeq} \mathcal{S}_1^{\text{asy}} + \mathcal{S}_2^{\text{asy}}, \tag{33}$$

where $\mathcal{S}_1^{\text{asy}}$ can be expressed, using some approximations in (29), as

$$\mathcal{S}_1^{\text{asy}} \underset{\varrho\to\infty}{\simeq} \begin{cases} \frac{\zeta_{\text{th}}}{\varrho\sigma^2\Omega_{cs}}, & \text{for } \gamma_{\text{th}} \geq \frac{\xi}{1-\xi}, \\ \frac{\zeta_{\text{th}}}{\varrho\sigma^2\Omega_{cs}}, & \text{for } \gamma_{\text{th}} < \frac{\xi}{1-\xi} \ \& \ \frac{\zeta_{\text{th}}}{P_c} \leq \frac{\xi\gamma_{\text{th}}}{\mathcal{C}}, \\ \Xi^{\text{asy}}(\gamma_{\text{th}}), & \text{for } \gamma_{\text{th}} < \frac{\xi}{1-\xi} \ \& \ \frac{\zeta_{\text{th}}}{P_c} > \frac{\xi\gamma_{\text{th}}}{\mathcal{C}}, \end{cases} \tag{34}$$

where $\Xi^{\text{asy}}(\gamma_{\text{th}})$ can be evaluated as

$$\Xi^{\text{asy}}(\gamma_{\text{th}}) \simeq \frac{\zeta_{\text{th}}}{P_c\Omega_{cs}} - \frac{1}{\mathcal{C}\Omega_{cs}}\left(\frac{\mathcal{A}}{\Omega_{sd}}\text{Ei}\left(\frac{-\mathcal{A}V}{\Omega_{sd}}\right) + \frac{\exp\left(\frac{-\mathcal{A}V}{\Omega_{sd}}\right)}{V}\right), \tag{35}$$

where $V = \frac{1}{\frac{\zeta_{\text{th}}}{\sigma^2}\mathcal{V}-\gamma_{\text{th}}\xi}$ and $\mathcal{V} = (1-\xi) - \gamma_{\text{th}}\xi$. Similarly, $\mathcal{S}_2^{\text{asy}}$ in (33) can be given by

$$\mathcal{S}_2^{\text{asy}} \underset{\varrho\to\infty}{\simeq} \begin{cases} 1, & \text{for } \gamma_{\text{th}} \geq \frac{\xi}{1-\xi}, \\ \mathcal{I}_2^{\text{asy}} + \Theta^{\text{asy}}(\gamma_{\text{th}}), & \text{for } \gamma_{\text{th}} < \frac{\xi}{1-\xi} \ \&\ \frac{\zeta_{\text{th}}}{P_c} < \frac{\xi\gamma_{\text{th}}}{\mathcal{C}}, \\ \Theta^{\text{asy}}(\gamma_{\text{th}}), & \text{for } \gamma_{\text{th}} < \frac{\xi}{1-\xi} \ \&\ \frac{\zeta_{\text{th}}}{P_c} \geq \frac{\xi\gamma_{\text{th}}}{\mathcal{C}}, \end{cases} \tag{36}$$

where $\mathcal{I}_2^{\text{asy}} \simeq \frac{\xi\gamma_{\text{th}}}{\mathcal{C}\Omega_{cs}} - \frac{\zeta_{\text{th}}}{\varrho\sigma^2\Omega_{cs}}$ and $\Theta^{\text{asy}}(\gamma_{\text{th}})$ is given by

$$\Theta^{\text{asy}}(\gamma_{\text{th}}) \simeq \left(1 - \exp\left(\frac{-\mathcal{A}\sigma^2}{\Omega_{sd}\zeta_{\text{th}}\mathcal{V}}\right)\right). \tag{37}$$

Finally, substituting (34) and (36) in (33), one can obtain the asymptotic expression of the outage probability for the secondary network.

B. WHEN SU IS ABLE TO DECODE THE PU'S SIGNAL

Next, we consider the case when the SU node D can successfully decode the PU's signal in the first phase. Consequently, D can eliminate the interference from primary signal in the second IP phase. With this, the resultant SNR at D, in the second IP phase, can be expressed as

$$\Lambda_{d,2}^{d} = \frac{(1-\xi)P_{H,s}\varrho|h_{cs}|^2|h_{sd}|^2}{\xi P_{H,s}|h_{sd}|^2 + P_c|h_{cs}|^2}. \tag{38}$$

1) OUTAGE PROBABILITY

The outage probability is obtained in the following lemma.

Lemma 3: When SU is able to decode the PU's signal, the outage probability of SU can be given by

$$\mathcal{P}_{\text{out},d}^{\text{Sec}}(\gamma_{\text{th}}) = \mathcal{D}_1 + \mathcal{D}_2. \tag{39}$$

Hereby, $\mathcal{D}_1$ can be obtained as

$$\mathcal{D}_1 = \begin{cases} 1 - \exp\left(\frac{-\zeta_{\text{th}}}{P_c\Omega_{cs}}\right), & \text{for } \frac{\zeta_{\text{th}}}{P_c} \leq \frac{\xi\gamma_{\text{th}}}{(1-\xi)\varrho}, \\ \Upsilon(\gamma_{\text{th}}), & \text{for } \frac{\zeta_{\text{th}}}{P_c} > \frac{\xi\gamma_{\text{th}}}{(1-\xi)\varrho}, \end{cases} \tag{40}$$

where $\Upsilon(\gamma_{\text{th}})$ is given by

$$\Upsilon(\gamma_{\text{th}}) = \sum_{t=0}^{1}(-1)^t\exp\left(\frac{-t\zeta_{\text{th}}}{P_c\Omega_{cs}}\right) - \sum_{u=0}^{\infty}\frac{(-1)^u}{u!}\left(\frac{\mathcal{A}}{\mathcal{Q}\Omega_{sd}}\right)^{-\frac{u+2}{2}} \times \left(\frac{\mathcal{A}}{(1-\xi)\varrho\Omega_{cs}\Omega_{sd}}\right)^{u+1}\exp\left(\frac{-\gamma_{\text{th}}\xi}{(1-\xi)\varrho\Omega_{cs}}\right) \times \exp\left(\frac{-\mathcal{A}}{2\mathcal{Q}\Omega_{sd}}\right)\mathcal{W}_{-\frac{u+2}{2},-\frac{u+1}{2}}\left(\frac{\mathcal{A}}{\mathcal{Q}\Omega_{sd}}\right), \tag{41}$$

with $\mathcal{Q} = \frac{(1-\xi)\varrho\zeta_{\text{th}}}{P_c} - \gamma_{\text{th}}\xi$. Similarly, $\mathcal{D}_2$ in (39) can be obtained as

$$\mathcal{D}_2 = \begin{cases} \mathcal{I}_3 + \mathcal{Z}(\gamma_{\text{th}}), & \text{for } \frac{\zeta_{\text{th}}}{P_c} < \frac{\xi\gamma_{\text{th}}}{(1-\xi)\varrho}, \\ \mathcal{Z}(\gamma_{\text{th}}), & \text{for } \frac{\zeta_{\text{th}}}{P_c} \geq \frac{\xi\gamma_{\text{th}}}{(1-\xi)\varrho}, \end{cases} \tag{42}$$

where $\mathcal{I}_3 = \exp(\frac{-\zeta_{\text{th}}}{P_c\Omega_{cs}}) - \exp(\frac{-\xi\gamma_{\text{th}}}{(1-\xi)\varrho\Omega_{cs}})$ and $\mathcal{Z}(\gamma_{\text{th}})$ is given by

$$\mathcal{Z}(\gamma_{\text{th}}) = \exp\left(\frac{-\mathcal{F}}{\Omega_{cs}}\right) - \sum_{v=0}^{\infty}\frac{1}{v!}\left(\frac{-1}{(1-\xi)\varrho\Omega_{cs}}\right)^v\left(\frac{\mathcal{F}}{\Omega_{cs}}\right)^{-\frac{v}{2}} \times \exp\left(\frac{-\mathcal{A}P_c}{(1-\xi)\varrho\zeta_{\text{th}}\Omega_{sd}} - \frac{\gamma_{\text{th}}\xi}{(1-\xi)\varrho\Omega_{cs}} - \frac{\mathcal{F}}{2\Omega_{cs}}\right) \times \left(\frac{\gamma_{\text{th}}\xi\mathcal{A}P_c}{(1-\xi)\varrho\Omega_{sd}\zeta_{\text{th}}}\right)^v\mathcal{W}_{-\frac{v}{2},\frac{1-v}{2}}\left(\frac{\mathcal{F}}{\Omega_{cs}}\right), \tag{43}$$

with $\mathcal{F} = \max(\frac{\xi\gamma_{\text{th}}}{(1-\xi)\varrho}, \frac{\zeta_{\text{th}}}{P_c})$.

Proof: See Appendix C. ■

Using (40) and (42), it is worth remarking that, unlike the previous case, the constraint on the spectrum sharing factor ξ is relaxed when the SU node is able to decode the PU's signal. Thus, it can be inferred that when the SU node has the ability to successfully decode the PU's signal, the performance of secondary system can be significantly improved as we shall observe later in Section VII through the numerical results.

2) ASYMPTOTIC ANALYSIS

At high SNR, we can express the outage probability, from (72), as

$$\mathcal{P}_{\text{out},d}^{\text{Sec,asy}}(\gamma_{\text{th}}) \underset{\varrho\to\infty}{\simeq} \mathcal{D}_1^{\text{asy}} + \mathcal{D}_2^{\text{asy}}, \tag{44}$$

where $\mathcal{D}_1^{\text{asy}}$ can be expressed, using (40), as

$$\mathcal{D}_1^{\text{asy}} \underset{\varrho\to\infty}{\simeq} \begin{cases} \frac{\zeta_{\text{th}}}{\varrho\sigma^2\Omega_{cs}}, & \text{for } \frac{\zeta_{\text{th}}}{P_c} \leq \frac{\xi\gamma_{\text{th}}}{(1-\xi)\varrho}, \\ \Upsilon^{\text{asy}}(\gamma_{\text{th}}), & \text{for } \frac{\zeta_{\text{th}}}{P_c} > \frac{\xi\gamma_{\text{th}}}{(1-\xi)\varrho}, \end{cases} \tag{45}$$

where $\Upsilon^{\text{asy}}(\gamma_{\text{th}})$ can be evaluated as

$$\Upsilon^{\text{asy}}(\gamma_{\text{th}}) \simeq \frac{\zeta_{\text{th}}}{\varrho\sigma^2\Omega_{cs}} - \frac{1}{\mathcal{E}\Omega_{cs}}\left(\frac{\mathcal{A}}{\Omega_{sd}}\text{Ei}\left(\frac{-\mathcal{A}V}{\Omega_{sd}}\right) + \frac{\exp\left(\frac{-\mathcal{A}V}{\Omega_{sd}}\right)}{V}\right), \tag{46}$$

with $\mathcal{E} = (1-\xi)\varrho$. Similarly, $\mathcal{D}_2^{\text{asy}}$ in (44) can be given, using (42), by

$$\mathcal{D}_2^{\text{asy}} \underset{\varrho\to\infty}{\simeq} \begin{cases} \mathcal{I}_3^{\text{asy}} + \mathcal{Z}^{\text{asy}}(\gamma_{\text{th}}), & \text{for } \frac{\zeta_{\text{th}}}{P_c} < \frac{\xi\gamma_{\text{th}}}{(1-\xi)\varrho}, \\ \mathcal{Z}^{\text{asy}}(\gamma_{\text{th}}), & \text{for } \frac{\zeta_{\text{th}}}{P_c} \geq \frac{\xi\gamma_{\text{th}}}{(1-\xi)\varrho}, \end{cases} \tag{47}$$

where $\mathcal{I}_3^{\text{asy}} \simeq \frac{\xi\gamma_{\text{th}}}{(1-\xi)\varrho\Omega_{cs}} - \frac{\zeta_{\text{th}}}{\varrho\sigma^2\Omega_{cs}}$ and $\mathcal{Z}^{\text{asy}}(\gamma_{\text{th}})$ is given by

$$\mathcal{Z}^{\text{asy}}(\gamma_{\text{th}}) \underset{\varrho\to\infty}{\simeq} \left(1 - \exp\left(\frac{-\mathcal{A}\sigma^2}{\Omega_{sd}\zeta_{\text{th}}\mathcal{V}}\right)\right). \tag{48}$$

On substituting (45) and (47) in (44), we can obtain the asymptotic outage probability expression.

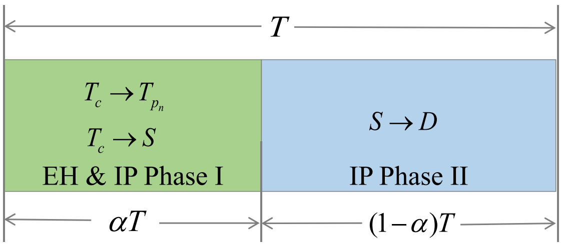

FIGURE 3. Time frame for successful primary's direct transmission.

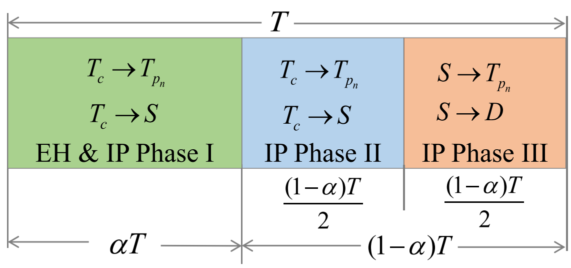

FIGURE 4. Time frame for unsuccessful primary's direct transmission.

V. AN IMPROVED ENERGY HARVESTING-BASED RELAYING SCHEME

In this section, we propose another relaying scheme for overlay spectrum sharing systems which improves the performance of both primary and secondary networks compared with the conventional fixed relaying scheme. In this scheme, the primary network invokes the relaying cooperation only when its direct transmission fails. Specifically, the first phase is dedicated to EH at the cooperative SU and to the information transfer of the PU. Only after this phase, when S has harvested a sufficient amount of energy, it starts the information processing in the next time slot. In particular, S harvests energy from the RF signal transmitted by T_c for a duration of αT and simultaneously T_c also transmits its information to its intended receiver T_{p_n}. Depending on the success/failure of the direct primary's transmission ($T_c \to T_{p_n}$), the relaying transmission is invoked. Thus, the mutual information of the direct primary transmission can be given as

$$\mathcal{I}_{cp_n} = \alpha \log_2\big(1 + \Lambda_{p_n,1}\big). \tag{49}$$

If T_{p_n} is able to successfully decode the information signal from T_c, i.e., if $\mathcal{I}_{cp_n} > r_{\text{th}}$, it sends an error-free one-bit feedback[4] to the cooperative node S indicating that the relaying cooperation is not needed. For this case, the remaining $(1-\alpha)T$ period is utilized for the information transmission of $S \to D$, as shown in Fig. 3. As such, the received signal at T_{p_n}, after the IP phase I, is as given in (2). On the other hand, the signal received at D, after the IP phase II, can be written as

$$y_{d,2}^{\text{IR}} = h_{sd}\sqrt{P_{H,s}^{\text{IR}}}x_s + n_{d,2}, \tag{50}$$

where $P_{H,s}^{\text{IR}}$ is the harvested power at the node S. Based on (50), the corresponding SNR at D is given by

$$\Lambda_{d,2}^{\text{IR}} = \frac{P_{H,s}^{\text{IR}}|h_{sd}|^2}{\sigma^2}. \tag{51}$$

It is important to note here that node S can utilize all the harvested power for its information transfer which is in contrast to the fixed relaying protocol wherein S has to split the total harvested power for the transmission of primary's information as well. Hereby, the transmitted power $P_{H,s}^{\text{IR}}$ at S can be expressed as

$$P_{H,s}^{\text{IR}} = \begin{cases} \frac{\eta\alpha P_c|h_{cs}|^2}{1-\alpha}, & \text{if } P_c|h_{cs}|^2 \le \zeta_{\text{th}}, \\ \frac{\eta\alpha\zeta_{\text{th}}}{1-\alpha}, & \text{if } P_c|h_{cs}|^2 > \zeta_{\text{th}}. \end{cases} \tag{52}$$

On the other hand, if T_{p_n} is unable to decode the signal from T_c in the first phase, i.e., if $\mathcal{I}_{cp_n} < r_{\text{th}}$, it sends a negative feedback to T_c and S. Consequently, the relaying cooperation is invoked and further information exchange operation will remain the same as of fixed relaying. For this case, the remaining $(1-\alpha)T$ period is subdivided into two equal IP phases of duration $\frac{(1-\alpha)T}{2}$ each, as shown in Fig. 4.

In the following sections, we assess the performance of primary and secondary networks for the proposed improved relaying protocol.

A. OUTAGE PROBABILITY OF PRIMARY NETWORK

The outage probability of the primary network for the proposed relaying scheme, with the application of selection cooperation, can be formulated as

$$\mathcal{P}_{\text{out}}^{\text{Pri,IR}}(\gamma_{\text{th}}) = \Pr\Big[\max\Big(\max_n\big(\Lambda_{p_n,1}\big), \Lambda_{p_{n^*},2}\Big) < \gamma_{\text{th}}, \max_n\big(\Lambda_{p_n,1}\big) < \gamma_{\text{th}}^{\text{IR}}\Big], \tag{53}$$

where the first term in the joint probability corresponds to the selection combining between the direct path ($T_c \to T_{p_{n^*}}$) and relayed path ($T_c \to S \to T_{p_{n^*}}$) while the other term accounts for the failure of the direct transmission. As such, (53) can be further simplified to express

$$\begin{aligned}\mathcal{P}_{\text{out}}^{\text{Pri,IR}}(\gamma_{\text{th}}) &= \Pr\Big[\max_n\big(\Lambda_{p_n,1}\big)<\gamma_{\text{th}}, \Lambda_{p_{n^*},2}<\gamma_{\text{th}}, \max_n\big(\Lambda_{p_n,1}\big)<\gamma_{\text{th}}^{\text{IR}}\Big] \\ &= \Pr\Big[\max_n\big(\Lambda_{p_n,1}\big)<\min\big(\gamma_{\text{th}}, \gamma_{\text{th}}^{\text{IR}}\big), \Lambda_{p_{n^*},2}<\gamma_{\text{th}}\Big], \end{aligned} \tag{54}$$

with $\gamma_{\text{th}}^{\text{IR}} = 2^{\frac{r_{\text{th}}}{\alpha}} - 1$. Owing to the independence between the two events in (54), we can write

$$\begin{aligned}\mathcal{P}_{\text{out}}^{\text{Pri,IR}}(\gamma_{\text{th}}) &= \underbrace{\Pr\Big[\max_n\big(\Lambda_{p_n,1}\big) < \min\big(\gamma_{\text{th}}, \gamma_{\text{th}}^{\text{IR}}\big)\Big]}_{\mathcal{P}_1^{\text{IR}}} \\ &\quad \times \underbrace{\Pr\big[\Lambda_{p_{n^*},2} < \gamma_{\text{th}}\big]}_{\mathcal{P}_2}, \end{aligned} \tag{55}$$

4. Hereby, it is assumed that the feedback/acknowledge time is negligible compared to the information processing time [46].

where $\mathcal{P}_1^{\text{IR}}$ can be readily obtained by replacing γ_{th} with $\min(\gamma_{\text{th}}, \gamma_{\text{th}}^{\text{IR}})$ in (12) and $\mathcal{P}_2$ is the same as obtained in (13).

Asymptotic Analysis: Hereby, asymptotic approximation for the outage probability can be obtained by reducing the expression in (55) at high SNR. For this, $\mathcal{P}_1^{\text{IR}}$ at high SNR, i.e., $\mathcal{P}_1^{\text{IR,asy}}$, can be readily obtained by replacing γ_{th} with $\min(\gamma_{\text{th}}, \gamma_{\text{th}}^{\text{IR}})$ in (21). Whereas, high SNR approximation of $\mathcal{P}_2$, i.e., $\mathcal{P}_2^{\text{asy}}$, is same as given in (22). Finally, on substituting $\mathcal{P}_1^{\text{IR,asy}}$ and $\mathcal{P}_2^{\text{asy}}$ in to (55), the asymptotic outage probability of the primary network for the improved EH-based relaying scheme can be derived.

B. OUTAGE PROBABILITY OF SECONDARY NETWORK

The outage probability of secondary network for the proposed improved relaying scheme in the considered EHMOSS system can be formulated as

$$\mathcal{P}_{\text{out}}^{\text{Sec,IR}}(\gamma_{\text{th}}) = \underbrace{\Pr\Big[\Lambda_{d,2}^{d} < \gamma_{\text{th}}, \max_n\big(\Lambda_{p_n,1}\big) < \gamma_{\text{th}}^{\text{IR}}\Big]}_{\mathcal{L}_1} + \underbrace{\Pr\Big[\Lambda_{d,2}^{\text{IR}} < \hat{\gamma}_{\text{th}}, \max_n\big(\Lambda_{p_n,1}\big) \geq \gamma_{\text{th}}^{\text{IR}}\Big]}_{\mathcal{L}_2}, \quad (56)$$

where $\hat{\gamma}_{\text{th}} = 2^{\frac{r_{\text{th}}}{1-\alpha}} - 1$. In (56), the term $\mathcal{L}_1$ accounts for the case when the direct primary transmission is not successful while the other term $\mathcal{L}_2$ captures the event when direct primary transmission is successful. At first, we re-express $\mathcal{L}_1$ to obtain

$$\mathcal{L}_1 = \underbrace{\Pr\Big[\Lambda_{d,2}^{d} < \gamma_{\text{th}}\Big]}_{\mathcal{L}_{11}} \underbrace{\Pr\Big[\max_n\big(\Lambda_{p_n,1}\big) < \gamma_{\text{th}}^{\text{IR}}\Big]}_{\mathcal{L}_{12}}. \quad (57)$$

It is worth noting that $\mathcal{L}_{11}$ is given by (71) while $\mathcal{L}_{12}$ can be readily obtained by replacing γ_{th} with $\gamma_{\text{th}}^{\text{IR}}$ in (12). Next, $\mathcal{L}_2$ in (56) can be expressed, due to underlying independence, as

$$\mathcal{L}_2 = \underbrace{\Pr\big[\Lambda_{d,2}^{\text{IR}} < \hat{\gamma}_{\text{th}}\big]}_{\mathcal{L}_{21}} \underbrace{\Pr\Big[\max_n\big(\Lambda_{p_n,1}\big) \geq \gamma_{\text{th}}^{\text{IR}}\Big]}_{\mathcal{L}_{22}}, \quad (58)$$

where $\mathcal{L}_{21}$ can be written, using (51), as

$$\mathcal{L}_{21} = \Pr\left[\frac{P_{H,s}^{\text{IR}}|h_{sd}|^2}{\sigma^2} < \hat{\gamma}_{\text{th}}\right]. \quad (59)$$

On substituting $P_{H,s}^{\text{IR}}$ from (52) in (59) and after performing various manipulations, we obtain $\mathcal{L}_{21}$ as

$$\mathcal{L}_{21} = \sum_{w=0}^{1}(-1)^w \exp\left(\frac{-2w\hat{\gamma}_{\text{th}}\mathcal{A}\sigma^2}{\gamma_{\text{th}}\Omega_{sd}\zeta_{\text{th}}} - \frac{w\zeta_{\text{th}}}{P_c\Omega_{cs}}\right) - \sum_{v=0}^{\infty}\frac{(-1)^v}{v!} \times \left(\frac{2\hat{\gamma}_{\text{th}}\mathcal{A}\sigma^2}{\gamma_{\text{th}}\Omega_{sd}\zeta_{\text{th}}}\right)^{-\frac{v+2}{2}} \left(\frac{2\hat{\gamma}_{\text{th}}\mathcal{A}}{\gamma_{\text{th}}\varrho\Omega_{cs}\Omega_{sd}}\right)^{v+1} \times \exp\left(\frac{-\hat{\gamma}_{\text{th}}\mathcal{A}\sigma^2}{\gamma_{\text{th}}\zeta_{\text{th}}\Omega_{sd}}\right) \times \mathcal{W}_{-\frac{u+2}{2},-\frac{u+1}{2}}\left(\frac{2\hat{\gamma}_{\text{th}}\mathcal{A}\sigma^2}{\gamma_{\text{th}}\zeta_{\text{th}}\Omega_{sd}}\right). \quad (60)$$

The other probability term $\mathcal{L}_{22}$ in (58) can be obtained as $\mathcal{L}_{22} = \prod_{n=1}^{N}\exp(\frac{-\gamma_{\text{th}}^{\text{IR}}}{\varrho\Omega_{cp_n}})$. Finally, substituting (57) and (58) in (56), we can obtain the outage probability for the secondary network.

Remark 2: The proposed improved relaying scheme has two main advantages: 1) This scheme makes an efficient use of available degrees of freedom[5] and thereby improves the performance of primary network significantly. 2) When primary network does not invoke relaying cooperation, the secondary node can exploit all the harvested power for its own information transmission and eventually the performance of secondary improves substantially.

Asymptotic Analysis: To obtain the asymptotic expression of outage probability in (56), we need to obtain the high SNR approximation of $\mathcal{L}_1$ and $\mathcal{L}_2$. Firstly, $\mathcal{L}_1$ at high SNR can be expressed, using (57), as $\mathcal{L}_1^{\text{asy}} \underset{\varrho\to\infty}{\simeq} \mathcal{L}_{11}^{\text{asy}}\mathcal{L}_{12}^{\text{asy}}$. Here, $\mathcal{L}_{11}^{\text{asy}}$ is same as given by (44), whereas, $\mathcal{L}_{12}^{\text{asy}}$ can be obtained by replacing γ_{th} with $\gamma_{\text{th}}^{\text{IR}}$ in (21). Next, we can write $\mathcal{L}_2$ at high SNR, using (58), as $\mathcal{L}_2^{\text{asy}} \underset{\varrho\to\infty}{\simeq} \mathcal{L}_{21}^{\text{asy}}\mathcal{L}_{22}^{\text{asy}}$. Hereby, $\mathcal{L}_{21}^{\text{asy}}$ can be expressed as $\mathcal{L}_{21}^{\text{asy}} \underset{\varrho\to\infty}{\simeq} 1 - \exp(\frac{2\hat{\gamma}_{\text{th}}\mathcal{A}\sigma^2}{\gamma_{\text{th}}\zeta_{\text{th}}\Omega_{sd}})$. On the other hand, $\mathcal{L}_{22}^{\text{asy}} \underset{\varrho\to\infty}{\simeq} 1$. Finally, substituting $\mathcal{L}_1^{\text{asy}}$ and $\mathcal{L}_2^{\text{asy}}$ in (56), we can obtain the asymptotic outage probability of the secondary network for the improved EH-based relaying scheme.

Remark 3: It is worth noting that, in contrast with fixed relaying, improved relaying is a more sophisticated scheme which may exhibit little more complexity due to involvement of the limited feedback mechanism. However, the performance improvement offered by this scheme overshadows its limitation and, therefore, it may be useful primarily for the applications where performance of the system is more important than the cost constraints. Whereas, fixed relaying is a simpler scheme and may be preferred where cost of the system is of paramount importance. Therefore, based on the cost and performance, any one of the relaying strategies can be employed in accordance to the preference.

VI. CONDITION FOR SPECTRUM SHARING

In this section, we obtain condition on the spectrum sharing factor ξ which can ensure that the performance of the direct transmission is worse off than the relaying transmissions with spectrum sharing. For this, the outage probability of primary network without spectrum sharing, i.e., direct transmission over the entire time period T, can be given by

$$\mathcal{P}_{\text{out}}^{\text{Pri,DL}}\big(\gamma_{\text{th}}^{\text{DL}}\big) = \Pr\Big[\max_n\big(\Lambda_{p_n,1}\big) < \gamma_{\text{th}}^{\text{DL}}\Big] = \prod_{n=1}^{N}\left(1 - \exp\left(-\frac{\gamma_{\text{th}}^{\text{DL}}}{\varrho\Omega_{cp_n}}\right)\right), \quad (61)$$

5. Degrees of freedom implies the number of available channels/paths for the primary user's information transmission. For instance, for transmission from T_c to T_{p_n}, there are two different spatial channels, i.e., direct path and relayed path via secondary node S.

where $\gamma_{\text{th}}^{\text{DL}} = 2^{r_{\text{th}}} - 1$. Based on this, the condition on ξ can be obtained by solving the respective constraints for fixed and improved relaying as follows

$$\mathcal{P}_{\text{out}}^{\text{Pri,DL}}\left(\gamma_{\text{th}}^{\text{DL}}\right) \geq \mathcal{P}_{\text{out}}^{\text{Pri}}(\gamma_{\text{th}})$$
$$\text{and } \mathcal{P}_{\text{out}}^{\text{Pri,DL}}\left(\gamma_{\text{th}}^{\text{DL}}\right) \geq \mathcal{P}_{\text{out}}^{\text{Pri,IR}}(\gamma_{\text{th}}), \tag{62}$$

where $\mathcal{P}_{\text{out}}^{\text{Pri,DL}}(\gamma_{\text{th}}^{\text{DL}})$ is given by (61) while $\mathcal{P}_{\text{out}}^{\text{Pri}}(\gamma_{\text{th}})$ and $\mathcal{P}_{\text{out}}^{\text{Pri,IR}}(\gamma_{\text{th}})$ are obtained using (20) and (55), respectively, in the manuscript. As such, an analytical solution of (62) is rather difficult to obtain. However, it can be obtained numerically using MATLAB or Mathematica. Alternatively, this condition can also be estimated using crossover points as shown in Fig. 6.

As such, we would like to emphasize here that, compared with the direct link transmission, the relaying strategies provide additional transmission opportunity to the secondary network and hence facilitate the efficient usage of the spectrum. Moreover, such spectrum sharing obligation may also be imposed by the spectrum regulatory bodies to accommodate new users owing to the growing spectrum scarcity. Further, in conventional spectrum sharing systems, the primary and secondary networks are referred to as licensed and unlicensed users, respectively. However, they can be the users belonging to the same network wherein one has high priority over the others and hence they transmit over the same spectrum to improve the efficiency of spectrum utilization.

VII. NUMERICAL AND SIMULATION RESULTS

In this section, representative numerical results for the performance of considered EHMOSS system are presented. Monte Carlo simulations are performed to corroborate the derived expressions. All the analytical curves are drawn after truncating the infinite series up to the initial seven terms to achieve a sufficient level of accuracy. Herein, we set several system parameters, unless otherwise specified, as $\Omega_{\iota\jmath} = 1$, $T = 1$ sec, $\zeta_{\text{th}} = 0$ dB, $r_{\text{th}} = 0.01$, and $\sigma^2 = 1$.

In Fig. 5, we have shown the curves when comparing the performance of considered relaying schemes with the direct link. It can be observed that, for $\xi = 0.2$, the outage probability of the direct link is better than the fixed relaying. At this value of the spectrum sharing factor, the direct link also performs better than the improved relaying but only in low SNR regime (0 to 5 dB). At SNR values greater than 5 dB, improved relaying clearly outperforms the direct link transmission. On the other hand, by increasing the value of the spectrum sharing factor to $\xi = 0.5$, the performance of fixed relaying approaches the direct link performance. Further, when ξ increases to $\xi = 0.8$, fixed relaying performs better than the direct link in the high SNR regime. Therefore, it can be noted that, by appropriately choosing the spectrum sharing factor, fixed relaying can perform better than direct link. Whereas, improved relaying significantly outperforms the direct transmission.

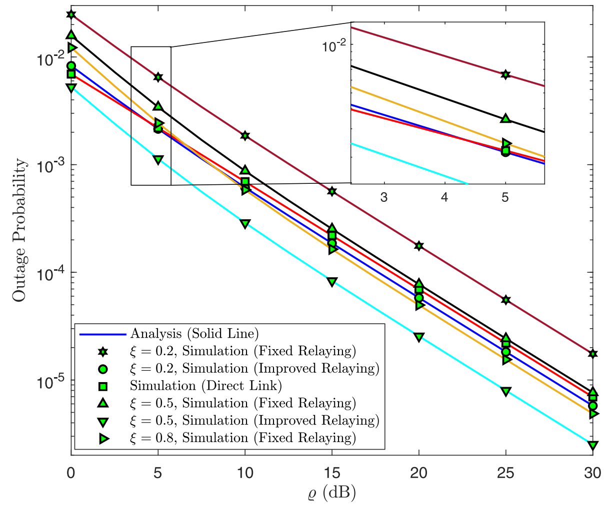

FIGURE 5. Outage probability comparison of primary network with direct link.

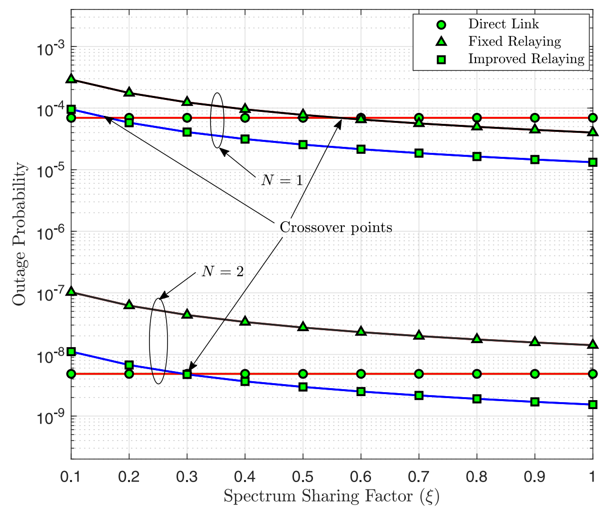

FIGURE 6. Outage probability of primary network against the spectrum sharing factor.

As shown in Fig. 6, we illustrate the impact of ξ on the performance of different transmission schemes at fix $\alpha = 0.6$, $\eta = 0.1$, and $\varrho = 20$ dB. It can be observed that the direct link performs better than fixed and improved relaying at lower values of ξ, i.e., $\xi <\approx 0.6$ and $\xi <\approx 0.2$, respectively. Nevertheless, as ξ increases the performance of the relaying strategies get better than direct link (see curves corresponding to $N = 1$). However, as N increases to 2, direct link always performs better than the fixed relaying. In contrast, improved relaying performs better than the direct link after a certain value of ξ. From the crossover points in the curves, we can obtain the condition on ξ which can ensure better relaying performance than the direct link. In particular, for $N = 1$, we can deduce that when $\xi >\approx 0.55$ and $\xi >\approx 0.16$, the performance of direct link is worse off than the fixed and improved relaying, respectively.

In Fig. 7, we plot the outage probability curves of primary network against ϱ for varying number of PUs N. For this, we set $\alpha = 0.6$, $\eta = 0.1$, and $\xi = 0.2$. Herein, the performance

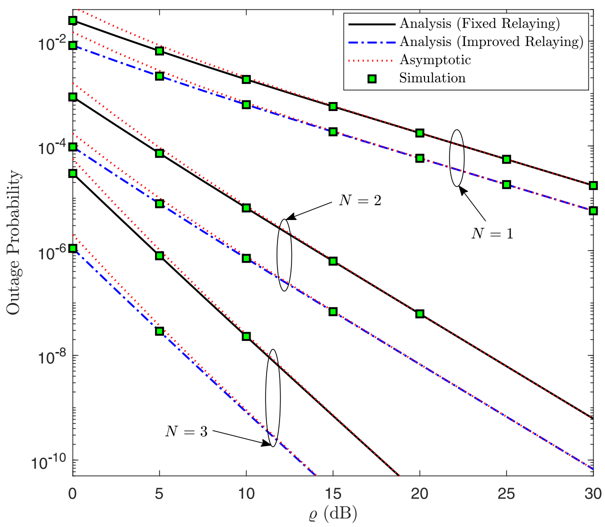

FIGURE 7. Outage probability of primary network for various *N*.

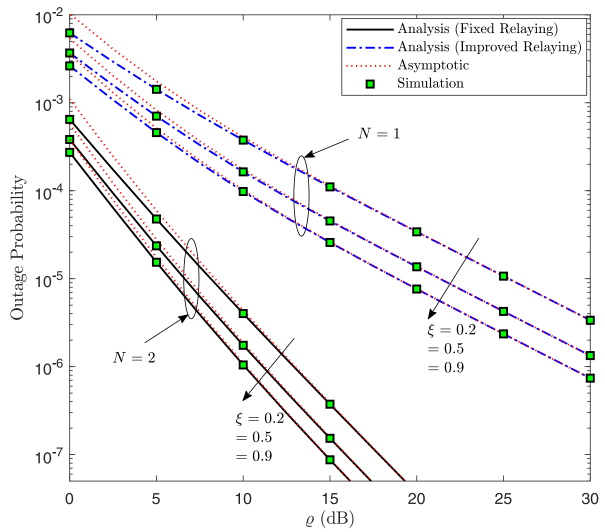

FIGURE 8. Outage probability of primary network for various ξ.

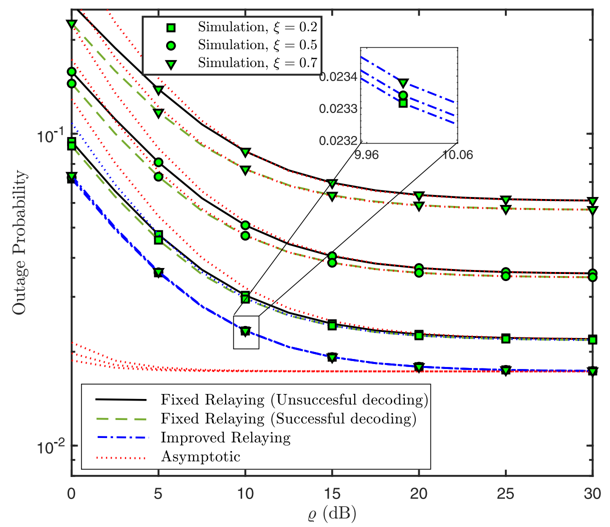

FIGURE 9. Outage probability of secondary network for various ξ.

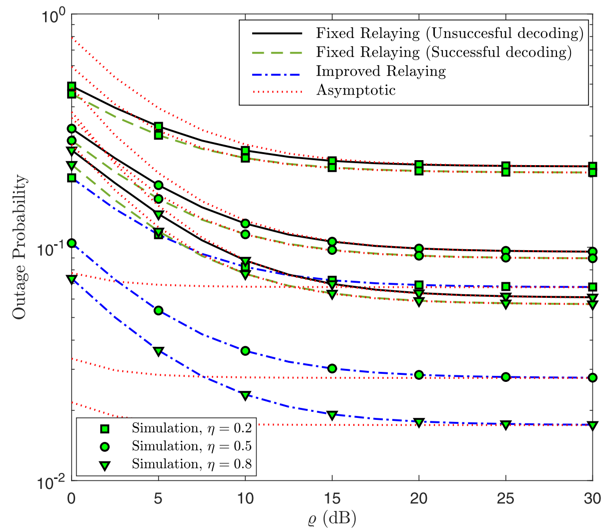

FIGURE 10. Outage probability of secondary network for various η.

improvement with N can be attributed to the exploitation of multiuser diversity gain. Further, we have shown that the proposed improved relaying scheme delivers significantly better performance as compared with the conventional fixed relaying scheme as it makes the efficient use of available degrees of freedom for the information transmission.

In Fig. 8, we analyze the impact of spectrum sharing factor ξ on the performance of primary network by plotting the outage probability curves against ϱ. Hereby, we set $\alpha = 0.6$ and $\eta = 0.2$. From the plots, it can be observed that as ξ increases the performance of primary network improves (see the curves corresponding to $N = 1$ for improved relaying and $N = 2$ for fixed relaying). This is due to the fact that higher values of ξ allocate more power for the primary transmission and hence results in better performance.

In Fig. 9, we plot the outage probability curves of the secondary network against ϱ and assuming $\alpha = 0.5$ and $\eta = 0.8$. Herein, we compare the performance of three different scenarios viz., when SU is unsuccessful in decoding the PU's signal, when SU is successful in decoding the PU's signal, and for the proposed improved relaying. As shown in the curves, when SU is able to decode the PU's signal, the performance of secondary network gets better since the SU can remove the interference of primary's signal. It can be seen from the various curves that the outage performance degrades with the increase in ξ, which is in contrast to the performance of primary network. As such, this is due to low power allocation towards the secondary transmission at high ξ. Note that the increase in ξ has nominal effect on the performance of the improved relaying scheme.

In Fig. 10, we plot the outage probability curves of secondary network against ϱ for different values of energy conversion efficiency η and by setting $\alpha = 0.5$ and $\xi = 0.7$. Apparently, the performance of secondary network improves with an increase in η which is associated with the fact that higher η implies more harvested power at the cooperative secondary node and thus better performance.

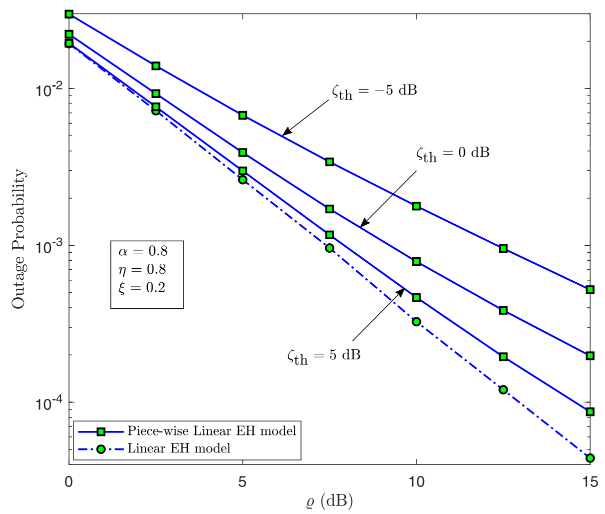

FIGURE 11. Performance comparison between linear and piece-wise linear EH models for primary network.

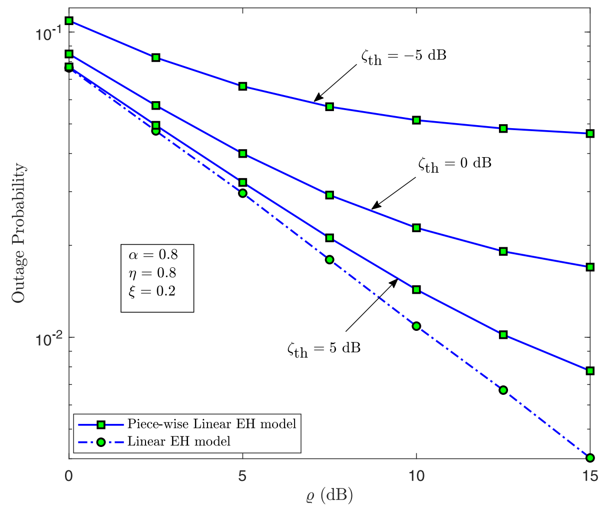

FIGURE 12. Performance comparison between linear and piece-wise linear EH models for secondary network.

In Fig. 11 and Fig. 12, we demonstrate a comparison between the conventional linear model and considered piece-wise linear model of EH for primary and secondary networks, respectively. Here, we obtain the numerical results for the linear EH model using the simulations. It can be observed from the curves that the performance gap between the two models becomes wider with an increase in the ϱ, showing that the linear model is accurate only in the low power regions. In addition, it can also be witnessed that as the saturation threshold ζ_{th} increases, the performance of piece-wise linear model converges towards the performance of linear model. For instance, see the curves corresponding to $\zeta_{th} = -5$ dB and $\zeta_{th} = 5$ dB. Though impractical, the conventional model of EH gives a better performance. From this observation, it can be concluded that the conventional linear model of EH can provide very misleading results for the deployment of future networks.

In Fig. 13 and Fig. 14, we illustrate the impact of time-splitting factor α on the performance of primary and secondary networks, respectively. It is evident from the corresponding curves that, when α increases, the outage performance improves up to a certain point and thereafter starts to deteriorate. For the primary network, the optimal α for the improved relaying is higher than the fixed relaying. For the secondary network, the optimal value of α is relatively higher which is owing to the fact that secondary transmission starts only after harvesting the energy from the primary transmitter, with the harvested energy being directly related with α.

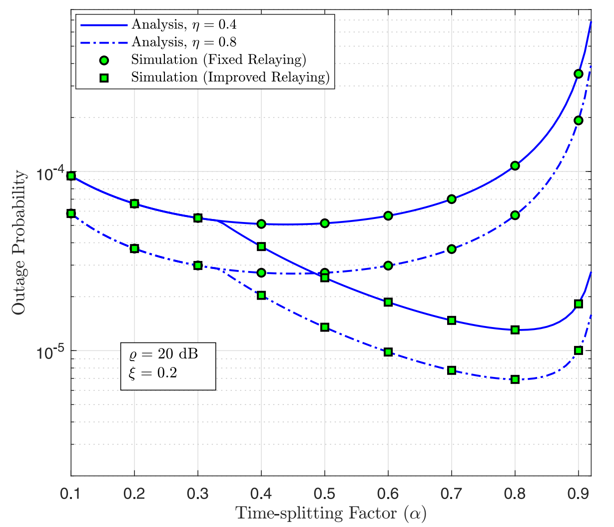

FIGURE 13. Outage probability of primary network against α.

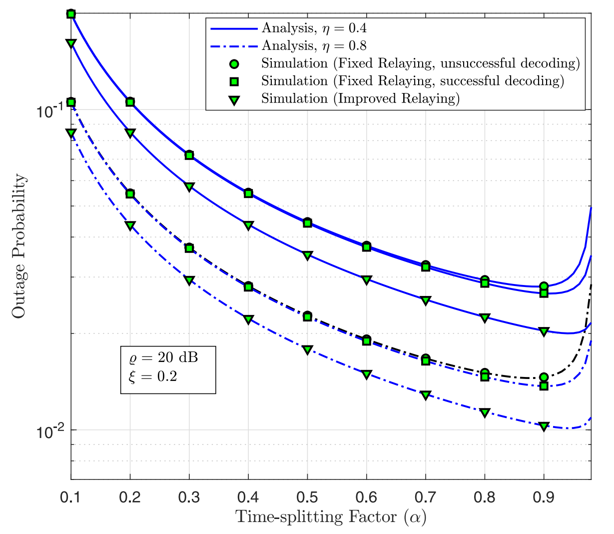

FIGURE 14. Outage probability of secondary network against α.

Finally, from Figs. 5-14, note that all the analytical curves are in perfect agreement with the simulation results. In addition, the asymptotic curves also follow the analytical curves at high ϱ. These observations validate the accuracy of all the derived expressions.

VIII. CONCLUSION

In this article, we have examined the outage performance of a piece-wise linear EHMOSS system over Rayleigh fading channels. Specifically, an energy-constrained SU node has been assumed to cooperate with the PU's transmission while simultaneously transmitting its own information. We have considered a piece-wise linear EH model which relies on the TS-based receiver architecture. We have shown that the spectrum sharing factor should be judiciously chosen to avoid the outage of secondary network. In addition, it has also been reported that the direct link can be quite useful for significantly enhancing the performance of primary network. Furthermore, we have proposed an improved relaying scheme which has been shown to substantially enhance the performance of both primary and secondary networks as compared to conventional fixed relaying. In particular, the proposed scheme has made the efficient use of available degrees of freedom to ameliorate the performance of primary network. On the other hand, when primary network did not invoke the cooperation, the secondary node got to utilize all the harvested power for its own information transmission which eventually enhanced the performance of secondary network considerably. We have also concluded that the conventional linear model of EH can provide very misleading results for the deployment of future networks.

APPENDIX A
PROOF OF LEMMA 1

Using (14), we can write $\mathcal{P}_{21}$ as

$$\begin{aligned}\mathcal{P}_{21} &= \Pr\left[\frac{\xi\varrho XY}{\xi Y + (1-\xi)\varrho XY + \frac{1-\alpha}{2\eta\alpha}} < \gamma_{\text{th}},\ \ P_c X \le \zeta_{\text{th}}\right]\\ &= \Pr\left[Y < \frac{\mathcal{A}}{\mathcal{B}X - \xi\gamma_{\text{th}}},\ \ X \le \frac{\zeta_{\text{th}}}{P_c}\right], \qquad (63)\end{aligned}$$

where $X = |h_{cs}|^2, Y = |h_{sp_n}|^2$ for notational simplicity. Further, based on the values of ξ, we can express (63) as

$$\mathcal{P}_{21} = \begin{cases} \int_{x=0}^{\frac{\zeta_{\text{th}}}{P_c}} f_X(x)dx, & \text{for } \gamma_{\text{th}} \ge \frac{\xi}{1-\xi},\\ \int_{x=0}^{\frac{\zeta_{\text{th}}}{P_c}} f_X(x)dx, & \text{for } \gamma_{\text{th}} < \frac{\xi}{1-\xi}\ \&\ \frac{\zeta_{\text{th}}}{P_c} \le \frac{\xi\gamma_{\text{th}}}{\mathcal{B}},\\ \Psi(\gamma_{\text{th}}), & \text{for } \gamma_{\text{th}} < \frac{\xi}{1-\xi}\ \&\ \frac{\zeta_{\text{th}}}{P_c} > \frac{\xi\gamma_{\text{th}}}{\mathcal{B}}, \end{cases} \qquad (64)$$

where $\Psi(\gamma_{\text{th}})$ can be derived as

$$\Psi(\gamma_{\text{th}}) = \underbrace{\int_{x=0}^{\frac{\xi\gamma_{\text{th}}}{\mathcal{B}}} f_X(x)dx}_{\mathcal{J}_1} + \underbrace{\int_{x=\frac{\xi\gamma_{\text{th}}}{\mathcal{B}}}^{\frac{\zeta_{\text{th}}}{P_c}} F_Y\left(\frac{\mathcal{A}}{\mathcal{B}x - \gamma_{\text{th}}\xi}\right) f_X(x)dx}_{\mathcal{J}_2}. \qquad (65)$$

Now $\mathcal{J}_1$ can be evaluated as $\mathcal{J}_1 = 1 - \exp(-\frac{\xi\gamma_{\text{th}}}{\mathcal{B}\Omega_{cs}})$. To evaluate $\mathcal{J}_2$, we perform the appropriate substitutions followed by some manipulations to obtain

$$\begin{aligned}\mathcal{J}_2 &= F_X\left(\frac{\zeta_{\text{th}}}{P_c}\right) - F_X\left(\frac{\xi\gamma_{\text{th}}}{\mathcal{B}}\right) - \frac{1}{\mathcal{B}\Omega_{cs}}\exp\left(-\frac{\xi\gamma_{\text{th}}}{\mathcal{B}\Omega_{cs}}\right)\\ &\times \int_{t=0}^{\frac{\mathcal{B}\zeta_{\text{th}}}{P_c} - \gamma_{\text{th}}\xi} \exp\left(-\frac{\mathcal{A}}{\Omega_{spt}} - \frac{t}{\mathcal{B}\Omega_{cs}}\right)dt. \qquad (66)\end{aligned}$$

To the best of the authors' knowledge, the integral form in (66) is intractable. Therefore, relying on the Maclaurin series expansion [47] of the term $\exp(-\frac{t}{\mathcal{B}\Omega_{cs}})$ and then solving the resultant integral with the aid of [33, eq. (3.381.6)], we can derive the analytical expression of $\Psi(\gamma_{\text{th}})$, after performing various algebric manipulations, as given in (30).

APPENDIX B
PROOF OF LEMMA 2

The outage probability of secondary network can be formulated, using (8), as

$$\begin{aligned}\mathcal{P}_{\text{out}}^{\text{Sec}}(\gamma_{\text{th}}) &= \Pr\left[\Lambda_{d,2} < \gamma_{\text{th}}\right]\\ &= \Pr\left[\frac{(1-\xi)\varrho P_{H,s}|h_{cs}|^2|h_{sd}|^2}{\xi\varrho P_{H,s}|h_{cs}|^2|h_{sd}|^2 + \xi P_{H,s}|h_{sd}|^2 + P_c|h_{cs}|^2} < \gamma_{\text{th}}\right].\end{aligned} \qquad (67)$$

By invoking $P_{H,s}$ from (1) in (67), we obtain

$$\begin{aligned}\mathcal{P}_{\text{out}}^{\text{Sec}}(\gamma_{\text{th}}) &= \underbrace{\Pr\left[\frac{(1-\xi)\varrho XZ}{\xi Z + \xi\varrho XZ + \frac{1-\alpha}{2\eta\alpha}} < \gamma_{\text{th}},\ \ X \le \frac{\zeta_{\text{th}}}{P_c}\right]}_{\mathcal{S}_1}\\ &+ \underbrace{\Pr\left[\frac{(1-\xi)\varrho XZ}{\xi Z + \xi\varrho XZ + \frac{1-\alpha}{2\eta\alpha\zeta_{\text{th}}}P_c X} < \gamma_{\text{th}},\ \ X > \frac{\zeta_{\text{th}}}{P_c}\right]}_{\mathcal{S}_2},\end{aligned} \qquad (68)$$

where $X = |h_{cs}|^2, Z = |h_{sd}|^2$ for notational simplicity. Hereby, $\mathcal{S}_1$ can be re-expressed as

$$\mathcal{S}_1 = \Pr\left[Z < \frac{\mathcal{A}}{\mathcal{C}X - \xi\gamma_{\text{th}}},\ \ X \le \frac{\zeta_{\text{th}}}{P_c}\right], \qquad (69)$$

with $\mathcal{C} = ((1-\xi) - \gamma_{\text{th}}\xi)\varrho$. Further, based on the limits of γ_{th}, (69) is obtained as given by (29) where $\Xi(\gamma_{\text{th}})$ can be evaluated as

$$\Xi(\gamma_{\text{th}}) = \int_{x=0}^{\frac{\xi\gamma_{\text{th}}}{\mathcal{C}}} f_X(x)dx + \int_{x=\frac{\xi\gamma_{\text{th}}}{\mathcal{C}}}^{\frac{\zeta_{\text{th}}}{P_c}} F_Z\left(\frac{\mathcal{A}}{\mathcal{C}x - \gamma_{\text{th}}\xi}\right) f_X(x)dx. \qquad (70)$$

After computing the involved integration in (70), one can obtain $\Xi(\gamma_{\text{th}})$ as given in (30). In a similar way, $\mathcal{S}_2$ can also be derived.

APPENDIX C
PROOF OF LEMMA 3

Using (38), the outage probability can be formulated as

$$\begin{aligned}\mathcal{P}_{\text{out},d}^{\text{Sec}}(\gamma_{\text{th}}) &= \Pr\left[\Lambda_{d,2}^{d} < \gamma_{\text{th}}\right]\\ &= \Pr\left[\frac{(1-\xi)\varrho P_{H,s}|h_{cs}|^2|h_{sd}|^2}{\xi P_{H,s}|h_{sd}|^2 + P_c|h_{cs}|^2} < \gamma_{\text{th}}\right]. \qquad (71)\end{aligned}$$

By substituting $P_{H,s}$ from (1) in (71), we obtain

$$\mathcal{P}_{\text{out},d}^{\text{Sec}}(\gamma_{\text{th}}) = \underbrace{\Pr\left[\frac{(1-\xi)\varrho XZ}{\xi Z + \frac{1-\alpha}{2\eta\alpha}} < \gamma_{\text{th}},\ \ X \le \frac{\zeta_{\text{th}}}{P_c}\right]}_{\mathcal{D}_1}$$

$$+ \underbrace{\Pr\left[\frac{(1-\xi)\varrho XZ}{\xi Z + \frac{1-\alpha}{2\eta\alpha\zeta_{\text{th}}} P_c X} < \gamma_{\text{th}},\ X > \frac{\zeta_{\text{th}}}{P_c}\right]}_{\mathcal{D}_2}. \tag{72}$$

Following the same lines of derivation as in Appendix B, one can arrive at $\mathcal{D}_1$ and $\mathcal{D}_2$ as given in (40) and (42), respectively.

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REFERENCES

[1] S. Solanki, P. K. Upadhyay, D. B. da Costa, H. Ding, and J. M. Moualeu, " Non-linear energy harvesting based cooperative spectrum sharing networks," in *Proc. Int. Symp. Wireless Commun. Syst. (ISWCS)*, Oulu, Finland, Aug. 2019, pp. 566–570.

[2] Y. Liu, Y. Zhang, R. Yu, and S. Xie, "Integrated energy and spectrum harvesting for 5G wireless communications," *IEEE Netw.*, vol. 29, no. 3, pp. 75–81, May/Jun. 2015.

[3] L. R. Varshney, "Transporting information and energy simultaneously," in *Proc. IEEE ISIT*, Toronto, ON, Canada, Jul. 2008, pp. 1612–1616.

[4] X. Zhou, R. Zhang, and C. K. Ho, "Wireless information and power transfer: Architecture design and rate-energy tradeoff," *IEEE Trans. Commun.*, vol. 61, no. 11, pp. 4754–4767, Nov. 2013.

[5] A. A. Nasir, X. Zhou, S. Durrani, and R. A. Kennedy, "Wireless-powered relays in cooperative communications: Time-switching relaying protocols and throughput analysis," *IEEE Trans. Commun.*, vol. 63, no. 5, pp. 1607–1622, May 2015.

[6] Y. Gu and S. Aïssa, "RF-based energy harvesting in decode-and-forward relaying systems: Ergodic and outage capacities," *IEEE Trans. Wireless Commun.*, vol. 14, no. 11, pp. 6425–6434, Nov. 2015.

[7] F. Benkhelifa, K. Tourki, and M.-S. Alouini, "Proactive spectrum sharing for SWIPT in MIMO cognitive radio systems using antenna switching technique," *IEEE Trans. Green Commun. Netw.*, vol. 1, no. 2, pp. 204–222, Jun. 2017.

[8] A. Goldsmith, S. A. Jafar, I. Maric, and S. Srinivasa, "Breaking spectrum gridlock with cognitive radios: An information theoretic perspective," *Proc. IEEE*, vol. 97, no. 5, pp. 894–914, May 2009.

[9] S. Leng and A. Yener, "Age of information minimization for an energy harvesting cognitive radio," *IEEE Trans. Cogn. Commun. Netw.*, vol. 5, no. 2, pp. 427–439, Jun. 2019.

[10] S. A. Mousavifar, Y. Liu, C. Leung, M. Elkashlan, and T. Q. Duong, " Wireless energy harvesting and spectrum sharing in cognitive radio," in *Proc. IEEE Veh. Technol. Conf. (VTC)*, Vancouver, BC, Canada, Sep. 2014, pp. 1–5.

[11] L. Sibomana, H.-J. Zepernick, and H. Tran, "Wireless information and power transfer in an underlay cognitive radio network," in *Proc. Int. Conf. Signal Process. Commun. Syst. (ICSPCS)*, Gold Coast, QLD, Australia, Dec. 2014, pp. 1–7.

[12] Y. Liu, S. A. Mousavifar, Y. Deng, C. Leung, and M. Elkashlan, "Wireless energy harvesting in a cognitive relay network," *IEEE Trans. Wireless Commun.*, vol. 15, no. 4, pp. 2498–2508, Apr. 2016.

[13] S. S. Kalamkar and A. Banerjee, "Interference-aided energy harvesting: Cognitive relaying with multiple primary transceivers," *IEEE Trans. Cogn. Commun. Netw.*, vol. 3, no. 3, pp. 313–327, Sep. 2017.

[14] K. Janghel and S. Prakriya, "Throughput of underlay cognitive energy harvesting relay networks with an improved time-switching protocol," *IEEE Trans. Cogn. Commun. Netw.*, vol. 4, no. 1, pp. 66–81, Mar. 2018.

[15] Z. Yan, S. Chen, X. Zhang, and H.-L. Liu, "Outage performance analysis of wireless energy harvesting relay-assisted random underlay cognitive networks," *IEEE Internet Things J.*, vol. 5, no. 4, pp. 2691–2699, Aug. 2018.

[16] Z. Ali, G. A. S. Sidhu, M. Waqas, L. Xing, and F. Gao, "A joint optimization framework for energy harvesting based cooperative CR networks," *IEEE Trans. Cogn. Commun. Netw.*, vol. 5, no. 2, pp. 452–462, Jun. 2019.

[17] X. Ding, Y. Zou, G. Zhang, X. Chen, X. Wang, and L. Hanzo, "The security-reliability tradeoff of multiuser scheduling aided energy harvesting cognitive radio networks," *IEEE Trans. Commun.*, vol. 67, no. 6, pp. 3890–3904, Jun. 2019.

[18] J. Ye, Z. Liu, H. Zhao, G. Pan, Q. Ni, and M.-S. Alouini, "Relay selections for cooperative underlay CR systems with energy harvesting," *IEEE Trans. Cogn. Commun. Netw.*, vol. 5, no. 2, pp. 358–369, Jun. 2019.

[19] Y. Han, A. Pandharipande, and S. H. Ting, "Cooperative decode-and-forward relaying for secondary spectrum access," *IEEE Trans. Wireless Commun.*, vol. 8, no. 10, pp. 4945–4950, Oct. 2009.

[20] S. Lee and R. Zhang, "Cognitive wireless powered network: Spectrum sharing models and throughput maximization," *IEEE Trans. Cogn. Commun. Netw.*, vol. 1, no. 3, pp. 335–346, Sep. 2015.

[21] G. Zheng, Z. Ho, E. A. Jorswieck, and B. Ottersten, "Information and energy cooperation in cognitive radio networks," *IEEE Trans. Signal Process.*, vol. 62, no. 9, pp. 2290–2303, May 2014.

[22] S. Yin, E. Zhang, Z. Qu, L. Yin, and S. Li, "Optimal cooperation strategy in cognitive radio systems with energy harvesting," *IEEE Trans. Wireless Commun.*, vol. 13, no. 9, pp. 4693–4707, Sep. 2014.

[23] P. M. Quang, T. T. Duy, and V. N. Q. Bao, "Energy harvesting-based spectrum access model in overlay cognitive radio," in *Proc. Int. Conf. Adv. Technol. Commun.*, Ho Chi Minh City, Vietnam, Oct. 2015, pp. 231–236.

[24] C. Zhai, J. Liu, and L. Zheng, "Cooperative spectrum sharing with wireless energy harvesting in cognitive radio networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 7, pp. 5303–5316, Jul. 2016.

[25] S. Kalamkar, J. P. Jeyaraj, A. Banerjee, and K. Rajawat, "Resource allocation and fairness in wireless powered cooperative cognitive radio networks," *IEEE Trans. Commun.*, vol. 64, no. 8, pp. 3246–3261, Aug. 2016.

[26] A. Banerjee, A. Paul, and S. P. Maity, "Joint power allocation and route selection for outage minimization in multihop cognitive radio networks with energy harvesting," *IEEE Trans. Cogn. Commun. Netw.*, vol. 4, no. 1, pp. 82–92, Mar. 2018.

[27] M. Li, H. Yin, Y. Huang, Y. Wang, and R. Yu, "Physical layer security in overlay cognitive radio networks with energy harvesting," *IEEE Trans. Veh. Technol.*, vol. 67, no. 11, pp. 11274–11279, Nov. 2018.

[28] J. Zhang, Y. Lu, and Y. Huang, "Simultaneous wireless information and power transfer for dynamic cooperative spectrum sharing networks," *IEEE Access*, vol. 7, pp. 823–834, Jan. 2019.

[29] T. Le, K. Mayaram, and T. Fiez, "Efficient far-field radio frequency energy harvesting for passively powered sensor networks," *IEEE J. Solid-State Circuits*, vol. 43, no. 5, pp. 1287–1302, May 2008.

[30] E. Boshkovska, D. W. K. Ng, N. Zlatanov, and R. Schober, "Practical non-linear energy harvesting model and resource allocation for SWIPT systems," *IEEE Commun. Lett.*, vol. 19, no. 12, pp. 2082–2085, Dec. 2015.

[31] W. P. M. H. Heemels, M. K. Camlibel, and J. M. Schumacher, "On the dynamic analysis of piecewise-linear networks," *IEEE Trans. Circuits Syst. I, Fundam. Theory Appl.*, vol. 49, no. 3, pp. 315–327, Mar. 2002.

[32] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3062–3080, Dec. 2004.

[33] I. S. Gradshteyn and I. M. Ryzhik, *Tables of Integrals, Series and Products*, 7th ed., New York, NY, USA: Academic, 2007.

[34] C. S. Patel and G. L. Stüber, "Channel estimation for amplify and forward relay based cooperation diversity systems," *IEEE Trans. Wireless Commun.*, vol. 6, no. 6, pp. 2348–2356, Jun. 2007.

[35] S. Solanki, P. K. Upadhyay, D. B. da Costa, P. S. Bithas, A. G. Kanatas, and U. S. Dias, "Joint impact of RF hardware impairments and channel estimation errors in spectrum sharing multiple-relay networks," *IEEE Trans. Commun.*, vol. 66, no. 9, pp. 3809–3824, Sep. 2018.

[36] B. Clerckx, E. Bayguzina, D. Yates, and P. D. Mitcheson, "Waveform optimization for wireless power transfer with nonlinear energy harvester modeling," in *Proc. Int. Symp. Wireless Commun. Syst. (ISWCS)*, Brussels, Belgium, Aug. 2015, pp. 276–280.

[37] L. Shi, L. Zhao, and K. Liang, "Power allocation for wireless powered MIMO transmissions with non-linear RF energy conversion models," *China Commun.*, vol. 14, no. 2, pp. 57–64, Feb. 2017.

[38] Y. Dong, M. J. Hossain, and J. Cheng, "Performance of wireless powered amplify and forward relaying over Nakagami-*m* fading channels with nonlinear energy harvester," *IEEE Commun. Lett.*, vol. 20, no. 4, pp. 672–675, Apr. 2016.

[39] J. Zhang and G. Pan, "Outage analysis of wireless-powered relaying MIMO systems with non-linear energy harvesters and imperfect CSI," *IEEE Access*, vol. 4, pp. 7046–7053, Oct. 2016.

[40] Y. Huang, T. Q. Duong, J. Wang, and P. Zhang, "Performance of multi-antenna wireless-powered communications with nonlinear energy harvester," in *Proc. IEEE Veh. Technol. Conf. (VTC)*, Toronto, ON, Canada, Sep. 2017, pp. 1–6.

[41] S. Pejoski, Z. H.-Velkov, and R. Schober, "Optimal power and time allocation for WPCNs with piece-wise linear EH model," *IEEE Wireless Commun. Lett.*, vol. 7, no. 3, pp. 364–367, Jun. 2018.
[42] X. Lei, L. Fan, D. S. Michalopoulos, P. Fan, and R. Q. Hu, "Outage probability of TDBC protocol in multiuser two-way relay systems with Nakagami- m fading," *IEEE Commun. Lett.*, vol. 17, no. 3, pp. 487–490, Mar. 2013.
[43] A. Bletsas, A. Khisti, D. P. Reed, and A. Lippman, "A simple cooperative diversity method based on network path selection," *IEEE J. Sel. Areas Commun.*, vol. 24, no. 3, pp. 659–672, Mar. 2006.
[44] A. Papoulis and S. U. Pillai, *Probability, Random Variables, and Stochastic Processes*, Boston, MA, USA: Tata McGraw-Hill Educ., 2002.
[45] H. Ding, J. Ge, D. B. da Costa, and Z. Jiang, "A new efficient low-complexity scheme for multi-source multi-relay cooperative networks," *IEEE Trans. Veh. Technol.*, vol. 60, no. 2, pp. 716–722, Feb. 2011.
[46] S. Solanki, P. K. Sharma, and P. K. Upadhyay, "Adaptive link utilization in two-way spectrum sharing relay systems under average interference-constraints," *IEEE Syst. J.*, vol. 12, no. 4, pp. 3461–3472, Dec. 2018.
[47] N. T. Do, D. B. da Costa, T. Q. Duong, V. N. Q. Bao, and B. An, "Exploiting direct links in multiuser multirelay SWIPT cooperative networks with opportunistic scheduling," *IEEE Trans. Wireless Commun.*, vol. 16, no. 8, pp. 5410–5427, Aug. 2017.

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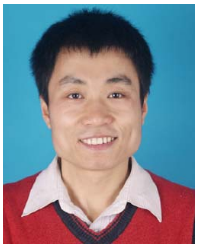

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