Joint Relay Selection, Full-Duplex and Device-to-Device Transmission in Wireless Powered NOMA Networks

HUU-PHUC DANG, MINH-SANG VAN NGUYEN, DINH-THUAN DO, HONG-LIEN PHAM, BASSANT SELIM, AND GEORGES KADDOUM

ABSTRACT
This paper investigates non-orthogonal multiple access (NOMA), cooperative relaying, and energy harvesting to support device-to-device (D2D) transmission. In particular, we deploy multiple relay nodes and a cell-center D2D device which can operate in full-duplex (FD) or half-duplex (HD) mode to communicate with a cell-edge D2D device. In this context, there are two possible signal transmission paths from the base station (BS) to the far D2D user either through multiple decode-and-forward (DF) relay nodes or through a near D2D user. Consequently, we propose three schemes to support D2D-NOMA systems, namely non-energy harvesting relaying (Non-EHR), energy harvesting relaying (EHR) and quantize-map-forward relaying (QMFR) schemes. For each of the proposed schemes, closed-form expressions of the outage probabilities of both D2D users are derived. Extensive Monte-Carlo simulation results are provided to validate the derived analytical expressions. The study results show that the proposed schemes can improve the outage performance compared to conventional orthogonal multiple access (OMA) schemes. Moreover, it is shown that the Non-EHR scheme achieves the best outage performance among the three considered schemes.

INDEX TERMS
Device-to-device, full-duplex, non-orthogonal multiple access, relay selection.

I. INTRODUCTION
The emerging non-orthogonal multiple access (NOMA) scheme is attracting considerable attention due to its capacity to support massive connectivity in numerous applications including multimedia applications and the Internet of Things (IoT) [1]. It was demonstrated that NOMA is superior to conventional orthogonal multiple access (OMA) schemes in terms of system throughput [2]. The main advantage is that NOMA achieves greater overall throughput than OMA methods in both uplink and downlink. Moreover, NOMA can be employed in relay networks to improve coverage [3]. In contrast to the traditional waterfilling scheme, to ensure user fairness, NOMA allocates more power to the clients with weaker channel conditions [4]. In addition, NOMA also provide higher reliability and achieves higher fairness among users thanks to combining with relaying techniques schemes [5]–[7]. Since NOMA systems benefit from low latency, improved system throughput, and fairness, NOMA has become very attractive where it is considered a strong candidate with the famous Orthogonal Frequency Division Multiple-Access (OFDMA) to 5G wireless network [8]. Therefore, the authors in [9] focused on relay selection techniques based on the NOMA principle. The research results demonstrated that joint cooperative relaying and NOMA can incredibly enhance the system’s performance compared to traditional OMA. Also, considering relay selection in NOMA systems, the research work in [10] has achieved interesting results in finding asymptotic and approximate expressions to the average sum rate in Amplify-and-Forward (AF) mode. In addition, another relay selection method based on partial channel state information (CSI) was proposed in [11]. Besides, assuming different NOMA relaying modes such as AF [12] and Decode-and-Forward (DF) [13], the authors...
in [14] introduced a relaying protocol called quantize-map-forward (QMF), adopted in NOMA to forward information. However, the above studies mostly use half-duplex (HD) technology, which is characterized by a limited spectrum efficiency. On the other hand, FD technology can be used to increase spectral efficiency in cellular networks [15]–[18].

To meet the requirements of explosive data traffic in 5G networks, ultra-dense heterogeneous networks are considered as a prominent technique [19]. In heterogeneous networks, device-to-device (D2D) communications is proposed as a promising solution for mobile data offloading in wireless networks, for enhancing the spectral efficiency of cellular networks, and for increasing the mobility without the help of base stations [20]. Moreover, D2D can be applied as an effective solution to support neighborhood based services such as social networking and data sharing when the devices are in close vicinity [20]. Although D2D communication has many benefits in cellular networks, the D2D users also interfere with each other. Therefore, interference management and energy efficiency are critical in D2D networks in order to minimize interference and increase the battery lifetime of the user equipment (UE) [21].

The combinations of D2D and NOMA yields promising outcomes that have been shown in [22] where the authors proposed a new approach based on combining the NOMA-based D2D users into groups that can share the same subchannels. In this context, the near user device can act as a relay node which assists the base station (BS) to transmit information to the far device [23]. In a similar study [24], the authors maximized the total rate of the D2D-NOMA system by proposing a joint sub-channel and power allocation scheme that satisfies the signal-to-interference-plus-noise ratio (SINR) requirements of all D2D users in the network. Furthermore, the resource allocation problem, based on joint subchannel and user pairing, and power control in NOMA D2D networks has been addressed in [25].

It is noted that the battery lifetime budget of users limits the system throughput performance in D2D underlaid cellular networks. Fortunately, in order to prolong the network lifetime, D2D underlaid cellular networks can benefit from energy harvesting [26]–[30]. The authors in [29] studied NOMA-based cellular networks allowing the energy harvesting-powered D2D devices to share the downlink resources of the cellular network. The energy harvesting constraints on the D2D links were investigated and the average energy efficiency of D2D links was maximized in [30].

A. MOTIVATION AND OUR CONTRIBUTIONS

Despite the reported advantages of NOMA and D2D schemes in recent works, several open problems need to be addressed in terms of energy efficiency, improving performance of far device, FD transmission, and transmit antenna selection (TAS). In this context, the authors in [31] presented the optimal performance of the D2D communication by jointly optimizing the power allocation and the resource block assignment. They introduced a distributed decision making (DDM) framework for NOMA systems by considering the successive interference cancellation (SIC) decoding order related to the NOMA-based cellular users. In [32], to minimize interference in hybrid D2D and cellular networks, a NOMA-assisted coordinated direct and relay transmission was proposed to fully achieve the inherent characterization of NOMA. Their proposed system further provided a potential scheme for hybrid networks to enhance the spectral efficiency and cell coverage. Motivated by the results in [23], [32], to improve the performance of D2D users, this paper studies three schemes for relay selection assisted D2D-NOMA systems by relying on transmit antenna selection and FD transmission. The main contributions of this paper are summarized as follows:

1) Different from [23], we propose three new D2D-NOMA communication network models. In addition, the combination with relay selection, TAS and energy harvesting to enhance performance of the cell-edge device and then spectral efficiency is also improved.

2) We derive exact expressions for the outage probability and system throughput of the three proposed schemes. The outage performance of the considered system in Scheme 1 is confirmed as the best case among three cases.

3) The derived expressions are validated via Monte Carlo simulations to corroborate the exactness of the analysis. Several important parameters that affect the system’s performance are considered and outage performance comparisons of the three schemes are presented to elaborate on their respective performances.

B. ORGANIZATION

The rest of this paper is structured as follows. The system model and the related assumptions of the three schemes are detailed in Section 2. Next, the outage probability analysis of the three schemes is presented in Section 3. Based on the analytical results of the outage probability, the system’s throughput is analyzed in section 4. Simulation results are presented in Section 5 while Section 6 concludes this work.

II. SYSTEM MODEL

We consider a downlink cellular system, depicted in Fig. 1, consisting of a base station (BS), D2D link containing the cell-center device $D_1$ and the cell-center device $D_2$. To robust signal transmission to the cell-edge device $D_2$, it is required $K$ decode-and-forward (DF) relaying nodes. In this NOMA scenario, the BS is equipped with $N$ antennas and is able to directly communicate with the cell-center device $D_1$ while the cell-edge device $D_2$ is served by $D_1$ and the selected relay. We assume that there is no direct link from BS to $D_2$ due to deep fading or obstacles. In this context, it is assumed that the FD-assisted relays are equipped with a pair of antennas, one for transmitting while the other is serving the purpose of receiving. Meanwhile, to enhance the transmission quality, only the best antenna at the BS and the best relay are selected.
to transmit the signal dedicated to $D_2$. In addition, $D_1$ also acts as a relay node that supports D2D transmission of signals from the BS to $D_2$ [23]. It is worth noting that $D_1$ and the relays are assumed to be able to switch the operating state from FD to HD mode and vice versa. On the other hand, the relays only serve for data transfer from the BS to $D_2$ and they are not assigned to serve $D_1$. In this scenario, let $g_{1,n}, g_{n,k}$ ($k = 1, 2, \ldots, K$ and $n = 1, 2, \ldots, N$), $h_1$, and $h_2$ denote the Rayleigh fading channel coefficients of the BS to $D_1$, BS to $R_k$, $D_1$ to $D_2$, and selected Relay $\rightarrow D_2$, respectively. Consequently, the channel gains $|g_{1,n}|^2$, $|g_{n,k}|^2$, $|h_1|^2$, and $|h_2|^2$ are independent exponential random variables with parameters $\lambda_{g_{1,n}}, \lambda_{g_{n,k}}, \lambda_{h_1}$, and $\lambda_{h_2}$, respectively. Moreover, since $D_1$ and the relays are equipped with two antennas and they can work in FD mode, we denote $h_1 \sim CN(0, \lambda_{h_1})$ and $h_2 \sim CN(0, \lambda_{h_2})$ are the Rayleigh distributed feedback channel coefficients of the loop self-interference (SI) at $D_1$ and $R_k$, respectively.\footnote{Similar with system model reported in [23], we focus on the performance improvement of the cell-edge device in D2D-NOMA systems. It is assumed that sophisticated channel estimation algorithms have been acquired with sufficient training information to obtain perfect CSI. Regarding FD, loop back signals still exist in the receiver due to imperfect interference cancellation.}

According to the principle of NOMA, the BS sends the superimposed NOMA signal $x^{NOMA}_S = \sqrt{a_1}P_Sx_1 + \sqrt{a_2}P_Sx_2$ to the $k^{th}$ relay and $D_1$, where $x_1$ and $x_2$ are the messages intended for $D_1$ and $D_2$, respectively. Here, $a_1, a_2$ ($i = 1, 2$) are the power allocation coefficients of the two devices $D_1, D_2$ respectively and these terms satisfying conditions, i.e. $a_2 > a_1 > 0$ and $a_1 + a_2 = 1$. Moreover, $P_S, P_R$, and $P_1$ are the transmission powers at the BS, the relays, and $D_1$, respectively. In this paper, we also denote the additive white Gaussian noise (AWGN) at the relay, devices in the network by $w_j \sim CN(0, \sigma_j^2)$, where $j = 1, \ldots, 4$.

In the following subsections, we consider three possible scenarios for the proposed D2D NOMA scheme where $D_1$ can operate without energy harvesting (Non-EHR), with energy harvesting (EHR), and by applying the quantize-map-forward relaying (QMFR) protocol.

### A. SCHEME 1: NON-ENERGY HARVESTING RELAYING

In this situation, $D_1$ does not harvest energy from the BS. In this context, from its $N$ antennas, the BS will select the best channel to transmit the signal to device $D_1$ and the $K$ relays. For the best link from BS $\rightarrow D_1$ and BS $\rightarrow R_k$, the best antenna of BS can be selected by the following criterion [34]

$$n^* = \arg \max_{n=1,\ldots,N} (|g_{1,n}|^2),$$

where $x = \{(1, n)\ or \ (n, k)\}$.

In the Non-EHR scheme, the received signal at $D_1$ is given by

$$y_{SD_1}^{NOMA} = g_{1,n}x_{S}^{NOMA} + w_1$$

$$= g_{1,n}\left(\sqrt{a_1}P_Sx_1 + \sqrt{a_2}P_Sx_2\right)$$

$$+ h_{D1}\sqrt{\omega P_1}x_{D1} + w_1,$$

where $x_{D1}$ denotes the loop interference signal of $D_1$, $\omega$ represents the FD/HD operation factor to indicate FD or HD activated at $D_1$ and $R_k$, i.e., $\omega = 1$ and $\omega = 0$ correspond to the FD and HD mode, respectively. Likewise, the received signal at the $k^{th}$ relay is given by

$$y_{SRKD}^{NOMA} = g_{n,k}x_{S}^{NOMA} + w_2$$

$$= g_{n,k}\left(\sqrt{a_1}P_Sx_1 + \sqrt{a_2}P_Sx_2\right)$$

$$+ h_{Rk}\sqrt{\omega P_R}x_r + w_2,$$

where $x_r$ denotes the loop interference signal of relay $R_k$.

In the second hop, the best path among the relays and $D_1$ is selected to forward the message to $D_2$. If the best path corresponds to a relay, $R_k$ decodes the received signal from the BS and forwards the message with power $P_R$ to $D_2$. The received signal at $D_2$ is expressed by

$$y_{SD_2}^{NOMA} = h_2\sqrt{P}x_{D2} + w_3.$$  \hspace{1cm} (4)

Regarding D2D link, $D_1$ forwards $x_2$ to $D_2$. Thus, the received signal at $D_2$ is expressed as

$$y_{D12}^{NOMA} = h_1\sqrt{P}x_{D2} + w_4.$$  \hspace{1cm} (5)

Precisely, after receiving the signal from BS, $D_1$ performs SIC to decode his message, i.e., it decodes $x_2$, subtracts it from the received signal and then decodes its own message $x_1$. Thus, the instantaneous signal to interference plus noise ratio at $D_1$ to decode $x_2$ is given as

$$y_{SD1-2}^{NOMA} = \frac{a_2P_S|g_{1,n}|^2}{a_1P_S|g_{1,n}|^2 + \omega P_1|h_{D1}|^2 + \sigma_0^2}$$

$$= \frac{a_2\rho|g_{1,n}|^2}{a_1\rho|g_{1,n}|^2 + \omega \rho|h_{D1}|^2 + 1},$$ \hspace{1cm} (6)
where $\rho = \frac{P_h}{\sigma^2_0}$ is the transmit signal-to-noise ratio (SNR). Without loss of generality, it is assumed that $P_S, P_R,$ and $P_1$ are the normalized transmission power at the BS, relays, and $D_1$, respectively. Assuming perfect SIC, the instantaneous SINR for decoding $x_1$ at $D_1$ is given as

$$\gamma_{SD1}^{\text{NOMA}} = \frac{a_1|\rho g_1|^2}{\omega |h_{D1}|^2 + 1}.$$  

(7)

Thus, if the $D_1 \rightarrow D_2$ link is stronger than the $R_k \rightarrow D_2$ link, $D_2$ will receive its signal $x_2$ from $D_1$. In this case, the received SINR at $D_2$ is given by

$$\gamma_{D2,x2}^{\text{NOMA}} = \frac{P_1|h_1|^2}{\sigma^2_0} = \rho |h_1|^2.$$  

(8)

Meanwhile, the instantaneous SINR at relay $R_k$ for detecting $x_2$ is evaluated as

$$\gamma_{SRK,x2}^{\text{NOMA}} = \frac{a_2P_S|g_{n',k}|^2}{a_1P_S|g_{n',k}|^2 + \omega P_R|h_{Rk}|^2 + \sigma^2_0} = \frac{a_2|\rho g_{n',k}|^2}{a_1|\rho g_{n',k}|^2 + \omega |h_{Rk}|^2 + 1}.$$  

(9)

Therefore, considering the link $R_k \rightarrow D_2$, the instantaneous SINR at $D_2$ is given by

$$\gamma_{RKD2,x2}^{\text{NOMA}} = \frac{P_R|h_2|^2}{\sigma^2_0} = \rho |h_2|^2.$$  

(10)

Regarding relay link, if the signal is transmitted from the BS to $D_2$ with the help of relay nodes, the best relay node is selected by the following criterion

$$k^* = \arg \max_{k=1,\ldots,K} \min \left( \gamma_{SRK,x2}^{\text{NOMA}}, \gamma_{RKD2,x2}^{\text{NOMA}} \right).$$  

(11)

In addition, the instantaneous SINR at relay $R_k$ for detecting $x_2$ is evaluated as

$$\gamma_{SRK,x2}^{\text{NOMA}} = \frac{a_2P_S|g_{n',k}|^2}{a_1P_S|g_{n',k}|^2 + \omega P_R|h_{Rk}|^2 + \sigma^2_0} = \frac{a_2|\rho g_{n',k}|^2}{a_1|\rho g_{n',k}|^2 + \omega |h_{Rk}|^2 + 1}.$$  

(12)

Therefore, considering the link $R_k \rightarrow D_2$, the instantaneous SINR at $D_2$ is given by

$$\gamma_{RKD2,x2}^{\text{NOMA}} = \frac{P_R|h_2|^2}{\sigma^2_0} = \rho |h_2|^2.$$  

(13)

$$\gamma_{D2}^{\text{NOMA}} = \max \left( \min \left( \gamma_{SD1 \rightarrow 2}^{\text{NOMA}}, \gamma_{D2,x2}^{\text{NOMA}} \right) \right).$$  

(14)

**B. SCHEME 2: ENERGY HARVESTING RELAYING (EHR)**

In this scheme, $D_1$ harvests energy from the BS in the first phase and uses such energy to transmit the signal to $D_2$ in the second phase. We assume that the energy obtained from the noise is very small and it can be ignored. Therefore, according to the power splitting protocol (PS) [33] for energy harvesting, the received signal at $D_1$ in the first phase is expressed as

$$\gamma_{SD1 \rightarrow 2}^{\text{NOMA-EH}} = \sqrt{(1 - \beta)g_1} \left( \sqrt{a_1P_Sx_1} + \sqrt{a_2P_Sx_2} \right) + h_{D1} \sqrt{\omega P_{1SD1} + w_1},$$  

where $\beta \in (0, 1)$ is the power splitting ratio. Therefore, the SINR at $D_1$ to decode $x_2$ is given by

$$\gamma_{SD1 \rightarrow 2}^{\text{NOMA-EH}} = \frac{(1 - \beta) a_2 \rho |g_{1,n'}|^2}{(1 - \beta) a_1 \rho |g_{1,n'}|^2 + \omega |h_{D1}|^2 + 1}.$$  

(15)

Assuming perfect SIC, the SINR for decoding $x_1$ at $D_1$ is given by

$$\gamma_{SD1}^{\text{NOMA-EH}} = \frac{(1 - \beta) a_1 \rho |g_{1,n'}|^2}{\omega |h_{D1}|^2 + 1}.$$  

(16)

Applying the PS protocol, the harvested energy is obtained as

$$E = \frac{T}{2} \eta \beta \left( P_s |g_{1,n'}|^2 + P_1 |h_{D1}|^2 \right),$$  

where $0 < \eta < 1$ is the energy conversion coefficient and $T$ is the block time. Then, the transmit power $\frac{T}{\eta} \beta$ at $D_1$ can be expressed as

$$P_1 = \frac{\eta \beta P_s |g_{1,n'}|^2}{1 - \eta \beta |h_{D1}|^2}.$$  

(17)

It is noted that the condition $|h_{D1}|^2 < \frac{1}{\eta \beta}$ must be satisfied. Hence, the SINR for $D_2$ to detect $x_2$ is given by

$$\gamma_{DK2,x2}^{\text{NOMA-EH}} = \frac{\eta \beta \rho |g_{1,n'}|^2 |h_1|^2}{1 - \eta \beta |h_{D1}|^2}.$$  

(18)

It is noted that the criterion for selecting the best antenna at the BS and the relays in this case is the same as in Scheme 1, i.e., the expressions in (1) and (11), respectively.

**C. SCHEME 3 (QMFR)**

In contrast to Scheme 1 and Scheme 2, $D_1$ applies the QMFR protocol [19] to decode its own information and then subtracts it from the superposed signal in the first phase. In this case, the SINR at $D_1$ to decode $x_1$ in the case of without energy harvesting at $D_1$ can be expressed as

$$\gamma_{SD1}^{\text{QMFR}} = \frac{a_1 \rho |g_{1,n'}|^2}{a_2 \rho |g_{1,n'}|^2 + \omega |h_{D1}|^2 + 1}.$$  

(19)

Following the cancellation of $x_1$, the signal intended for $D_2$ is decoded and re-transmitted to $D_2$ via $D_1$. In this case,
the SINR at $D_1$ to detect $x_2$ can be expressed as

$$\gamma_{SD1,x_2} = \frac{a_2 \rho |g_{1,2}^\ast|^2}{\omega \rho |h_{D1}|^2 + 1}. \quad (22)$$

For the case of energy harvesting at $D_1$, the SINR at $D_1$ for decoding $x_1$ is calculated as

$$\gamma_{SD1,x_1} = \frac{(1 - \beta) a_1 \rho |g_{1,1}^\ast|^2}{(1 - \beta) a_2 \rho |g_{1,2}^\ast|^2 + \omega \rho |h_{D1}|^2 + 1}, \quad (23)$$

and the SINR at $D_1$ to detect $x_2$ can be expressed as

$$\gamma_{SD1,x_2} = \frac{(1 - \beta) a_2 \rho |g_{1,2}^\ast|^2}{(1 - \beta) a_2 \rho |g_{1,2}^\ast|^2 + \omega \rho |h_{D1}|^2 + 1}. \quad (24)$$

Similarly, the relays employ the QMFR protocol to decode $x_1$ and $x_2$. Hence, the instantaneous SINR at $R_k$ for detecting $x_1$ and $x_2$ can be calculated as

$$\gamma_{SRK,x_1} = \frac{a_1 \rho |g_{n,k}^\ast|^2}{a_2 \rho |g_{n,k}^\ast|^2 + \omega \rho |h_k|^2 + 1}, \quad (25)$$

and

$$\gamma_{SRK,x_2} = \frac{a_2 \rho |g_{n,k}^\ast|^2}{\omega \rho |h_k|^2 + 1}. \quad (26)$$

respectively.

Finally, in this scheme, the best relay node is also selected by the following criterion

$$k_{QMF}^* = \arg \max_{k=1,\ldots,K} \left( \gamma_{QMF}^{SRK,x_1}, \gamma_{QMF}^{SRK,x_2}, \gamma_{QMF}^{NOMA} \right). \quad (27)$$

### III. OUTAGE PROBABILITY ANALYSIS

In this section, we investigate the outage probability of $D_1$ and $D_2$ considering the aforementioned schemes.

#### A. SCHEME 1

1) OUTAGE PROBABILITY OF $D_1$

In this case, according to the principle of NOMA, an outage event at $D_1$ will occur when $D_1$ cannot detect $x_1$ successfully. Therefore, the outage probability of $D_1$ can be expressed as

$$OP_{1-NOMA}^F = 1 - \Pr \left( \gamma_{SD1,x_1} \geq \epsilon_1^F, \gamma_{SD1,x_2} \geq \epsilon_2^F \right), \quad (28)$$

where $\omega = 1$, $\epsilon_1^F = 2R_1 - 1$ is the SNR threshold, with $R_1$ being the target rate of $D_1$, while $\epsilon_2^F = 2R_2 - 1$, $R_2$ is the target rate of $D_2$.

**Theorem 1:** The outage probability of $D_1$ in Scheme 1 is obtained as

$$OP_{1-NOMA}^F = 1 - \sum_{n=1}^{N} \left( \frac{N}{n} \right) (-1)^{n-1} \frac{\lambda_{g,1,n}}{\omega \rho \lambda_1 \lambda_{hD1} + \lambda_{g,1,n}} \exp \left( -\frac{n \psi_1}{\lambda_{g,1,n}} \right). \quad (29)$$

which is valid for $\epsilon_2 > \epsilon_1^F a_1$ and $\psi_1 = \max \left( \frac{\epsilon_2^F}{a_2 \rho + \epsilon_1^F a_1 \rho}, \frac{\epsilon_2^F}{a_2 \rho} \right)$.

**Proof:** By substituting (6) and (7) into (28), the outage probability of $D_1$ is obtained as

$$OP_{1-NOMA}^F = 1 - \Pr \left( |g_{1,1}^\ast|^2 \geq (a \rho |h_{D1}|^2 + 1) \right) \psi_1 = 1 - \int_0^\infty \left( 1 - F_{|g_{1,1}^\ast|^2}(\omega \rho x + 1) \right) f_{|h_{D1}|^2}(x) dx. \quad (30)$$

According to [34], the cumulative distribution functions (CDFs) and the probability density functions (PDFs) of the random variables $|g_{1,1}^\ast|^2$ and $|g_{n,k}^\ast|^2$ are given by

$$F_{|g_{1,1}^\ast|^2}(x) = 1 - \sum_{n=1}^{N} \left( \frac{N}{n} \right) (-1)^{n-1} \frac{n x}{\lambda_x}. \quad (31)$$

and

$$f_{|g_{1,1}^\ast|^2}(x) = \sum_{n=1}^{N} \left( \frac{N}{n} \right) (-1)^{n-1} \frac{n x}{\lambda_x}. \quad (32)$$

respectively. Therefore, the outage probability of $D_1$ is obtained as

$$OP_{1-NOMA}^F = 1 - \sum_{n=1}^{N} \left( \frac{N}{n} \right) (-1)^{n-1} \frac{1}{\lambda_{g,1,n}} \times \int_0^\infty \exp \left( -\frac{n (\omega \rho x + 1) \psi_1}{\lambda_{g,1,n}} \right) \exp \left( -\frac{x}{\lambda_{hD1}} \right) dx. \quad (33)$$

It is noted that the other channels, i.e., $h_1, h_2$ and all loop feedback channels follow the Rayleigh distribution with PDF and CDF $f_x(x) = \frac{1}{\lambda} x e^{-\frac{x}{\lambda}}$ and $F_x(x) = 1 - e^{-\frac{x}{\lambda}}$, respectively. Following some mathematical simplifications, the expected formula is derived. This completes the proof. \(\square\)

2) OUTAGE PROBABILITY OF $D_2$

Because $D_2$ receives the signal $x_2$ from either $D_1$ or the best relay $R_k^*$, an outage event at $D_2$ happens if $D_1$ cannot successfully detect $x_2$ or $D_2$ cannot successfully decode $x_2$ from $D_1$ if the D2D link is selected. Otherwise, the outage event occurs if the best relay $R_k^*$ cannot decode $x_2$ or $D_2$ cannot successfully decode the signal forwarded from the relay. Thus, the outage probability of $D_2$ can be formulated as

$$OP_{2-NOMA}^F = \Pr \left[ \max_{k=1,\ldots,K} \min \left( \frac{\gamma_{SRK,x_2}^{NOMA}}{\gamma_{SD1,x_2}^{NOMA}}, \frac{\gamma_{SRK,x_2}^{NOMA}}{\gamma_{RKD2,x_2}^{NOMA}} \right) \psi_2 < \epsilon_2^F \right], \quad (34)$$

which is valid for $\epsilon_2 > \epsilon_2^F a_2$ and $\psi_2 = \max \left( \frac{\epsilon_2^F}{a_2 \rho + \epsilon_1^F a_1 \rho}, \frac{\epsilon_2^F}{a_2 \rho} \right)$.
Theorem 2: The outage probability of $D_2$ in Scheme 1 is obtained as (35) and it is shown at the bottom of this page.

Proof: See Appendix A.

B. SCHEME 2

1) OUTAGE PROBABILITY OF $D_1$

Here, we explore the situation where $D_1$ harvests energy from the RF signal that is sent from the BS. Following the same approach as in Scheme 1, the outage probability of $D_1$ is formulated as

$$OP_{1-NOMA}^{FD-EH} = 1 - Pr\left(\gamma_{SD1}^{NOMA-EH} \geq \varepsilon_2^{FD}, \gamma_{SRK}^{NOMA-EH} \geq \varepsilon_1^{FD}\right).$$ (36)

Theorem 3: The closed-form expression for the outage probability at $D_1$ in this scheme is given in (37) at the bottom of the next page.

2) OUTAGE PROBABILITY OF $D_2$

Based on (34), the outage probability of $D_2$ in this case is formulated as

$$OP_{2-NOMA}^{FD-EH} = \Pr\left[\max_{k=1, \ldots, K} \left(\min\left(\gamma_{SD1}^{NOMA-EH}, \gamma_{SD1}^{NOMA-EH}\right) < \varepsilon_1^{FD}, \min\left(\gamma_{SRK}^{NOMA-EH}, \gamma_{SRK}^{NOMA-EH}\right) < \varepsilon_2^{FD}\right)\right] = \Pr\left[\min_{k=1, \ldots, K} \left(\gamma_{SD1}^{NOMA-EH}, \gamma_{SRK}^{NOMA-EH}\right) > \varepsilon_1^{FD}, \gamma_{SRK}^{NOMA-EH} > \varepsilon_2^{FD}\right].$$ (38)

Theorem 4: For Scheme 2, the outage probability of $D_2$ is obtained in (39) and it is displayed at the bottom of the next page.

Proof: See Appendix B.

C. SCHEME 3

In this subsection, we investigate the outage probability of $D_1$ and $D_2$ for the cases of QMFR with energy harvesting at $D_1$ (QMFR EH) and without energy harvesting at $D_1$ (QMFR Non-EH), respectively.

1) OUTAGE PROBABILITY OF $D_1$

In this scheme, an outage event occurs at $D_1$ if it cannot detect its own signal. Therefore, the outage probability of $D_1$ in the case of QMFR Non-EH and QMFR EH are given by

$$OP_{1-NOMA}^{FD-QMF-EH} = 1 - Pr\left(\gamma_{SD1}^{QMF-EH} \geq \varepsilon_1^{FD}\right),$$ (40)

and

$$OP_{1-NOMA}^{FD-QMF-EH} = 1 - Pr\left(\gamma_{SD1}^{QMF-EH} \geq \varepsilon_1^{FD}\right),$$ (41)

respectively.

Theorem 5: For QMFR Non-EH and QMFR EH, the outage probability of $D_1$ can be obtained as (42) and (43), respectively, which is valid for $a_1 > \varepsilon_1^{FD} a_2$, otherwise $D_1$ is always in outage.

Proof: See Appendix C.

2) OUTAGE PROBABILITY OF $D_2$

Similarly, we evaluate the outage probability of $D_2$ with and without energy harvesting at $D_1$.

In case $D_1$ is not energy harvesting, the outage probability at $D_2$ can be formulated as

$$OP_{2-NOMA}^{FD-QMF} = \left[1 - \Pr\left(\gamma_{SD1}^{QMF} \geq \varepsilon_2^{FD}, \gamma_{SD2}^{QMF} \geq \varepsilon_2^{FD}\right)\right] \times \prod_{k=1}^{K} \left[1 - \Pr\left(\gamma_{SRK}^{QMF} \geq \varepsilon_1^{FD}, \gamma_{SRK}^{QMF} \geq \varepsilon_1^{FD}\right)\right].$$ (44)

Theorem 6: The outage probability of $D_2$ in case of QMFR Non-EH is evaluated as

$$OP_{2-NOMA}^{FD-QMF} = \left[1 - \sum_{r=1}^{N} \left(\begin{array}{c} N \\ n \end{array}\right) (-1)^{n-1} \lambda_{g1,n} \exp\left(-\frac{\theta a_1 \rho - \varepsilon_1^{FD}}{\rho \lambda_{h1}}\right)\right] \times \prod_{k=1}^{K} \left[1 - \sum_{r=1}^{N} \left(\begin{array}{c} N \\ n \end{array}\right) (-1)^{n-1} \lambda_{gk,k} \exp\left(-\frac{\theta a_1 \rho - \varepsilon_1^{FD}}{\rho \lambda_{h2}}\right)\right],$$ (45)

which is valid for $a_1 > \varepsilon_1^{FD} a_2$ and

$$\theta = \max\left(\begin{array}{c} \varepsilon_1^{FD}, \varepsilon_2^{FD} \end{array}\right).$$ (46)

Proof: See Appendix D.

Besides, the outage probability of $D_2$ in the case of energy harvesting at $D_1$, i.e., QMFR EH scenario, is formulated as

$$OP_{2-NOMA}^{FD-QMF-EH} = \left[1 - \Pr\left(\gamma_{SD1}^{QMF-EH} \geq \varepsilon_1^{FD}\right)\right].$$
\[ \gamma_{\text{SRK},1,x_2}^\text{OMF-EH} \geq \varepsilon_2^{FD} \gamma_{\text{D1},x_2}^\text{NOMA-EH} \geq \varepsilon_2^{FD} \] 

\[ \prod_{k=1}^{K} \left[ 1 - \text{Pr} \left( \gamma_{\text{SRK},1,x_2}^\text{OMF} \geq \varepsilon_1^{FD}, \gamma_{\text{D1},x_2}^\text{NOMA} \geq \varepsilon_2^{FD} \right) \right]. \]  

(46)

**Theorem 7:** For QMFR EH, the outage probability of D₂ is obtained in (47), shown at the bottom of the next page, where

\[ \zeta = \max \left( \frac{\varepsilon_1^{FD}}{(1 - \beta)(\mu_1 - \varepsilon_1^{FD} \omega_1^{FD})}, \frac{\varepsilon_2^{FD}}{(1 - \beta) \omega_1^{FD}} \right) \] 

and the condition of \( a_1 > \varepsilon_1^{FD} a_2 \) must be guaranteed.

**Proof:** See Appendix E.

It is noted that the outage probability for the three schemes assuming HD mode can be obtained by setting \( \omega = 0 \) and replacing \( \varepsilon_i^{FD} = 2^{R_i} - 1 \) by \( \varepsilon_i^{HD} = 2^{2R_i} - 1 (i = 1, 2) \), in the corresponding FD outage probability expressions.

**Corollary:** From the outage probability expressions derived above, the system throughput of the aforementioned FD and HD NOMA scenario for each scheme is obtained as

\[ \Gamma_v = (1 - \text{OP}_{v-1}^{FD-NOMA}) \Gamma_1 + (1 - \text{OP}_{v-2}^{FD-NOMA}) \Gamma_2, \]  

(48)

where \( v = (1, 2, 3) \) denotes Scheme 1, scheme 2 and scheme 3, respectively and \( u = \{FD, HD, FD_{EH}, HD_{EH}, FD_{OMF}, HD_{OMF}, FD_{OMF}_{EH}, HD_{OMF}_{EH} \} \) denotes the considered protocol in the three schemes.

**IV. NUMERICAL RESULTS**

In this section, we examine the accuracy of the derived analytical results and assess the performance of the considered system by Monte Carlo simulations. Without loss of generality, we assume that the power allocation coefficients of NOMA are \( a_1 = 0.3 \) and \( a_2 = 0.7 \) for \( D_1 \) and \( D_2 \), respectively. In addition, it is assumed that the distance between the devices in the system normalized to one. In this context, unless otherwise stated, the solid lines denote the derived analytical results while the respective Monte-Carlo simulation results are presented using the markers. Thus, it can be observed that the analytical curves perfectly match the corresponding simulation results which demonstrates the accuracy of derived analytical expressions. We call bit per channel user in short as BPCU.

\[\text{OP}_{1-\text{NOMA}}^{FD-EH} = 1 - \int_0^\infty \left( 1 - F_{[\gamma_{D1}]}(x) \right) f_{[\gamma_{D1}]}(x) dx \]

\[= 1 - \int_0^\infty \sum_{n=1}^{N} \binom{N}{n} (-1)^{n-1} \exp \left( -\frac{n(\omega_1 + 1)}{\lambda_{g1,n}} \right) \frac{1}{\lambda_{hD1}} \exp \left( -\frac{x}{\lambda_{hD1}} \right) dx \]

\[= 1 - \sum_{n=1}^{N} \binom{N}{n} (-1)^{n-1} \frac{1}{\lambda_{hD1}} \exp \left( -\frac{n\psi_1}{\lambda_{g1,n}} \right) \int_0^\infty \exp \left( -\frac{\omega_1 n}{\lambda_{g1,n}} + \frac{1}{\lambda_{hD1}} x \right) dx \]

\[= 1 - \sum_{n=1}^{N} \binom{N}{n} (-1)^{n-1} \frac{(1 - \beta) \lambda_{g1,n}}{n \omega_1 \lambda_{g1,n}} \exp \left( -\frac{n\psi_1}{(1 - \beta) \lambda_{g1,n}} \right) \]  

(37)

\[\text{OP}_{2-\text{NOMA}}^{FD-EH} = \left[ 1 - \sum_{n=1}^{N} \binom{K}{n} (-1)^{n-1} \frac{1}{\lambda_{hD1}} \exp \left( -\frac{\omega_1 n}{\lambda_{g1,n}} \right) \right] \]

\[\times \frac{1}{\lambda_{h1}} \int_0^\infty \frac{\rho y \lambda_{g1,n}}{n \omega_1 \lambda_{g1,n}} \left[ \exp \left( -\frac{1}{\beta} - 1 \right) - \frac{n \epsilon_2^{FD}}{\eta \rho \lambda_{g1,n}} - \frac{1}{\lambda_{hD1}} - \exp \left( -\frac{n \epsilon_2^{FD}}{\eta \rho \lambda_{g1,n}} - \frac{1}{\lambda_{hD1}} \right) \right] dy \]

\[\times \prod_{k=1}^{K} \left( 1 - \sum_{n=1}^{N} \binom{N}{n} (-1)^{n-1} \frac{(a_2 - \epsilon_2^{FD}) \rho \lambda_{g1,n}}{n \omega_1 \rho \lambda_{h1,k} + (a_2 - \epsilon_2^{FD}) \rho \lambda_{g1,n}} \exp \left( -\frac{n \epsilon_2^{FD}}{a_2 - \epsilon_2^{FD}} \right) - \frac{\epsilon_2^{FD}}{\rho \lambda_{h2}} \right) \]  

(39)

\[\text{OP}_{1-\text{NOMA}}^{FD-QMF} = 1 - \sum_{n=1}^{N} \binom{N}{n} (-1)^{n-1} \frac{(a_1 - \epsilon_1^{FD} a_2) \rho \lambda_{g1,n}}{n \omega_1 \rho \lambda_{hD1} + (a_1 - \epsilon_1^{FD} a_2) \rho \lambda_{g1,n}} \exp \left( -\frac{n \epsilon_1^{FD}}{a_1 - \epsilon_1^{FD} a_2} \right) \]  

(42)

\[\text{OP}_{1-\text{NOMA}}^{FD-QMF_{EH}} = 1 - \sum_{n=1}^{N} \binom{N}{n} (-1)^{n-1} \frac{(a_1 - \epsilon_1^{FD} a_2) \rho \lambda_{g1,n}}{n \omega_1 \rho \lambda_{hD1} + (a_1 - \epsilon_1^{FD} a_2) \rho \lambda_{g1,n}} \exp \left( -\frac{n \epsilon_1^{FD}}{a_1 - \epsilon_1^{FD} a_2} \right) \]  

(43)
A. SCHEME 1: NON ENERGY HARVESTING - NON-EHR

This subsection examines the system’s outage probability when there is no energy harvesting at $D_1$. To this end, Fig. 2 shows the outage probability versus SNR which are achieved from the expression (28), (29) and HD mode, respectively. It can be seen that the performance of FD NOMA is better than HD NOMA at low SNR, i.e., SNR from 10 dB to 25 dB, but the performance of the HD NOMA mode is superior in the high SNR region (SNR $\geq 30$ dB). This is because as the SNR increases, the FD mode is strongly influenced by self-interference which consequently decreases the performance.

Furthermore, in Fig. 2, it is shown that the NOMA technique outperforms the conventional OMA technology where the signal transmission is performed in three time slots, i.e., the BS sends the signal $x_1$ to $D_1$ in the first time slot and $x_2$ to $D_2$ in the second time slot, while in the last time slot, $D_1$ decodes and forwards the signal $x_2$ to $D_2$.

The outage performance of $D_2$ is shown in Fig. 3, where it is clearly observed that the outage performance of the FD NOMA mode is superior to both the HD NOMA and the OMA mode. Moreover, looking at Fig. 4, it’s also noticed that when increasing the number of relay nodes, the performance is also improved, since increasing the relay nodes will improve the channel diversity gain. In other words, an outage event will be more difficult to happen.
In Fig. 5, the comparison of the outage performance between $D_1$ and $D_2$ in both HD NOMA and FD NOMA with different power allocation coefficients has been expressed. There is a large outage performance gap between $D_1$ and $D_2$ when the SNR increases from 25 (dB) to 40 (dB). In addition, it can be recognized that the outage probability curves of $D_2$ are almost unchanged a lot when changing the value of $a_1$. However, it has great impact on the outage probability of $D_1$. This implies that there should be a reasonable strategy in selecting the power allocation coefficients when deploying real network in the future.

The influence of the number of antennas at the BS on the outage performance of the system is clearly shown in Fig. 6. We can see that the system’s outage performance follows the same trend for the different numbers of antennas considered; however, increasing the number of antennas greatly improves the outage performance, especially for Scheme 1.

In Fig. 7, we plot and compare the throughput of the FD NOMA and HD NOMA cases obtained in (48). The black solid curves and the red solid curve denote the FD and HD NOMA cases, respectively, while the dashed curves represent the OMA scheme. It is observed that the FD NOMA system throughput is superior to the HD NOMA and OMA cases, especially in the low SNR region and for low SI values while higher SI values significantly affect the performance of FD NOMA, making it perform the worst among the 3 considered scenarios.

**B. SCHEME 2: ENERGY HARVESTING- EHR**

In this subsection, the outage performance of $D_1$ and $D_2$ is for the energy harvesting case.

Fig. 8 and Fig. 9 show the FD and HD modes outage performance of $D_1$ and $D_2$ with various target rates, respectively. Similarly to the Scheme 1 case, the outage performance of $D_1$ and $D_2$ in FD mode is better than HD mode where, generally the performance of NOMA surpasses that of the conventional the OMA scheme. Besides, when the objective rate is reduced, the outage performance of the two users is also improved.

Fig. 10 compares the outage probabilities of $D_1$ and $D_2$ in HD and FD mode. It can be seen that the outage performance of $D_1$ in FD mode is better than HD mode when the SNR is between 0 dB and 25 dB. In addition, when increasing the power allocation factor of $D_1$, i.e., $a_1$, the outage performance of $D_1$ is improved. For $D_2$, the outage performance in FD mode is always better than HD mode. However, it is noted that according to the NOMA principle, when increasing $a_1$, this means reducing $a_2$. Hence, the outage performance of $D_2$...
is decreased. Moreover, it can be observed from Fig. 10 that the outage performance of $D_2$ is superior to $D_1$ and the higher the SNR, the more obvious the superiority is.

C. SCHEME 3: QMF RELAYING - QMFR

In this subsection, the outage performance for the case of QMFR EH and QMFR Non-EH in FD and HD mode is verified. In particular, the outage performance of $D_1$ and $D_2$ in both cases, with and without energy harvesting are considered.

The outage probability of $D_1$ in the QMFR Non-EH and QMFR EH are shown in Fig. 11 and Fig. 12, respectively. It can be seen that the FD mode achieves higher performance than the HD mode in the SNR region from 0 to 20 dB. Especially, when increasing $R_1 = 0.3$ PBCU, there is an outage event that occurs in HD mode while the outage performance of FD mode is still guaranteed. The reason behind this is that when $a_1 = 0.3$ and $R_1 = 0.3$ PBCU, the condition in (40), i.e., $a_1 > \varepsilon_1^{FD}$ is guaranteed for the FD mode, but the condition for HD mode, i.e., $a_1 > \varepsilon_1^{HD}$ is no longer guaranteed, so the outage probability in HD mode will be one. Besides, one can see from Fig. 11 and Fig. 12 that the outage probability of $D_1$ is affected by the energy harvesting. This proves that the outage probability of $D_1$ in this Scheme is not greatly influenced by the energy harvesting process. Additionally, it is noticed that OMA has a better out-
FIGURE 12. Outage probability of $D_1$ for the QMFR EH versus SNR for different values of $R_1$ when $\lambda_{g1,n} = 1$, $\lambda_{hD1} = 0.01$, $\beta = 0.6$, and $N = 2$.

FIGURE 13. Outage probability of $D_2$ in the case of QMFR EH and QMFR Non-EH protocol with different values of $R_1$ and $R_2$ when $\lambda_{g1,n} = 1$, $\lambda_{gmn,k} = 5$, $\lambda_{h1} = 4$, $\lambda_{h2} = 1$, $\lambda_{hD1} = \lambda_{hD2} = 0.01$, $\eta = \beta = 0.6$, and $N = K = 2$.

The outage performance of $D_2$ with both NOMA and OMA schemes are shown in Fig. 14 and Fig. 15 for the FD and HD modes, respectively. It can be seen from Fig. 14 that the QMFR EH and QMFR Non-EH protocols have a lower outage probability than OMA in FD mode. However, for HD mode, which is shown in Fig. 15, the outage performance of OMA is slightly better than the QMFR EH and QMFR Non-EH protocols in the low SNR region and vice versa in the high SNR area. The reason for this is that $D_1$ may be in outage protocol. In addition, when the target rate is increased from 0.1 to 0.25 BPCU, the QMFR Non-EH achieves relatively better outage performance than the QMFR EH. Besides, when increasing $R_1$ and $R_2$, i.e., $R_1 = R_2 = 0.25$ BPCU, there is a big gap between FD and HD mode. In other words, the superiority of FD mode over HD is more evident when the target rate is increased.

The outage performance of $D_2$ in both NOMA and OMA schemes are shown in Fig. 14 and Fig. 15 for the FD and HD modes, respectively. It can be seen from Fig. 14 that the QMFR EH and QMFR Non-EH protocols have a lower outage probability than OMA in FD mode. However, for HD mode, which is shown in Fig. 15, the outage performance of OMA is slightly better than the QMFR EH and QMFR Non-EH protocols in the low SNR region and vice versa in the high SNR area. The reason for this is that $D_1$ may be in outage protocol. In addition, when the target rate is increased from 0.1 to 0.25 BPCU, the QMFR Non-EH achieves relatively better outage performance than the QMFR EH. Besides, when increasing $R_1$ and $R_2$, i.e., $R_1 = R_2 = 0.25$ BPCU, there is a big gap between FD and HD mode. In other words, the superiority of FD mode over HD is more evident when the target rate is increased.
the chances of satisfying this condition which increases the outage performance of $D_2$. In addition, we also find from Fig. 16 that the outage performance of $D_2$ in QMFR EH is lower than $D_2$ in the QMFR Non-EH protocol when the SNR increases.

Fig. 17 plots the outage probability of $D_2$ in EH mode and compares between schemes 2 and 3. Here, it is demonstrated that the outage performance is improved when the energy conversion factor is increased. Moreover, for $D_2$, scheme 2 achieves better performance than scheme 3.

Fig. 18 compares the outage probability of $D_2$ in Scheme 1, scheme 2 and scheme 3 to each other when changing the number of relay nodes. Besides, the impact of the number of relay nodes on the outage performance of $D_2$ is also considered. For simplicity, Fig. 18 shows only the FD mode. The simulation and analysis results have demonstrated that the outage performance is significantly improved when the number of relay increases. Moreover, it is also shown that Scheme 1 achieves the best outage performance.

The general comparison between the outage performance of the three schemes is shown in Fig. 19 and Fig. 20 for the FD and HD modes, respectively where it is shown that Scheme 1 has a superior performance compared to the other schemes.

Fig. 21 shows the outage probability of the three schemes in FD mode versus the power allocation coefficient $a_1$. As mentioned above, the condition for the outage performance is guaranteed to be $a_2 > e_2^{FD} a_1$ for schemes 1 and 2, while for scheme 3, it is $a_1 > e_1^{FD} a_2$. Therefore, when $R_1 = R_2 = 0.4$ BPCU, the condition becomes $a_2 > 0.3 a_1$ for schemes 1 and 2, and $a_1 > 0.3 a_2$ for scheme 3. It can be observed from Fig. 21 that schemes 1 and 2 will be in outage when $a_1 > 0.7$ while scheme 3 is in outage when $a_2 > 0.7$.
$a_1 \leq 0.3$ or $a_1 = 1$, this is completely consistent with the conditions analyzed. In addition, the optimal power allocation coefficient for the three schemes can be determined. Specifically, the optimal values of $a_1$ for schemes 1, 2, and 3 are 0.1, 0.2 and 0.5, respectively.

Fig. 22 compares the throughput of all three schemes when $a_1 = 0.3$ and $R_1 = R_2 = 0.2$ BPCU in order to ensure that $a_2 > \varepsilon^1_2 a_1$ and $a_1 > \varepsilon^l_1 a_2$, $l = \{FD, HD\}$, in both FD and HD mode. It is noticed that all three proposed schemes have good throughput when the SNR is high. Furthermore, the FD mode achieves higher throughput than the HD mode while Scheme 1 shows the best performance.

V. CONCLUSION

In this paper, three novel FD cooperative relaying NOMA schemes for D2D communications have been proposed and analyzed. Precisely, closed form outage probability and throughput expressions for the proposed schemes have been evaluated. Monte-Carlo simulations results were presented to corroborate the derived analytical results. It was shown
that the proposed schemes can significantly improve the outage performance compared to conventional OMA schemes where Scheme 1 achieves the best performance. Additionally, the combination of relaying with energy harvesting has brought great performance improvement to the system. Finally, interestingly, it has shown that the outage performance of FD NOMA is better than its HD counterpart.

**APPENDIX A**

**PROOF OF THE THEOREM 2**

From the expression (34), we can be obtained as

\[
OP_{FD-NOMA}^F = \left[ 1 - \Pr \left( \min \left( \frac{\gamma_{SD1-2}}{\gamma_{D1x2}}, \frac{\gamma_{SRKx2}}{\gamma_{RDKx2}} \right) \geq \epsilon_2^F \right) \right] \\
\times \prod_{k=1}^{K} \left[ 1 - \Pr \left( \min \left( \frac{\gamma_{SD1-2}}{\gamma_{D1x2}}, \frac{\gamma_{SRKx2}}{\gamma_{RDKx2}} \right) \geq \epsilon_2^F \right) \right].
\]

(A.1)

where the first term of probability in (A.1) is calculated as (A.2).

Similarly, the second term of probability in (A.1) can be expressed as (A.3).

It is noted that the (A.2) and (A.3) can be obtained by the condition of \(a_2 > \epsilon_2^F a_1\). The proof is completed.

**APPENDIX B**

**PROOF OF THE THEOREM 3**

The expression (38) can be expressed as (B.1).

From the first term of the expression in (B.1), we can rewrite:

\[
M = 1 - \Pr \left( \gamma_{SD1-2}^\text{EH} \geq \epsilon_2^F, \gamma_{D1x2}^\text{EH} \geq \epsilon_2^F \right) \\
= 1 - \Pr \left( \gamma_{SD1-2}^\text{EH} \geq \epsilon_2^F \right) \Pr \left( \gamma_{D1x2}^\text{EH} \geq \epsilon_2^F \right).
\]

(B.2)

\[
A = 1 - \Pr \left( \gamma_{SD1-2}^\text{EH} \geq \epsilon_2^F \right) \times \Pr \left( \gamma_{D1x2}^\text{EH} \geq \epsilon_2^F \right) \\
= 1 - \Pr \left( \frac{|g_{1,n}|^2}{\rho_{h_{D1}}} \geq \frac{\epsilon_2^F \sigma^2}{\rho_1} + \frac{\epsilon_2^F}{\rho_{h_{D1}}} \right) \times \Pr \left( \frac{|h_1|^2}{\rho} \geq \frac{\epsilon_2^F}{\rho} \right) \\
= 1 - \exp \left( -\frac{\epsilon_2^F}{\rho_{h_{D1}}} \right) \times \int_0^\infty \left( 1 - F \left( \frac{|g_{1,n}|^2}{\rho_{h_{D1}}} \right) \right) \frac{a_2 \rho - \epsilon_2^F \rho_{h_{D1}}}{\rho_{h_{D1}}} \left( x \right) dx \\
= 1 - \sum_{n=1}^N \left( \begin{array}{c} N \\ n \end{array} \right) (-1)^{n-1} \frac{1}{\lambda_{D1}} \exp \left( -\frac{ne_2^F \rho_{h_{D1}}}{a_2 \rho - \epsilon_2^F \rho_{h_{D1}}} \lambda_{g_{1,n}} \right) \exp \left( -\frac{ne_2^F \rho_{h_{D1}}}{a_2 \rho - \epsilon_2^F \rho_{h_{D1}}} \lambda_{g_{1,n}} \right)
\]

(A.2)

\[
B = \prod_{k=1}^K \left( 1 - \Pr \left( \frac{|g_{n,k}|^2}{\rho_{h_{Kx2}}} \geq \frac{\epsilon_2^F}{\rho_{h_{Kx2}}} \right) \right) \\
= \prod_{k=1}^K \left( 1 - \Pr \left( \frac{|g_{n,k}|^2}{\rho_{h_{Kx2}}} \geq \frac{\epsilon_2^F}{\rho_{h_{Kx2}}} \right) \right) \\
= \prod_{k=1}^K \left( 1 - \exp \left( -\frac{\epsilon_2^F}{\rho_{h_{Kx2}}} \right) \int_0^\infty \left( 1 - F \left( \frac{|g_{n,k}|^2}{\rho_{h_{Kx2}}} \right) \right) \frac{a_2 \rho - \epsilon_2^F \rho_{h_{Kx2}}}{\rho_{h_{Kx2}}} \left( x \right) dx \\
= \prod_{k=1}^K \left( 1 - \exp \left( -\frac{\epsilon_2^F}{\rho_{h_{Kx2}}} \right) \right) \sum_{n=1}^N \left( \begin{array}{c} N \\ n \end{array} \right) (-1)^{n-1} \frac{1}{\lambda_{h_{Kx2}}} \exp \left( -\frac{ne_2^F \rho_{h_{Kx2}}}{a_2 \rho - \epsilon_2^F \rho_{h_{Kx2}}} \lambda_{g_{n,k}} \right) \exp \left( -\frac{ne_2^F \rho_{h_{Kx2}}}{a_2 \rho - \epsilon_2^F \rho_{h_{Kx2}}} \lambda_{g_{n,k}} \right)
\]

(A.3)
where the first term of the probability expression in (B.2) is calculated as (B.3) and the second term can be expressed as (B.4).

It is noted that the (B.3) and (B.4) can be obtained by the condition of \( a_2 > \varepsilon_F^2 a_1 \) and \( |h_{D1}|^2 < \frac{1}{\eta h_1} \), respectively.

By substituting (B.3) and (B.4) into (B.2) and combine with (A.3), the proof is completed.

**APPENDIX C**

**PROOF OF THE THEOREM 5**

Substituting the expression (21) into (40), the outage probability at \( D_1 \) in the case of QMFR Non-EH is calculated as (C.1).

\[
OP_{2-NOMA}^{FD-EH} = \Pr(\min(\gamma_{SD1}^{\text{NOMA-EH}}, \gamma_{D12}^{\text{NOMA-EH}}) < \varepsilon_F^2) \times \Pr(\max_{k=1}^{K} \min(\gamma_{SRK_{k,x_2}}^{\text{NOMA}}, \gamma_{RKD_{k,x_2}}^{\text{NOMA}}) < \varepsilon_F^2)
\]

\[
= \left[1 - \Pr(\min(\gamma_{SD1}^{\text{NOMA-EH}}, \gamma_{D12}^{\text{NOMA-EH}}) \geq \varepsilon_F^2)\right] \times \prod_{k=1}^{K} \left(1 - \Pr(\min(\gamma_{SRK_{k,x_2}}^{\text{NOMA}}, \gamma_{RKD_{k,x_2}}^{\text{NOMA}}) \geq \varepsilon_F^2)\right)
\]

\[
M_1 = \Pr\left(|g_{1,n}|^2 \geq \varepsilon_F^2 \frac{\rho \left(1 - \beta\right) (a_2-a_1 \varepsilon_F^2)}{\rho \left(1 - \beta\right) (a_2-a_1 \varepsilon_F^2)} \right)
\]

\[
= \int_0^{1} \left(1 - F_{|g_{1,n}|^2} \left(\frac{\varepsilon_F^2 \rho \phi x + \varepsilon_F^2}{\rho \left(1 - \beta\right) (a_2-a_1 \varepsilon_F^2)}\right)\right) f_{|h_{D1}|^2}(x) \, dx
\]

\[
= \sum_{n=1}^{\infty} \left[(-1)^{n-1} \frac{1}{\lambda_{D1}} \exp\left(-\frac{n \varepsilon_F^2}{\rho \left(1 - \beta\right) (a_2-a_1 \varepsilon_F^2)} \rho \lambda_{1,n}\right)\right] \frac{\rho \lambda_{1,n}}{\lambda_{D1}} \exp\left(-\frac{x}{\lambda_{D1}}\right) \, dx
\]

\[
M_2 = \Pr\left(|g_{1,n}|^2 \geq \varepsilon_F^2 \frac{\left(1 - \eta \beta \phi\right)}{\eta \beta \phi}\right)
\]

\[
= \int_0^{1} \int_0^{\frac{1}{\eta \beta \phi \lambda_{1,n}}} \sum_{n=1}^{\infty} \left(\frac{N}{n}\right) (-1)^{n-1} \exp\left(-\frac{n \varepsilon_F^2}{\eta \beta \phi \lambda_{1,n}}\right) \frac{1}{\lambda_{D1}} \exp\left(-\frac{x}{\lambda_{D1}}\right) \frac{1}{\lambda_{h_1}} \exp\left(-\frac{y}{\lambda_{h_1}}\right) \, dx \, dy
\]

\[
= \sum_{n=1}^{\infty} \left[(-1)^{n-1} \frac{1}{\lambda_{D1}} \lambda_{h_1} \int_0^{\frac{1}{\eta \beta \phi \lambda_{1,n}}} \exp\left(-\frac{n \varepsilon_F^2}{\eta \beta \phi \lambda_{1,n}}\right) \frac{1}{\lambda_{D1}} \exp\left(-\frac{x}{\lambda_{D1}}\right) \frac{1}{\lambda_{h_1}} \exp\left(-\frac{y}{\lambda_{h_1}}\right) \, dx \right] dy
\]

\[
= \sum_{n=1}^{\infty} \left[(-1)^{n-1} \frac{1}{\lambda_{h_1}} \int_0^{\infty} \frac{\rho \lambda_{1,n}}{n \varepsilon_F^2 \lambda_{D1} + \rho \lambda_{1,n}} \left[\exp\left(-\frac{\left(\frac{n \varepsilon_F^2}{\rho \lambda_{1,n}} - 1\right)}{\eta \lambda_{D1}} - 1\right) - 1\right] \exp\left(-\frac{n \varepsilon_F^2}{\eta \beta \phi \lambda_{1,n}} - \frac{y}{\lambda_{h_1}}\right) \, dy \right] dy
\]
According to (D.2), the expressions $E_1$ and $E_2$ can be calculated as follows, respectively.

$$E_1 = \Pr \left[ |g_{1,n}|^2 \geq (\omega \rho |h_D|^2 + 1) \right] \times \max \left( \frac{\epsilon_1^{FD}}{a_1 \rho - \epsilon_1^{FD} a_2 \rho}, \frac{\epsilon_2^{FD}}{a_2 \rho} \right)$$

$$= \Pr \left[ |g_{1,n}|^2 \geq (\omega \rho |h_D|^2 + 1) \theta \right]$$

\[\begin{align*}
\text{OP}^{FD\text{-QMF}}_{1\text{-NOMA}} &= 1 - \Pr \left( |g_{1,n}|^2 \geq \frac{\epsilon_1^{FD} \omega \rho |h_D|^2 + \epsilon_1^{FD}}{(1 - \beta) \left( a_1 \rho - \epsilon_1^{FD} a_2 \rho \right)} \right) \\
&= 1 - \int_0^\infty \sum_{n=1}^N \binom{N}{n} (-1)^{n-1} \exp \left( -\frac{n \left( \epsilon_1^{FD} \omega \rho x + \epsilon_1^{FD} \right)}{(1 - \beta) \left( a_1 \rho - \epsilon_1^{FD} a_2 \rho \right)} \lambda h_D \right) \frac{1}{\lambda h_D} \exp \left( -\frac{x}{\lambda h_D} \right) dx \\
&= 1 - \sum_{n=1}^N \binom{N}{n} (-1)^{n-1} \frac{1}{\lambda h_D} \exp \left( -\frac{n \epsilon_1^{FD}}{(1 - \beta) \left( a_1 \rho - \epsilon_1^{FD} a_2 \rho \right)} \lambda g_{1,n} \right) \int_0^\infty \exp \left( -\frac{n \epsilon_1^{FD} \omega \rho x}{(1 - \beta) \left( a_1 \rho - \epsilon_1^{FD} a_2 \rho \right)} + 1 \right) dx \\
&\quad \times \int_0^\infty \exp \left( -\frac{n \epsilon_1^{FD} \omega \rho}{(1 - \beta) \left( a_1 \rho - \epsilon_1^{FD} a_2 \rho \right)} + 1 \right) x dx \quad \text{(C.1)}
\end{align*}\]

\[\begin{align*}
\text{OP}^{FD\text{-QMF\text{-EH}}}_{1\text{-NOMA}} &= 1 - \Pr \left( |g_{1,n}|^2 \geq \frac{\epsilon_1^{FD} \omega \rho |h_D|^2 + \epsilon_1^{FD}}{(1 - \beta) \left( a_1 \rho - \epsilon_1^{FD} a_2 \rho \right)} \right) \\
&= 1 - \int_0^\infty \sum_{n=1}^N \binom{N}{n} (-1)^{n-1} \exp \left( -\frac{n \left( \epsilon_1^{FD} \omega \rho x + \epsilon_1^{FD} \right)}{(1 - \beta) \left( a_1 \rho - \epsilon_1^{FD} a_2 \rho \right)} \lambda h_D \right) \frac{1}{\lambda h_D} \exp \left( -\frac{x}{\lambda h_D} \right) dx \\
&= 1 - \sum_{n=1}^N \binom{N}{n} (-1)^{n-1} \frac{1}{\lambda h_D} \exp \left( -\frac{n \epsilon_1^{FD}}{(1 - \beta) \left( a_1 \rho - \epsilon_1^{FD} a_2 \rho \right)} \lambda g_{1,n} \right) \int_0^\infty \exp \left( -\frac{n \epsilon_1^{FD} \omega \rho x}{(1 - \beta) \left( a_1 \rho - \epsilon_1^{FD} a_2 \rho \right)} + 1 \right) dx \\
&\quad \times \int_0^\infty \exp \left( -\frac{n \epsilon_1^{FD} \omega \rho}{(1 - \beta) \left( a_1 \rho - \epsilon_1^{FD} a_2 \rho \right)} + 1 \right) x dx \quad \text{(C.2)}
\end{align*}\]

\[\begin{align*}
\text{OP}^{FD\text{-QMF}}_{2\text{-NOMA}} &= \left[ 1 - \Pr \left( \gamma_{SD1}^{QMF} \geq \epsilon_1^{FD}, \gamma_{SD1,x_2}^{QMF} \geq \epsilon_2^{FD}, \gamma_{NOMA}^{FD} \geq \epsilon_2^{FD} \right) \right] \\
&\quad \times \prod_{k=1}^K \left( 1 - \Pr \left( \gamma_{SRK,x_1}^{QMF} \geq \epsilon_1^{FD}, \gamma_{SRK,x_2}^{QMF} \geq \epsilon_2^{FD}, \gamma_{RKD2,x_2}^{QMF} \geq \epsilon_2^{FD} \right) \right). \quad \text{(D.1)}
\end{align*}\]

\[\begin{align*}
E &= 1 - \Pr \left( \gamma_{SD1}^{QMF} \geq \epsilon_1^{FD}, \gamma_{SD1,x_2}^{QMF} \geq \epsilon_2^{FD} \right) \times \Pr \left( \gamma_{NOMA}^{FD} \geq \epsilon_2^{FD} \right). \quad \text{(D.2)}
\end{align*}\]

\[\begin{align*}
F &= \prod_{k=1}^K \left( 1 - \Pr \left( \gamma_{SRK,x_1}^{QMF} \geq \epsilon_1^{FD}, \gamma_{SRK,x_2}^{QMF} \geq \epsilon_2^{FD} \right) \right) \times \Pr \left( \gamma_{RKD2,x_2}^{QMF} \geq \epsilon_2^{FD} \right). \quad \text{(D.3)}
\end{align*}\]

\[\begin{align*}
\text{OP}^{FD\text{-QMF\text{-EH}}}_{2\text{-NOMA}} &= \left[ 1 - \Pr \left( \gamma_{SD1}^{QMF\text{-EH}} \geq \epsilon_1^{FD}, \gamma_{SD1,x_2}^{QMF\text{-EH}} \geq \epsilon_2^{FD}, \gamma_{NOMA}^{QMF\text{-EH}} \geq \epsilon_2^{FD} \right) \right] \\
&\quad \times \prod_{k=1}^K \left( 1 - \Pr \left( \gamma_{SRK,x_1}^{QMF} \geq \epsilon_1^{FD}, \gamma_{SRK,x_2}^{QMF} \geq \epsilon_2^{FD}, \gamma_{RKD2,x_2}^{QMF} \geq \epsilon_2^{FD} \right) \right) \quad \text{(E.1)}
\end{align*}\]
Substituting (D.1) and (D.5) into (D.2) and substituting (D.3), the proof is completed.
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GEORGES KADDOUM received the bachelor’s degree in electrical engineering from the École Nationale Supérieure de Techniques Avancées (ENSTA Bretagne), Brest, France, and the M.S. degree in telecommunications and signal processing (circuits, systems, and signal processing) from the Université de Bretagne Occidentale and Telecom Bretagne (ENSTB), Brest, in 2005, and the Ph.D. degree (Hons.) in signal processing and telecommunications from the National Institute of Applied Sciences (INSA), University of Toulouse, Toulouse, France, in 2009. He is currently an Associate Professor and a Tier 2 Canada Research Chair with the École de Technologie Supérieure (ÉTS), Université du Québec, Montréal, Canada. He has published over 200 journal and conference papers and has two pending patents. His recent research activities cover mobile communication systems, modulations, security, and space communications and navigation. He was awarded the ÉTS Research Chair in physical-layer security for wireless networks, in 2014, and the prestigious Tier 2 Canada Research Chair in wireless IoT networks, in 2019. Since 2010, he has been a Scientific Consultant in the field of space and wireless telecommunications for several U.S. and Canadian companies. He received the Best Papers Awards at the 2014 IEEE International Conference on Wireless and Mobile Computing, Networking, Communications (WIMOB), with three coauthors, and at the 2017 IEEE International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC), with four coauthors. He also received the IEEE TRANSACTIONS ON COMMUNICATIONS Exemplary Reviewer Award for the year 2015 and 2017. In addition, he received the Research Excellence Award of the Université du Québec, in 2018, and the Research Excellence Award from the ÉTS in recognition of his outstanding research outcomes, in 2019. He is currently serving as an Associate Editor of the IEEE TRANSACTIONS ON INFORMATION FORENSICS AND SECURITY, and the IEEE COMMUNICATIONS LETTERS.