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Optimal Resource and Power Allocation With Relay Selection for RF/RE Energy Harvesting Relay-Aided D2D Communication

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ABSTRACT Device-to-device (D2D) communication is considered as a promising technology for improving both the spectral and energy efficiencies of cellular networks by reusing the resources of conventional cellular users (CUs) for direct communication of two nearby devices in a spatial manner. When the channel between the two D2D devices is highly attenuated, it is necessary to use an intermediate relay to achieve reliable and flexible relay-aided D2D communication. In order to motivate the cooperative relays to participate, it is assumed that they can harvest energy from radio frequency (RF) signals based on the power splitting (PS) protocol as well as renewable energy (RE) sources. However, resource sharing between the cellular and relay-aided D2D links leads to mutual interference that degrades their sum rate. Considering the energy-harvesting relays (EHRs) and downlink (DL) resource sharing, this paper aims to maximize the sum rate of both the links without degrading the quality of service (QoS) requirements of all users. Our maximization problem is formulated as a mixed-integer nonlinear programming (MINLP) problem that cannot be solved in a straightforward manner. Therefore, we propose a low complexity algorithm, namely the resource and power allocation with relay selection EH-aided algorithm (RPRS-EH), which determines the reuse partners, the PS factor sub-optimal value with optimal links power allocation, and provides two different strategies for optimal relay selection. The numerical results show the behavior of the proposed algorithm under various parameters as well as its considerable performance when compared to one of the most recent algorithms in terms of the links sum rate and relay energy efficiency.

INDEX TERMS Device-to-device, relay-aided, energy harvesting, resource allocation, power splitting, decode-and-forward, power allocation, relay selection.

I. INTRODUCTION

Cellular networks suffer from the exponential growth of tele-traffic volume. This is due to the rapid spread of smart devices with their new services and applications such as Voice Over IP (VOIP), video streaming, and real-time surveillance [1]–[3]. To address these challenges, the fifth-generation (5G) mobile communication standards proposed new technologies like Device-to-Device (D2D) communication, massive MIMO, millimeter-wave, and ultra-dense networks [4]–[8].

D2D communication is one of the most promising technologies that attracts wide attention not only from the academia but also from the industry. This is because of its obvious capability on improving both the spectral and energy efficiencies of cellular networks. Such improvement is realized by allowing two nearby users to share the same resources of conventional cellular users (CUs) and communicate directly with each other without the intervention of the base station (BS) [9]–[14]. However, many challenges

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should be taken into account during the design of a new D2D communication paradigm such as the mutual interference between cellular and D2D links due to the same spectrum resources sharing. Therefore, recent research activities for resource allocation (RA) and power allocation (PA) schemes were presented in [15]–[19]. In [15], the downlink (DL) resource reuse was considered by formulating a joint resource block (RB) and PA problem to maximize the sum-rate of the D2D links. Furthermore, the quality of service (QoS) constraints of the cellular links were taken into consideration. Three kinds of RA modes, namely NorMod, SepMod, and CellMod, were proposed in [16], where the D2D user shared both the uplink (UL) and DL resources of CU. The BS picked out one of the three modes to maximize the sum-rate. In addition, the optimum PA for each of the aforementioned RA modes was derived. In [17], a distributed, self-organized channel and PA scheme was introduced in order to maximize the throughput of D2D pairs considering the QoS of CUs. A joint RB scheduling and power control scheme for D2D communications in LTE-Advanced networks to maximize the spectrum utilization was proposed in [18]. In [19], a joint RA and power control paradigm for energy efficient D2D communications underlying cellular networks was introduced.

Due to the need for extending the communication range as well as enhancing both reliability and flexibility of wireless communication, the relay-aided wireless networks appeared on the horizon [20]–[22]. Consequently, direct D2D communication can be extended into a relay-aided manner when the distance between the D2D transmitter (DT) and receiver (DR) is long and/or the channel between them is highly attenuated [23]–[28]. Two main protocols have been presented in the literature for the relay-aided D2D wireless networks [20], [21]: 1) the amplify-and-forward (AF) protocol where the relay receives the signal from the source, amplifies it, and retransmits it to the destination considering that the amplification and retransmission operations consume energy, and 2) the decode-and-forward (DF) protocol where the signal is received by the relay, decoded, and then re-encoded before retransmitted to the destination. Although the decoding, encoding, and retransmission processes in the DF protocol consume an amount of energy, it is more preferred in applications that require higher performance. This is due to the decoding and encoding advantages [22].

Using the DF protocol, a multi-hop relay-assisted D2D strategy was proposed in [23] to be compared with the classical cellular communication and direct D2D communication in terms of sum-rate. The results showed that the DF relay-assisted D2D strategy outperformed the others. In [24], a practical distributed RA scheme based on the message passing (MP) algorithm for relay-raided D2D communications was introduced. The paper assumed that the D2D traffic was carried through a number of relay nodes as participants in the network-assisted D2D communication. Also, the MP algorithm was considered to maximize the network sum-rate under power constraints. Using the relays for assisting the UEs to communicate with the BS in order to maximize the network sum-rate was proposed in [25]. The Kuhn-Munkres (KM) and greedy algorithms were considered for relay selection, whereas the results showed that the KM algorithm achieved a slightly higher sum-rate than that of the greedy algorithm. In [26], the performance of a relay-aided D2D communication network was analyzed, where the relay nodes could participate in both the cellular and D2D links. The paper considered a low complexity distributed approach for the RA using the stable matching concept. In [27], the authors proposed a quantum coral reefs optimization algorithm (QCROA) that optimally allocated the DL RBs and transmission powers for cooperative D2D users underlying CUs in heterogeneous networks. In addition, the QoS constraints of all users were considered and one of the idle users (IUs) was selected to assist the D2D links transmission. A cross-layer relay selection scheme that took into account more than single criterion was proposed in [28]. The relay selection criteria were the end-to-end data rate, relay-capable UE (RUE) remaining battery time, and end-to-end transmission delay on the relay-assisted D2D path.

In conventional relay-aided D2D communication, the relay nodes (RNs) consume their own energy to perform data transmission between the DT and DR without getting any benefit. Thus, the energy harvesting (EH) technology can play an important role to motivate them to participate in such communication. This can be done by allowing them to harvest energy either from the radio frequency (RF) or renewable energy (RE) sources. The RF EH is performed based on the simultaneous wireless information and power transfer (SWIPT) technology [29]–[38]. On the other hand, the RE energy is collected from different sources such as solar or vibration [15], [39], [40]. In the literature of wireless EH, two main protocols have been proposed i.e., the time splitting (TS) and power splitting (PS) [41]. For the PS protocol, the relay splits a portion of the received signal for EH. However, for the TS protocol, dedicated harvesting time is allocated for the relay to harvest energy from the source received signal.

As far as we know, the integration between the EH and relay-aided D2D communication is still in its infancy. However, some valuable studies have been done [31], [40], [42], [43], [45]–[48]. The integration between the clustering and D2D communication considering EH DF relays that could harvest energy from the RF signal received from the BS was presented in [31]. The proposed design showed a consistent performance to be used in disaster and emergency situations. An algorithm for EH relays (EHRs) in heterogeneous multi-tier networks was introduced in [40]. Each relay was assumed to have its harvesting unit (i.e. solar cell and battery) and energy was collected as packets that arrived in a Poisson process. In [42], D2D communication underlying cellular network was proposed, where a fraction of the CU spectrum was utilized by D2D communication. The authors considered that the D2D users could harvest the RF energy from the ambient cellular interference willing to act as relays for the machine-type communications (MTC) traffic. The study [44] derived a closed-form of the outage probability for direct and relay-aided EH D2D communication assuming the DF and PS protocols in Nakagami fading channel. A half-duplex DF cognitive D2D communication underlying cellular network with the TS EH relaying protocol was presented in [45]. The authors proposed an efficient design that achieved the optimal TS ratio for the EH by relays. In addition, closed-form expressions for the outage probability, sum bit error rate, average EE, and instantaneous rate were derived. In [46], mobile relays that could harvest the RF energy from the BS signal to enhance D2D communication system reliability was presented. Also, a closed-form expression for the outage probability was derived to explore the effect of network parameters on it. Based on the PS protocol, the authors in [47] proposed a public safety approach that enabled the devices out of the BS coverage to communicate with each other in a relay-aided D2D communication manner. In addition, the relays were considered to harvest energy from the RF signal received from the BS. In [48], a hybrid protocol with TS and PS capabilities was proposed to allow certain D2D users to harvest energy and share the spectrum of the CU using the DF relaying protocol in order to achieve a required data rate.

A. MOTIVATION AND CONTRIBUTIONS

To the best of our knowledge, combining both RF and RE EH technologies to be utilized in D2D communication has not been investigated yet, which motivates us to present this work. The main advantage of the RF energy is its availability all the time, while the main advantage of the RE energy is the providing of the attached nodes with a significant amount of energy during availability. Therefore, providing the relays with these two EH technologies motivates them to participate in the relay-aided D2D communication and prolongs network lifetime as well. It is important to note that depending only on the RF energy for relays without the support of different sources like RE may cause undesired QoS level or transmission outage at the DR. This is due to the low energy harvested by relays according to the concept of SWIPT technology [29]–[38].

In contrast to most of the previous work, the DL spectrum sharing is considered in our model as it fits the proposed PA strategy that assigns maximum transmission power to the cellular links (i.e. BS). Since the D2D links are assumed to be at the cell boundary, they are not affected by the interference received from the BS even if it transmits with maximum power. If the UL spectrum sharing is considered with the maximum PA for the CUs, they could be somewhere next to the D2D links thus impose severe interference on the DRs. Moreover, the optimization and analysis of the joint DL RA and PA problem with relay selection for EH relay-aided D2D communication underlying conventional cellular network have not been widely investigated. Proposing such a model is one of the main motivation points behind this work as well. Also, the proposed DL spectrum sharing model can be improved using MIMO and beamforming technologies in order to increase the RF EH amount received by the D2D links from the BS [32]. Furthermore, this work can be readily extended to uplink resource reuse scenarios by considering the SINR analysis at the BS.

In this paper, we consider a number of cooperative relay-aided D2D communication links that reuse the DL subcarriers of conventional CUs. The D2D relays are assumed to use the DF protocol and harvest the RF energy from the received signals based on the PS EH protocol in addition to the RE energy from the attached solar panels. Our aim is to maximize the sum-rate of both the relay-aided D2D and cellular links. This is done by investigating the DL resource and PA with relay selection for the EH relay-aided D2D communication underlying the conventional cellular network.

Unlike the UL RA for relay-aided D2D communication algorithm (for convenience, we call it Uplink RA) [49], the RA is performed by selecting the reuse partners based on the conventional approach of channel gain information. The conventional approach considers both the channel attenuation coefficient and distance between the DT and CU. However, the Uplink RA algorithm considered the interference-limited area (ILA) based scheme and district partition mechanism for selecting the reuse partners. Hence, the channel gain coefficient was not taken into account for selecting the reuse partners of the Uplink RA algorithm. Also, contrary to [49], the proposed relay selection strategy that aims at maximizing the sum-rate of both the links performs relay selection such that the overall sum-rate of both the links is maximized. However, only the relay-aided D2D link rate maximization was considered for the Uplink RA algorithm. Furthermore, we not only maximize the sum-rate of both the links more than that of the Uplink RA algorithm but also consider the network EE by conserving the residual energy of the participating relays.

The main contributions of our work can be summarized as follows:

- Our maximization problem is formulated as a mixed integer nonlinear programming (MINLP) problem of the DL RA, PS factor optimization with PA, and optimal relay selection for the relay-aided D2D communication underlying the conventional cellular network. We aim to maximize the sum-rate of the cellular and relay-aided D2D links by considering their QoS requirements as well as the EH constraints, maximum power limit of the subcarriers, and BS maximum power budget.
- Our MINLP problem is complex and cannot be solved in a straightforward manner. Thus, a simple, non-iterative, and low complexity algorithm called the resource and PA with relay selection EH-aided (RPRS-EH) algorithm is proposed. The RPRS-EH algorithm is divided into three main sub-algorithms. The first sub-algorithm determines the optimal reuse partners, while the second sub-algorithm determines the sub-optimal value of the PS factor and allocates the power for the links optimally. The third sub-algorithm provides two optimal relay selection strategies based on the tradeoff concept in economics, which are supposed to contribute too many

D2D applications. The first strategy performs relay selection such that the sum-rate of both the links is maximized, which is the main aim of our work. On the other hand, the second strategy selects the relays such that the total amount of the energy transferred from the selected relay to its neighbors is maximized.
- Numerical results show the behavior of the proposed RPRS-EH algorithm versus various parameters and that it improves the sum-rate of both the cellular and D2D relay-aided links. In addition, the results depict that the RPRS-EH algorithm outperforms the Uplink RA algorithm in terms of the maximum achieved sum-rate of both the links and EE of the relays as well.

B. PAPER ORGANIZATION
The rest of this paper is organized as follows. In section II, the system model is presented including the EH, relay energy, and transmission models as well as the problem formulation. The proposed algorithm RPRS-EH is discussed in section III in order to solve the three main sub-problems that aim to maximize the sum-rate of both the cellular and relay-aided D2D links. In section IV, the performance of the proposed algorithm is investigated and compared to one of the most recent algorithms. Finally, the conclusions of this paper are presented in section V.

II. SYSTEM MODEL
We consider a DL resource sharing scenario in a single micro-cell with a BS that is located at the center of the cell, multiple active CUs, and a number of relay-aided D2D links. Considering public safety networks with enhancing network coverage, the DT and DR pairs are assumed to be fixed and located at the boundary of the cell [39]. Therefore, there is no direct link between the D2D devices and the BS. Let the distance between the DT and DR to be long and their channel is highly attenuated so that direct communication between them is also not possible. Thus, the DT and DR aim to perform their transmission through the help of multiple EHRs, denoted by $R_l, l = 1, 2, \ldots L$, which are randomly placed within the communication range of both the terminals. Each R_l is assumed to be a half-duplex and hybrid RF/RE-based EHR that operates with DF protocol.

Let the set of the cellular and D2D links to be denoted as $\mathbb{K} = \{1, 2, \ldots, K\}$ and $\mathbb{M} = \{1, 2, \ldots, M\}$, respectively. The communication channels are assumed to be independent and identically distributed (i.i.d.) Rayleigh channels with perfect channel state information (CSI) availability. The Rayleigh fading is considered to investigate the worst case scenario regarding the amount of the energy transferred between the devices excluding the impact of the line-of-sight component. The channel attenuation coefficient and distance between any two nodes x and y are denoted by h_{xy} and d_{xy}, respectively. For simplicity, $\alpha_{xy} = \frac{|h_{xy}|^2}{d_{xy}^{\nu}}$ is used throughout this paper in order to represent the effect of the channel gain with path loss exponent ν.

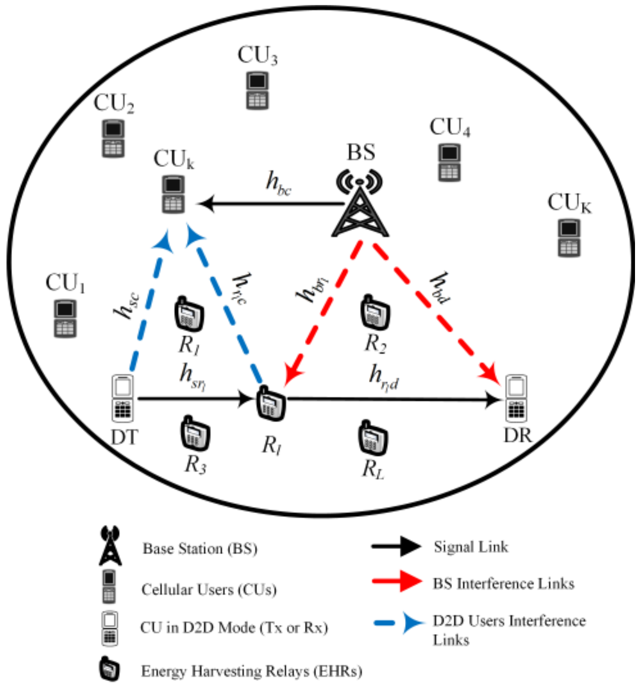

FIGURE 1. System model of the relay-aided D2D communication underlying conventional DL cellular network.

Furthermore, each transmission time period is considered to be finite and is divided into equal Q time slots, where each time slot q is of duration T_c and is divided into two sub-slots (i.e. τ_1 and τ_2) of equal size $T_c/2$. In the first sub-slot (τ_1), the BS sends its message to the CU, while at the same time the DT sends its message to one of the relays (i.e. R_l) along the path to the DR. In the second sub-slot (τ_2), the BS again sends its message to the CU while the relay R_l, in turn, sends the received message to the DR using the DF protocol. Without loss of generality, for every time slot q, the channel gain $\alpha_{xy,q}$ between any two nodes x and y is assumed to be constant.

Also, it is assumed that both the cellular and relay-aided D2D links share the same DL spectrum, where a set of N orthogonal frequency division multiplexing (OFDM) subcarriers is available and denoted as $\mathbb{N} = \{1, 2, \ldots, N\}$. In addition, each relay-aided D2D pair is allowed to reuse only one subcarrier, where the same subcarrier is assigned to both DT-R_l and R_l-DR links for the same time slot q. Fig. 1 shows a scenario of picking up a relay-aided D2D link m ($1 \leq m \leq M$) that includes relay l ($1 \leq l \leq L$) underlying a cellular link k ($1 \leq k \leq K$) as both of them share the same subcarrier n ($1 \leq n \leq N$). It is important to note that when R_l is selected to participate in the relay-aided D2D link, we denote it as $\mathcal{R}_\psi$ (i.e. $l = \psi$) for notation convenience. Table 1 summarizes all notations used throughout this paper.

A. ENERGY HARVESTING MODEL
In this paper, each R_l is considered as a hybrid RF/RE-based EHR with two energy harvesters [50], [51]. One can harvest the RF energy from the received signals coming from the DT, $\mathcal{R}_\psi$, and BS, while the other harvester can harvest the

TABLE 1. List of notations.

Symbol	Description
$\mathbb{K}$	Set of cellular links
$\mathbb{M}$	Set of D2D links
$\mathbb{N}$	Set of subcarriers
$\mathbb{L}$	Set of relays
$\mathbb{R}_N$	Set of non-selected relays
$\mathbb{R}_C$	Set of candidate relays
$P_{b,q}$	BS transmission power during time slot q
$P_{s,q}$	DT transmission power during time slot q
$E^{RF}_{r_l,q}$	Relay RF harvested energy during time slot q
$P^{RF}_{r_l,q}$	Relay transmission power comes from RF EH during time slot q
$E^{RE}_{r_l,q}$	Relay RE harvested energy during time slot q
$P^{RE}_{r_l,q}$	Relay transmission power comes from RE EH during time slot q
$E^{h}_{r_l,q}$	Relay harvested energy (RF+RE) during time slot q
$E^{Res}_{r_l,q}$	Residual energy of relay l at the end of time slot q
$E^{C}_{r_l,q}$	Energy consumption of relay l during time slot q
$P_{r_l,q}$	Total relay transmission power during time slot q
$x_{ab,q}$	Transmitted symbol between any two nodes a and b during time slot q
T_c	Time slot duration
$h_{xy,q}$	Channel attenuation coefficient between node x and y during time slot q
d_{xy}	Distance between node x and y
$\alpha_{xy,q}$	Channel gain between node x and y during time slot q
ν	Path loss exponent
R_l	EH relay l (EHR)
$\mathcal{R}_\psi$	Selected EH relay ($l = \psi$)
$\zeta_{mr_l,q}$	Binary variable to indicate relay l status during time slot q
$\beta_{mk,q}$	Binary variable to indicate subcarrier assignment status between relay-aided D2D link m and cellular link k during time slot q
$\rho_{r_l,q}$	PS ratio of relay l during time slot q ($l = \psi$ if relay l is selected)
$\rho^{opt}_{r_l,q}$	Adaptive sub-optimal PS factor value of relay l during time slot q
η^{RF}	RF conversion efficiency coefficient

RE energy from the solar sources. Since the relay-aided D2D links lie at the cell boundary, the energy harvested from the BS interference is negligible. The relay status (*selected/non-selected*) determines the amount of the RF EH based on the following criterion. For selected relay $\mathcal{R}_\psi$, it is assumed to operate with the PS protocol and harvest a portion of the DT received signal with PS ratio $\rho_{r_\psi,q}$ $(0 < \rho_{r_\psi,q} < 1)$ during τ_1. The harvested RF energy supports the relay transmission power during τ_2 when retransmitting the DT signal to the DR. However, the set of non-selected EHRs $\mathbb{R}_N$ located within the transmission range of the DT and $\mathcal{R}_\psi$ are supposed to keep silent and adjust their frequencies to the same shared subcarrier n. They are able to harvest the RF energy from the DT signal during τ_1 and $\mathcal{R}_\psi$ signal during τ_2 with $\rho_{r_l,q} = 1$. The conversion efficiency coefficient of the RF source is considered during the RF EH, which is denoted by η^{RF} and lies in the interval [0,1].

On the other hand, it is assumed that each R_l is also equipped with a solar panel that is capable of harvesting the RE energy from the ambient environment. In addition, the offline approach for energy management is considered as it is assumed that the relay R_l has the full knowledge of the amount of the EH and its arrival time [52]. Considering the discrete time EH model, the energy arrives at the beginning of each time slot and is stored for later use taking into account the relay maximum storage capacity to avoid battery overflow. Also, the causality constraint is considered as the energy may not be used before it is harvested. According to the National Renewable Energy Laboratory (NREL) real-life data set, the mean and variance solar EH during the day time are $0.024W/m^2$ and $4.3W/m^2$, respectively. These values are used in our model [39], [53]. Furthermore, this paper considers the harvest-store-use transmission management approach in which the energy storage and retrieval from the battery is assumed to be neglected [54].

B. RELAY ENERGY MODEL

The total energy harvested by R_l during time slot q is given by [54]:

$$\begin{aligned} E^{h}_{r_l,q} &= E^{RF}_{r_l,q} + E^{RE}_{r_l,q} \\ &= \zeta^{(n)}_{mr_l,q}\big[(\eta^{RF}\rho_{r_l,q}P_{s,q}\alpha_{sr_l,q})\frac{T_c}{2}\big]_{(l=\psi)} \\ &\quad + (1-\zeta^{(n)}_{mr_l,q})\big[\eta^{RF}P_{s,q}\alpha_{sr_l,q}\frac{T_c}{2} \\ &\quad + \eta^{RF}P_{r_\psi,q}\alpha_{r_\psi r_l,q}\frac{T_c}{2}\big]_{(l\neq\psi)} + E^{RE}_{r_l,q}T_c \end{aligned} \tag{1}$$

where $E^{RF}_{r_l,q}$ and $E^{RE}_{r_l,q}$ are the RF and RE harvested energies by relay l during time slot q, respectively. The binary variable $\zeta^{(n)}_{mr_l,q}$ indicates the status of the l^{th} relay as either selected or non-selected to participate in relay-aided D2D link m sharing subcarrier n. If the relay R_l is selected, $\zeta^{(n)}_{mr_l,q} = 1$; otherwise, $\zeta^{(n)}_{mr_l,q} = 0$. In case of selection (i.e. $l = \psi$), the relay R_l harvests from the DT power $P_{s,q}$ during τ_1 with conversion efficiency coefficient η^{RF} and PS factor $\rho_{r_l,q}$, where $\alpha_{sr_l,q}$ is the channel gain between the DT and relay l. On the other hand, if R_l is a non-selected relay (i.e., $l \neq \psi$), it harvests from $P_{s,q}$ during τ_1 and from the selected relay's power $P_{r_\psi,q}$ during τ_2, where $\alpha_{r_\psi r_l,q}$ is the channel gain between $\mathcal{R}_\psi$ and R_l. In addition, both the selected and non-selected relays harvest the RE by means of their attached solar panel, where the energy arrives at the beginning of each time slot q every T_c.

Moreover, the total harvested power represented by $P^{RF}_{r_l,q}$ and $P^{RE}_{r_l,q}$ motivates the relay R_l to participate in the relay-aided D2D link transmission. In this case, the relay significantly depends on the harvested energy rather than relying entirely on its residual energy. Fig. 2 depicts the block diagram of the RE and RF EH model for a selected and

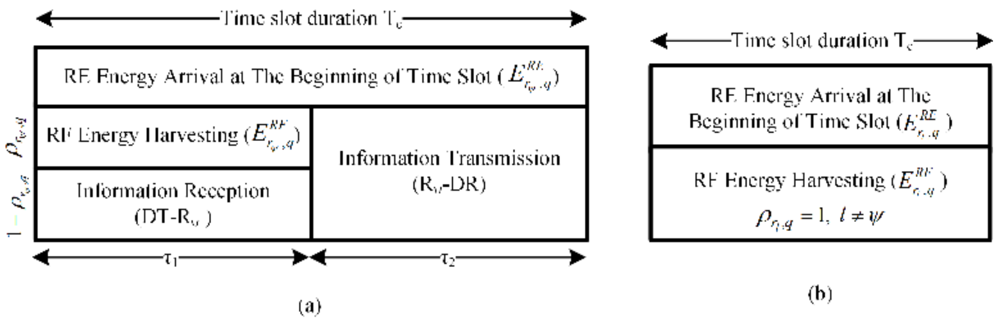

FIGURE 2. Block diagram of RE and RF EH model during time slot q for (a) selected relay (b) non-selected relay.

non-selected relay during time slot q as well as the amount of the harvested energy and its harvesting time for each relay.

At the end of each time slot q, the residual energy of the l^{th} relay, taking into account battery maximum capacity E_{max} to avoid overflow, is denoted by:

$$E^{Res}_{r_l,q} = \min\Bigg\{E_{max}, \Bigg(\zeta^{(n)}_{mr_l,q}[E^{Res}_{r_l,q-1} + E^h_{r_l,q} - E^C_{r_l,q}] + (1-\zeta^{(n)}_{mr_l,q})[E^{Res}_{r_l,q-1} + E^h_{r_l,q}]\Bigg)\Bigg\} \tag{2}$$

where $E^C_{r_l,q}$ is the energy consumption of the relay R_l, *if selected*, during time slot q.

C. TRANSMISSION MODEL

In this model, we pick up a relay-aided D2D link m among the available M links considering the PS protocol for the relays RF EH, where the role of the RE to support the total relay transmission power $P_{r_l,q}$ is clarified in section III.

As mentioned before, the data transmission of each time slot q is performed in two sub-slots (i.e. τ_1 and τ_2). For the first sub-slot τ_1, the received signal at the CU is:

$$S^{(\tau_1)}_{c,q} = \sqrt{P_{b,q}}\frac{h_{bc,q}}{\sqrt{d^{\nu}_{bc}}}x_{bc,q} + \sqrt{P_{s,q}}\frac{h_{sc,q}}{\sqrt{d^{\nu}_{sc}}}x_{sr_l,q} + n_{c,q} \tag{3}$$

where $P_{b,q}$ is the BS transmission power, $h_{bc,q}$ and d_{bc} are the attenuation coefficient and distance between the BS and CU, respectively, $x_{bc,q}$ is the transmitted symbol from the BS to the CU, and ν is the path loss exponent. $P_{s,q}$ is the DT transmission power, while $h_{sc,q}$ and d_{sc} are the attenuation coefficient and distance between the DT and CU, respectively. The transmitted symbol from the DT to the relay R_l is $x_{sr_l,q}$, while the additive white Gaussian noise (AWGN) is combined with the noise generated from the passband to baseband conversion at the CU and is denoted as $n_{c,q}$ with variance $\sigma^2_{c,q}$. The signal-to-interference-noise ratio (SINR) at the CU is given by:

$$\gamma^{(\tau_1)}_{c,q} = \frac{P_{b,q}\alpha_{bc,q}}{P_{s,q}\alpha_{sc,q} + \sigma^2_{c,q}} \tag{4}$$

where $\alpha_{bc,q}$ is the channel gain between the BS and CU and $\alpha_{sc,q}$ is between the DT and CU. The received signal at the relay R_l can be expressed as follows:

$$S^{(\tau_1)}_{r_l,q} = \sqrt{(1-\rho_{r_l,q})P_{s,q}}\frac{h_{sr_l,q}}{\sqrt{d^{\nu}_{sr_l}}}x_{sr_l,q} + \sqrt{P_{b,q}}\frac{h_{br_l,q}}{\sqrt{d^{\nu}_{br_l}}}x_{bc,q} + n_{r_l,q} \tag{5}$$

where $\rho_{r_l,q}$ is the PS factor of relay l during time slot q to be optimized, $h_{sr_l,q}$ and d_{sr_l} are the attenuation coefficient and distance between the DT and R_l, respectively. $(1-\rho_{r_l,q})P_{s,q}\alpha_{sr_l,q}$ is the part of the received signal that is used for information decoding. The other part of the received signal is harvested by the relay l and stored in its battery for τ_2 transmission. The amount of the RF harvested energy during time slot q is $E^{RF}_{r_l,q} = [\eta^{RF}\rho_{r_l,q}P_{s,q}\alpha_{sr_l,q}]\frac{T_c}{2}$ so the part of the l^{th} relay total transmission power that comes from the RF harvesting is $P^{RF}_{r_l,q} = \frac{E^{RF}_{r_l,q}}{T_c/2} = \eta^{RF}\rho_{r_l,q}P_{s,q}\alpha_{sr_l,q}$. The attenuation coefficient and distance between the BS and R_l are $h_{br_l,q}$ and d_{br_l}, respectively. The combined noise at the l^{th} relay is denoted by $n_{r_l,q}$ with variance $\sigma^2_{r_l,q}$. As aforementioned, it is assumed that the harvested power from the BS interference signal is negligible as it is very low when compared to the signal received from the DT as the D2D pair is located at the cell boundary [55]. Also, the noise power is not considered for harvesting due to its tiny value.

The SINR at the relay l is given by:

$$\gamma^{(\tau_1)}_{r_l,q} = \frac{(1-\rho_{r_l,q})P_{s,q}\alpha_{sr_l,q}}{P_{b,q}\alpha_{br_l,q} + \sigma^2_{r_l,q}} \tag{6}$$

For the second sub-slot τ_2 of time slot q, the received signal at the CU is:

$$S^{(\tau_2)}_{c,q} = \sqrt{P_{b,q}}\frac{h_{bc,q}}{\sqrt{d^{\nu}_{bc}}}x_{bc,q} + \sqrt{P^{RF}_{r_l,q}}\frac{h_{r_lc,q}}{\sqrt{d^{\nu}_{r_lc}}}S^{(\tau_1)}_{r_l,q} + n_{c,q} \tag{7}$$

where the channel attenuation coefficient and distance between the relay R_l and CU are given by $h_{r_lc,q}$ and d_{r_lc}, respectively. The SINR at the CU is given by:

$$\gamma^{(\tau_2)}_{c,q} = \frac{P_{b,q}\alpha_{bc,q}}{P^{RF}_{r_l,q}\alpha_{r_lc,q} + \sigma^2_{c,q}} \tag{8}$$

where $\alpha_{r_l c,q}$ is the channel gain between the relay R_l and CU during sub-slot τ_2 of time slot q. The received signal at the DR can be expressed as follows:

$$S_{d,q}^{(\tau_2)} = \sqrt{P_{r_l,q}^{RF}}\frac{h_{r_l d,q}}{\sqrt{d_{r_l d,q}^{v}}}S_{r_l,q}^{(\tau_1)} + \sqrt{P_{b,q}}\frac{h_{bd,q}}{\sqrt{d_{bd,q}^{v}}}x_{bc,q} + n_{d,q} \quad (9)$$

where $h_{r_l d,q}$ and $d_{r_l d}$ are the channel attenuation coefficient and distance between the relay R_l and DR, respectively. The channel attenuation coefficient and distance between the BS and DR are $h_{bd,q}$ and d_{bd}, respectively. The AWGN and conversion noises at the DR are denoted together by $n_{d,q}$ with variance $\sigma_{d,q}^2$. The SINR at the DR is given by:

$$\gamma_{d,q}^{(\tau_2)} = \frac{P_{r_l,q}^{RF}\alpha_{r_l d,q}}{P_{b,q}\alpha_{bd,q} + \sigma_{d,q}^2} \quad (10)$$

where $\alpha_{r_l d,q}$ is the channel gain between the relay R_l and DR during time slot q, while the channel gain between the BS and DR is $\alpha_{bd,q}$.

The subcarrier assignment is denoted by a binary variable $\beta_{mk,q}^{(n)}$, which is defined as:

$$\beta_{mk,q}^{(n)} = \begin{cases} 1, & \text{if relay-aided D2D link } m \text{ shares} \\ & \text{subcarrier } n \text{ with CU link } k\,. \\ 0, & \text{otherwise.} \end{cases} \quad (11)$$

The sum-rate of both cellular link k and relay-aided D2D link m that share the same subcarrier n, considering the PS EH protocol at the relays, is given by:

$$\sum_{m\in\mathbb{M}} R^{sum} = \sum_{m\in\mathbb{M}} R_{C,q} + R_{D,q} \quad (12)$$

where $R_{C,q}$ and $R_{D,q}$ are the data rates of cellular link k and relay-aided D2D m, respectively, and are given as:

$$R_{C,q} = \sum_{n\in\mathbb{N}}\sum_{k\in\mathbb{K}}\sum_{l\in\mathbb{L}} \beta_{mk,q}^{(n)}\zeta_{mr_l,q}^{(n)}(R_{C,q}^{(\tau_1)} + R_{C,q}^{(\tau_2)}) \quad (13)$$

$$R_{D,q} = \sum_{n\in\mathbb{N}}\sum_{k\in\mathbb{K}}\sum_{l\in\mathbb{L}} \beta_{mk,q}^{(n)}\zeta_{mr_l,q}^{(n)}\min\{R_{D,q}^{(\tau_1)}, R_{D,q}^{(\tau_2)}\} \quad (14)$$

where $R_{C,q}^{(\tau_1)} = \frac{B}{2}\log_2(1+\gamma_{c,q}^{(\tau_1)})$, $R_{C,q}^{(\tau_2)} = \frac{B}{2}\log_2(1+\gamma_{c,q}^{(\tau_2)})$, $R_{D,q}^{(\tau_1)} = \frac{B}{2}\log_2(1+\gamma_{r_l,q}^{(\tau_1)})$, and $R_{D,q}^{(\tau_2)} = \frac{B}{2}\log_2(1+\gamma_{d,q}^{(\tau_2)})$.

D. PROBLEM FORMULATION

In this section, the problem of the relay-aided D2D communication links underlying the conventional cellular links using the DL spectrum sharing with EH capability for relays is formulated. The main aim is to maximize the sum-rate of both the relay-aided D2D and cellular links. This is achieved by selecting the best partner for each D2D link m among the available K CUs to share the same subcarrier n using an appropriate RA scheme during each time slot q. In addition, the transmit powers of both the links should be optimally allocated. Also, we aim at optimizing the PS factor $\rho_{r_l,q}$ for each relay l to measure its performance individually then the best relay is selected. The EH, QoS of both the links, subcarriers reuse, and power constraints are considered as well as the maximum power budget of the BS and maximum allowed transmission power of the subcarriers. Clearly, the optimization problem can be formulated as a constrained objective function (OF) over vectors $\boldsymbol{\rho_{r_l}}$, $\boldsymbol{P_s}$, $\boldsymbol{P_{r_l}}$, $\boldsymbol{\beta_{mk}^{(n)}}$, and $\boldsymbol{\zeta_{mr_l}^{(n)}}$, which is given as:

$$\max_{\rho_{r_l}^{opt}, P_s, P_b, P_{r_l}, \beta_{mk}^{(n)}, \zeta_{mr_l}^{(n)}} \sum_{m\in\mathbb{M}} R^{sum} \quad (15a)$$

$$\text{subject to: } \sum_{m=1}^{M}\sum_{k=1}^{K}\beta_{mk,q}^{(n)} \le 1 \quad \forall n$$

$$,\text{where } \beta_{mk,q}^{(n)} = \{0,1\}, \forall k,m,n \quad (15b)$$

$$0 \le \rho_{r_l,q}^{opt} \le 1, \quad \forall l \quad (15c)$$

$$\min\{\gamma_{c,q}^{(\tau_1)}, \gamma_{c,q}^{(\tau_2)}, \gamma_{r_l,q}^{(\tau_1)}, \gamma_{d,q}^{(\tau_2)}\} \ge \gamma_{min} \quad (15d)$$

$$0 \le P_{b,q}^{(n)} \le P_b^{max} \quad \forall n \quad (15e)$$

$$0 \le P_{i,q}^{(n)} \le P_{max},$$

$$\text{where } i \in \{b, s, r_l\}, \quad \forall l, n \quad (15f)$$

$$\sum_{m=1}^{M}\sum_{l=1}^{L}\zeta_{mr_l,q}^{(n)} \le 1 \quad \forall n$$

$$,\text{where } \zeta_{mr_l,q}^{(n)} = \{0,1\}, \forall l,m,n \quad (15g)$$

$$P_{r_l,q}^{(n)}\frac{T_c}{2} \le E_{r_l,q}^{h} + E_{r_l,q-1}^{Res} \quad \forall l, n \quad (15h)$$

$$E_{r_l,q}^{Res} \le E_{max} \quad \forall l \quad (15i)$$

where (15a) represents the MOF of maximizing the sum of the data rates of the cellular and relay-aided D2D links over N subcarriers. Constraint (15b) ensures that only one OFDMA subcarrier n is shared between the relay-aided D2D and cellular links. The interval in which the optimal value of the PS factor lies is defined in constraint (15c). In addition, the QoS constraints for all links are presented by (15d) ensuring that the SINR of each link does not get below a required value γ_{min}. Constraint (15e) ensures that the PA of the BS should not exceed its power budget P_b^{max}. Whereas, constraint (15f) guarantees that the practical transmit powers of all links are always not beyond the maximum power limit P_{max}. It is stated in constraint (15g) that each relay-aided D2D link employs only one relay node R_l that shares a single subcarrier n. Whereas, constraints (15h) and (15i) depict the energy causality and overflow constraints, respectively.

It is clear that (15) is an MINLP problem with a non-convex OF (15a) since it contains two binary variables $\beta_{mk,q}^{(n)}$ and $\zeta_{mr_l,q}^{(n)}$ in addition to non-linear constraint (15d). Hence, the problem is considered as an NP-hard problem and it is difficult to be solved for an optimal solution in a straightforward manner [56]. Therefore, we decompose our main problem into a number of sub-problems and propose a simple, non-iterative, and low complexity algorithm that solves each sub-problem individually as presented in the following section.

III. RESOURCE AND POWER ALLOCATION WITH RELAY SELECTION ENERGY HARVESTING-AIDED (RPRS-EH) ALGORITHM

In this section, our main problem is addressed as three main sub-problems, which are the 1) RA sub-problem, 2) determination of the adaptive sub-optimal value of PS factor with optimal PA sub-problem, and 3) relay selection sub-problem. To deal with this, we present the RPRS-EH algorithm that is divided into three main sub-algorithms. Each sub-algorithm represents a strategy that is able to solve one of the aforementioned sub-problems as the following.

A. INTERFERENCE MITIGATION RESOURCE ALLOCATION STRATEGY (IMRA)

We propose a DL RA strategy, called IMRA, that selects the partners of the relay-aided D2D links among the available CUs such that the sum-rate is maximized. Although the strategy is based on the conventional approach of channel gain information [39], it is an efficient scheme for the proposed model. Whereas, it considers the channel gain between the DT and its partner CU_k rather than considering the distance between them only [49]. It is clear that the low mutual channel gain $\alpha_{sc,q}$ between the DT of link m and its partner CU_k mitigates the interference between them and as a result increases the SINR as depicted in (4). The gain between the BS and D2D devices is ignored since it is assumed that the D2D pairs are located at the cell boundary so, the interference received from the BS toward the devices is not that effective. Our RA problem for relay-aided D2D link m is presented as the following:

$$\max_{\beta_{mk,q}^{(n)}} \sum_{m\in\mathbb{M}} R^{sum} \quad (16a)$$

$$\text{subject to (15b)} \quad (16b)$$

The details of the proposed RA strategy IMRA are shown in Sub-Algorithm 1. The sub-algorithm takes the set of subcarriers $\mathbb{N}$ and channel gain matrix $\boldsymbol{\alpha}$ as the inputs to return subcarrier assignment matrix of CUs U_c and D2D links partner matrix U_p. In step 1, each CU k is assigned only one subcarrier n according to constraint (15b), where the assignment information is stored in matrix U_c. The partner selection process is performed in step 2, where each D2D link m selects its partner among the set of the cellular users such that their mutual channel gain is minimum. It is important to note that after the selection of relay $\mathcal{R}_\psi$, the DT and $\mathcal{R}_\psi$ use the same subcarrier n of the selected partner k during each time slot transmission.

B. MAXIMUM-RATE BOUNDARIES POWER ALLOCATION BASED ON EH CAPABILITIES (MBPA-EH)

After the selection of the reuse partners, another strategy that represents the second sub-problem, namely MBPA-EH, is proposed. The MBPA-EH strategy finds the sub-optimal value of the PS factor (i.e. $\rho_{r_l,q}^{opt}$) for each relay l that maximizes the data rate of the relay-aided D2D link during

Sub-Algorithm 1 Interference Mitigation Resource Allocation (IMRA)

Input: $\mathbb{N}$, Channel gain matrix ($\boldsymbol{\alpha}$).
Output: CUs subcarrier assignment matrix U_c, Partner Matrix of D2D links U_p.

Step 1: Assign only one subcarriers to each CU
for $i = 1$ to K **do**
    Assign subcarrier n to link k in U_c.
end for
Step 2: Select reuse partners
for each D2D link m in $\mathbb{M}$ **do**
    Find the CU k with minimum mutual gain (α_{mk}) with link m (i.e., α_{mk})
    $U_p \leftarrow (m, k)$
    D2D link m and cellular user k are partners
end for

τ_1 and τ_2. In addition, we aim to efficiently allocate the power of the BS, DT, and each R_l considering the QoS constraint in (15d), the power constraints in (15e) and (15f), and the causality constraint in (15h). The MBPA-EH sub-problem represented by the PS factor optimization and PA for fixed subcarriers is given as:

$$\max_{\rho_{r_l,q}^{opt}, P_{s,q}, P_{b,q}, P_{r_l,q}} \sum_{m\in\mathbb{M}} R^{sum} \quad (17a)$$

$$\text{subject to (15c), (15d), (15e), (15f), and (15h).} \quad (17b)$$

where the details of the MBPA-EH strategy is presented as the following.

1) PS FACTOR OPTIMIZATION

Here, we determine the sub-optimal PS factor of each R_l that enables the relay to harvest RF energy as much as it can from the DT received signal considering the QoS requirements. This happens despite the fact that the RE harvested energy participates in the total relay transmission power $P_{r_l,q}$, where the PS factor value is changed adaptively with the channel conditions.

It is known that for the DF protocol, the $\min\{\gamma_{r_l,q}^{(\tau_1)}, \gamma_{d,q}^{(\tau_2)}\} = \min\{\frac{(1-\rho_{r_l,q})P_{s,q}\alpha_{sr_l,q}}{P_{b,q}\alpha_{br_l,q}+\sigma_{r_l,q}^2}, \frac{\eta^{RF}\rho_{r_l,q}P_{s,q}\alpha_{sr_l,q}\alpha_{r_ld,q}}{P_{b,q}\alpha_{bd,q}+\sigma_{d,q}^2}\}$ is maximized when all of its arguments are equal [57]; hence, the optimal value of $\rho_{r_l,q}$ can be obtained by equating $\gamma_{r_l,q}^{(\tau_1)}$ and $\gamma_{d,q}^{(\tau_2)}$ as:

$$\rho_{r_l,q}^{*} = \frac{1}{1+\frac{X_1 Y_1}{Z_1}} \quad (18)$$

where $X_1 = P_{b,q}\alpha_{br_l,q} + \sigma_{r_l,q}^2$, $Y_1 = \eta^{RF}\alpha_{r_ld,q}$, and $Z_1 = P_{b,q}\alpha_{bd,q} + \sigma_{d,q}^2$. It is clear from (18) that the value of the PS factor is adaptive to the gains of BS-R_l, R_l-DR, and BS-DR channels including the channel attenuation coefficient and distance between every two nodes. Numerically, it is found that the value of the PS factor does not lie in the interval [0,1] and is always more than 1. That means, the relay needs to harvest the full received power to be able to achieve its required rate during τ_2 (i.e., R_l-DR) transmission; therefore, the data rate during τ_1 (i.e., DT-R_l) is zero.

To solve this problem, we suggest another adaptive sub-optimal value for the PS factor, called $\rho_{r_l,q}^{opt}$, that is always within the required interval [0,1]. The value of $\rho_{r_l,q}^{opt}$ is identical to $\rho_{r_l,q}^{*}$ shown in (18) except that it depends on the channel attenuation coefficient h_{xy} without depending on the path loss term $d_{xy}^{-\nu}$ between any two nodes x and y. Surely, only the amount of RF harvested power $P_{r_l,q}^{RF}$ due to $\rho_{r_l,q}^{opt}$ is not sufficient for the relay transmission during sub-slot τ_2. Thus, the role of relay RE harvested power $P_{r_l,q}^{RE}$ appears to offset this power shortage as shown in the following subsection. The value of the adaptive sub-optimal PS factor is given by $\rho_{r_l,q}^{opt} = 1/(1 + \frac{X_2 Y_2}{Z_2})$, where $X_2 = P_{b,q}h_{br_l,q} + \sigma_{r_l,q}^2$, $Y_2 = \eta^{RF} h_{r_l d,q}$, and $Z_2 = P_{b,q}h_{bd,q} + \sigma_{d,q}^2$.

2) POWER ALLOCATION

We present a PA scheme that allocates power to the BS, DT, and R_l such that the sum-rate of both the relay-aided D2D and cellular links is maximized. In addition, the QoS constraints of all links are taken into account as well as the causality constraint of the relay transmission power. Because the CU is considered as the primary user in the proposed relay-aided D2D communication model, it is prioritized over the DT and relay l by allocating it the maximum power limit P_{max}. In this case, the D2D links lie at the boundary of the cell and are not seriously affected by the BS interference. Therefore, for fixed subcarriers, known value of the PS factor for each relay, and constant cellular link power $P_b = P_{max}$, the PA problem is given as:

$$\max_{P_{s,q},P_{r_l,q}} R^{sum} \tag{19a}$$

$$\text{subject to (15d), (15f), and (15h).} \tag{19b}$$

Now, the PA problem is to allocate the optimal power to the DT and R_l considering the energy causality and QoS constraints of all links. In order to meet the QoS requirements of both the cellular and relay-aided D2D links with respect to the minimum desired SINR γ_{min}, we derive the lower and higher bounds of both $P_{s,q}$ and $P_{r_l,q}$ during τ_1 and τ_2, respectively.

In agreement with (15d) and (15f) and by substituting with γ_{min} in (6) and (4), the lower and higher bounds of DT transmit power $P_{s,q}$ during τ_1 can be obtained respectively as:

$$P_{S_{Low},q} = \frac{\gamma_{min}(P_{b,q}\alpha_{br_l,q} + \sigma_{r_l,q}^2)}{(1-\rho_{r_l,q}^{opt})\alpha_{sr_l,q}} \tag{20}$$

$$P_{S_{High},q} = \min\left\{P_{max}, \frac{P_{b,q}\alpha_{bc,q} - \gamma_{min}\sigma_{c,q}^2}{\gamma_{min}\alpha_{sc,q}}\right\} \tag{21}$$

where $P_{S_{Low},q}$ preserves the minimum SINR requirements of DT-R_l link and $P_{S_{High},q}$ preserves the minimum SINR requirements of the cellular link during τ_1.

Similarly, by substituting with γ_{min} in (10) and (8), the lower and higher bounds of relay l transmit power $P_{r_l,q}$ during τ_2 can be obtained respectively as:

$$P_{R_{Low},q} = \frac{\gamma_{min}(P_{b,q}\alpha_{bd,q} + \sigma_{d,q}^2)}{\alpha_{r_l d,q}} \tag{22}$$

$$P_{R_{High},q} = \min\left\{P_{max}, P_{r_l,q}^{Av.}, \frac{P_{b,q}\alpha_{bc,q} - \gamma_{min}\sigma_{c,q}^2}{\gamma_{min}\alpha_{r_l c,q}}\right\} \tag{23}$$

where $P_{r_l,q}^{Av.}$ is the R_l available power at the current time slot q that equals to the total harvested power during current time slot q from both the RF and RE in addition to the residual power of the last time slot $q-1$. Adding $P_{r_l,q}^{Av.}$ to the higher bound of relay l transmission power ensures the causality constraints in (15h). Also, $P_{R_{Low},q}$ ensures the minimum SINR requirements of R_l-DR link and $P_{R_{High},q}$ ensures the minimum SINR requirements of the cellular link during τ_2.

Assuming that relay-aided D2D link m shares the subcarrier n with CU k; thus, the sum-rate formula represented by (19a) can be written as:

$$\begin{aligned}
&\max_{P_{s,q},P_{r_l,q}} \sum_{m\in\mathbb{M}} R_{C,q} + R_{D,q} \\
&= \max_{P_{s,q},P_{r_l,q}} \left(R_{C,q}^{(\tau_1)} + R_{C,q}^{(\tau_2)} + \min\left\{R_{D,q}^{(\tau_1)}, R_{D,q}^{(\tau_2)}\right\}\right) \\
&= \max_{P_{s,q},P_{r_l,q}} \frac{B}{2}\Big(\log_2(1+\gamma_{c,q}^{(\tau_1)}) + \log_2(1+\gamma_{c,q}^{(\tau_2)}) \\
&\quad + \min\left\{\log_2(1+\gamma_{r,q}^{(\tau_1)}), \log_2(1+\gamma_{d,q}^{(\tau_2)})\right\}\Big)
\end{aligned} \tag{24}$$

which is equivalent to [49]:

$$\begin{aligned}
&\max_{P_{s,q},P_{r_l,q}} \left(1 + \frac{A}{P_{s,q}B + \sigma_{c,q}^2}\right)\left(1 + \frac{A}{Pr_l, qC + \sigma_{c,q}^2}\right) \\
&\times \min\left\{\left(1 + DP_{s,q}\right), \left(1 + EP_{r_l,q}\right)\right\}
\end{aligned} \tag{25}$$

where $A = P_{b,q}\alpha_{bc,q}$, $B = \alpha_{sc,q}$, $C = \alpha_{r_l c,q}$, $D = \frac{(1-\rho_{r_l,q})\alpha_{sr_l,q}}{P_{b,q}\alpha_{br_l,q} + \sigma_{r_l,q}^2}$, and $E = \frac{\alpha_{r_l d,q}}{P_{b,q}\alpha_{bd,q} + \sigma_{d,q}^2}$.

Following [49] and [58], it is important to note that the formula in (25) represents a convex function which maximum value lies at a boundary point of the constraints (See Appendix A for the convexity derivation of (25)). Our constraints here are represented by the lower and higher bounds of $P_{s,q}$ and $P_{r_l,q}$ that equate the two rates $R_{D,q}^{(\tau_1)}$ and $R_{D,q}^{(\tau_2)}$ in order to maximize the relay-aided D2D rate during the two sub-slots.

Since $P_{S_{Low},q}$ and $P_{R_{Low},q}$ correspond to each other as they ensure γ_{min} during τ_1 and τ_2, respectively, the lower power pair of the maximization problem is composed as $P_L = \{P_{S_{Low},q}, P_{R_{Low},q}\}$.

For $P_{S_{High},q}$, its corresponding relay transmission power $P_{R_{High},q}^{*}$ that equates the two D2D rates during τ_1 and τ_2 (i.e., $\gamma_{r_l,q}^{(\tau_1)} = \gamma_{d,q}^{(\tau_2)}$) is found, where the two values compose the first higher power pair $P_{H_1} = \{P_{S_{High},q}, P_{R_{High},q}^{*}\}$. Similarly, for $P_{R_{High},q}$, its corresponding value is obtained by equating the two rates that results $P_{S_{High},q}^{*}$ to compose

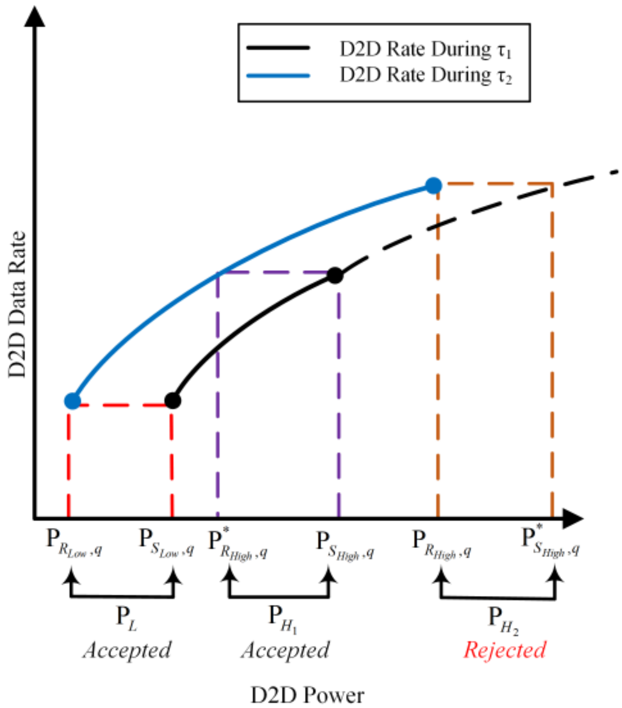

FIGURE 3. Lower and higher bounds of D2D power vs data rate during τ_1 and τ_2.

$P_{H_2} = \{P^*_{S_{High},q}, P_{R_{High},q}\}$. Fig. 3 depicts the case in which $R^{(\tau_2)}_{D,q} > R^{(\tau_1)}_{D,q}$ during time slot q as an example. It is clear from the figure that each $P_{s,q}$ and $P_{r_l,q}$ of the same pair corresponds to each other, where both of them achieve an equal relay-aided D2D rate. Also, the figure shows that the value of $P^*_{S_{High},q}$ exceeds the practical range of $P_{s,q}$; thus P_{H_2} is rejected. Now, the optimal PA of the relay-aided D2D problem $\{P^{opt}_{s,q}, P^{opt}_{r_l,q}\}$ resides on the two pairs P_L and P_{H_1} depending on which pair maximizes the objective function in (25). Similarly, the problem is solved if $R^{(\tau_2)}_{D,q} < R^{(\tau_1)}_{D,q}$.

The details of the proposed MBPA-EH strategy are shown in Sub-Algorithm 2 that consists of two steps. Step 1 finds the sub-optimal value of the PS factor for each relay l, which is adaptive to channel attenuation coefficient h. In step 2, the optimal pair of $P_{s,q}$ and $P_{r_l,q}$ that maximizes the sum-rate for both the links is determined based on the available information of the constraints of the higher and lower bounds.

Sub-Algorithm 2 Maximum-Rate Boundaries Power Allocation Based on EH Capabilities (MBPA-EH)

Input: P_{max}, γ_{min}, E_{max}, η^{RF}, Channel gain matrix ($\boldsymbol{\alpha}$).
Output: $\rho^{opt}_{r_l,q}$, $P^{opt}_{s,q}$, $P^{opt}_{r_l,q}$, $\forall l$.

Initialization: $P_{b,q} = P_{max}$
Step 1: Calculate $\rho^{opt}_{r_l,q}$ for each relay l
for $l = 1$ to L **do**
  $X_2 = P_{b,q}h_{br_l,q} + \sigma^2_{r_l,q}$, $Y_2 = \eta^{RF} h_{r_ld,q}$, and $Z_2 = P_{b,q}h_{bd,q} + \sigma^2_{d,q}$.
  $\rho^{opt}_{r_l,q} = 1/(1 + \frac{X_2 Y_2}{Z_2})$.
end for
Step 2: Allocate power for DT and R_l
for each relay $l \in \mathbb{L}$ **do**
  Calculate $P_{S_{Low},q}$, $P_{S_{High},q}$, $P_{R_{Low},q}$, and $P_{R_{High},q}$ according to (20), (21), (22), and (23), respectively.
  Set $P_L = \{P_{S_{Low},q}, P_{R_{Low},q}\}$.
  Calculate $P^*_{R_{High},q} = \frac{D}{E} P_{S_{High},q}$.
  Set $P_{H_1} = \{P_{S_{High},q}, P^*_{R_{High},q}\}$.
  Calculate $P^*_{S_{High},q} = \frac{E}{D} P_{R_{High},q}$.
  Set $P_{H_2} = \{P^*_{S_{High},q}, P_{R_{High},q}\}$.
  Compare P_{H_1} and P_{H_2} to accept the practical pair and set it as P_H.
  Check which pair between P_L and P_H maximizes the sum-rate function in (25).
  Assign optimal values to $P^{opt}_{s,q}$ and $P^{opt}_{r_l,q}$.
end for

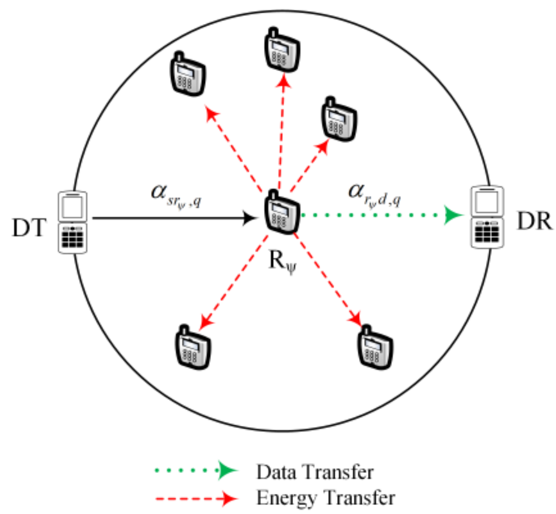

FIGURE 4. Optimal relay selection in RPRS-EH Algorithm.

C. RELAY SELECTION STRATEGIES

In economics as well as several fields of engineering, there is always a tradeoff between performance metric $\mathcal{X}$ and another performance metric $\mathcal{Y}$ [59]. The main rule is "In order to gain one, we have to sacrifice the other". In the light of this concept, we tradeoff between the maximum sum-rate achieved and maximum wireless energy transfer to the surrounding relays during the relay selection process, which is depicted in Fig. 4. It is assumed that the two D2D terminals are separated by distance $\mathcal{D}$ and there is a circle with radius $\frac{\mathcal{D}}{2}$, called relays selection circle (RSC), which center is the midpoint of the distance between the two terminals. Relays that located inside the RSC are considered as a set of candidate relays $\mathbb{R}_C$ as one of them is selected due to its special position between the DT and DR. In Fig. 4, the dotted green arrow represents the flow of the information from the selected relay R_ψ to the destination DR, while the dashed red arrows represent the energy transfer flows from R_ψ to the set of non-selected relays $\mathbb{R}_N$.

Consequently, we propose two strategies for relay selection. The first strategy is called the sum-rate maximization relay selection (SRM-RS) strategy, which selects a relay among the candidates such that the sum-rate of both the relay-aided D2D and cellular links is maximized. To maximize the sum-rate of both the links is the main aim of our paper. The problem of the SRM-RS strategy is formulated as:

$$R_{\psi}^{SM} = \max_{\zeta_{mr_l,q}} R^{sum} \tag{26a}$$
$$\text{subject to (15g), and (15i).} \tag{26b}$$

where R_{ψ}^{SM} refers to the selected relay that achieves the sum-rate maximization. The second strategy is called the energy transfer maximization relay selection (ETM-RS) strategy, which selects the relay that maximizes the sum of the energy transfer to $\mathbb{R}_N$. The ETM-RS relay selection problem is as follows:

$$R_{\psi}^{ET} = \max_{\zeta_{mr_l,q}} \sum_{l=1(l\neq\psi)}^{L} (E_{r_\psi r_l}^{RF}) \tag{27a}$$
$$\text{subject to (15g), and (15i).} \tag{27b}$$

where $E_{r_\psi r_l}^{RF}$ denotes the sum of the RF energy transferred from R_ψ to its neighbor R_l. It is important to note that the SRM-RS strategy is more useful for applications that require high data rate. Whereas, the ETM-RS strategy is more useful for applications when it is needed to increase the relays motivation to participate in the relay-aided D2D link. Achieving a high degree of motivation for relays is essential when the integration between the multi-hop D2D communication and ultra-dense networks is required as an example.

The detailed relay selection strategies are depicted in the three steps Sub-Algorithm 3. The sub-algorithm takes the sub-optimal PS factor, optimal power allocated to the DT and R_l, and links channel gain as the inputs. It returns the optimal relay R_{ψ}^{SM} or R_{ψ}^{ET}, energy harvested by relays (*selected and non-selected*), and their residual energies in addition to the sum-rate and energy transfer matrices of relays as the outputs. We can switch between step 1 and 2 based on which relay selection strategy is needed.

In step 1, the sum-rate of each relay l is calculated, stored in matrix U_{SR}, and the relay that achieves the maximum sum-rate is selected according to (26a) then assigned to be R_{ψ}^{SM}. Step 2 depicts the relay selection strategy based on the energy transfer maximization, where the sum of the energy transferred from each R_l to the other relays is calculated and stored in matrix U_{ET}. Thereafter, according to (27a), relay l that achieves the greatest amount of energy transfer to its neighbors is selected and assigned to be R_{ψ}^{ET}. In step 3, according to (1) and (2), the amount of energy harvested by each R_l is calculated as well as its residual energy taking into account the overflow constraint in (15i).

D. RPRS-EH ALGORITHM

In this subsection, the aforementioned three sub-algorithms are composed into a complete algorithm that is able to maximize the constrained objective function in (15a). The details of the RPRS-EH algorithm are depicted in Algorithm 4, which consists of three main steps. In step 1, the RA strategy IMRA is performed to allocate the subcarriers for the CUs and to select the reuse partners among the cellular and relay-aided D2D links according to the channel gain information. The IMRA strategy considers a single subcarrier for reuse as mentioned in (15b). In step 2, the MBPA-EH sub-algorithm calculates an adaptive sub-optimal value of the PS factor for each relay and optimally allocates the power for all transmitters considering all relays for selection. Also, it takes into account the minimum SINR requirements, power, and causality constraints in (15d), (15f), and (15h), respectively. In step 3, the relays are selected to maximize either the sum-rate of both the links or the amount of energy transfer from the selected relay to its neighbors. Then, the amount of energy harvested by each relay is calculated in addition to its residual energy considering the overflow constraint in (15i).

Sub-Algorithm 3 Sum-Rate Maximization and Energy Transfer Maximization Relay Selection Strategies (SRM-RS and ETM-RS)

Input: $\rho_{r_l,q}^{opt}$, $P_{s,q}^{opt}$, $P_{r_l,q}^{opt}$, Channel gain matrix ($\boldsymbol{\alpha}$).
Output: R_{ψ}^{SM}, R_{ψ}^{ET}, $E_{r_l,q}^{h}$, $E_{r_l,q}^{Res}$, Relays sum-rate matrix U_{SR}, Relays energy transfer matrix U_{ET}.

```
if SRM-RS strategy is considered then
    Step 1: Determine R_ψ^SM
    for each relay l in 𝕃 that lies in the RSC do
        Calculate the sum-rate achieved by relay l according
        to (26a) and store it in U_SR.
        Find R_l that achieves maximum sum-rate.
        R_ψ^SM ← R_l
    end for
else if ETM-RS strategy is considered then
    Step 2: Determine R_ψ^ET
    for each relay l in 𝕃 that lies in the RSC do
        Calculate the sum of the energy transferred from R_l
        to the others (See (1) and (27a)), and store it in U_ET.
        Find R_l that achieves maximum sum of energy
        transferred.
        R_ψ^ET ← R_l
    end for
end if
Step 3: Determine EH and residual energy for relays
after selection
for l = 1 to L do
    if l = ψ then
        Calculate E_{r_l,q}^h and E_{r_l,q}^Res according to (1) and (2),
        respectively, given ζ_{r_l,q} = 1
    else
        Calculate E_{r_l,q}^h and E_{r_l,q}^Res according to (1) and (2),
        respectively, given ζ_{r_l,q} = 0
    end if
end for
```

It is important to note that from one side, the RPRS-EH algorithm is considered as a centralized algorithm in terms of subcarrier assignment, RA, and PA of the cellular links, which is performed by the BS. From the other side, it is considered as a distributed algorithm as the D2D links are responsible for their PA, where the selected relay determines its transmission power based on its available energy resources. The energy resources include the RF and RE energy arrival as well as the relay residual energy. For peer device discovery, the open discovery approach is assumed as the devices are detected as long as they are within the proximity of their neighbors without the need for any explicit permission. This is suitable for the public safety scenario that is considered in our model [60]. For achieving low signaling overhead in addition to high EE for the devices, the partially network-assisted discovery approach is also assumed. In this approach, the BS periodically broadcasts the set of the important control signals that can be used for transmitting and receiving the discovery beacons. D2D users who want to participate in the relay-aided D2D communication listen to these beacons within their subcarriers [61].

IV. NUMERICAL ANALYSIS

In this section, we first evaluate the performance of the RPRS-EH algorithm with respect to the sum-rate achieved of both the cellular and relay-aided D2D links as well as the EE realized by the selected relays. In addition, the two relay selection strategies SRM-RS and ETM-RS are considered. Second, the proposed algorithm is compared to the Uplink RA algorithm considering the relay-aided mode (R-relay) [49]. Table 2 shows the main simulation parameters used for our results. The performance of picking up one relay-aided D2D link m to share the resources with cellular user k is considered throughout all the results. Furthermore, the Monte Carlo simulation is performed to determine the average values of the results per time slot. As mentioned before, it is assumed that there is no direct link between the DT and DR due to the long distance and high channel attenuation between them. Thus, the minimum value of $\mathcal{D}$ is set as 40 m to see how the RPRS-EH algorithm performs in such environment. Also, the EH data is obtained from the real-life solar EH data set that is available at the NREL during the month of June at Los Angeles city. Moreover, each relay node is attached with a small solar cell of dimensions 90mm × 25mm (LxW) [39], [53].

A. RPRS-EH ALGORITHM PERFORMANCE

Fig. 5 shows the impact of the distance between the DT and DR on the average sum-rate of the proposed RPRS-EH algorithm. The results include the two relay selection strategies SRM-RS and ETM-RS for $K = 10$, $M = 5$, $L = 200$, and $N = 5$. It is illustrated that the average sum-rate decreases upon increasing the distance between the DT and DR for the two curves. As expected, the RPRS-EH algorithm with the SRM-RS relay selection strategy shows better performance in terms of the sum-rate maximization when compared to the same algorithm with the ETM-RS strategy. This is because of the ETM-RS relay selection strategy that focuses on maximizing the sum of the energy transfer from the selected relay to its neighbors rather than the sum-rate maximization like SRM-RS.

Algorithm 4 RPRS-EH

Input: $\mathbb{N}, P_{max}, \gamma_{min}, E_{max}, \eta^{RF}, \boldsymbol{\alpha}$.
Output: U_c, U_p, U_{SR}, U_{ET}, R_{ψ}^{SM}, R_{ψ}^{ET}, $E_{r_l,q}^{h}$, $E_{r_l,q}^{Res}$, $\rho_{r_l,q}^{opt}$, $P_{s,q}^{opt}$, $P_{r_l,q}^{opt}$, $\forall l$.

Initialization: $P_{b,q} = P_{max}$
Step 1: Resource allocation strategy (IMRA)
Assign single subcarriers n to each CU k and update U_c using Sub-Algorithm 1.
Perform subcarrier partner selection for relay-aided D2D link m among the available CUs based on minimum mutual channel gain using Sub-Algorithm 1 then update U_p.
Step 2: PS optimization and Power allocation strategy (MBPA-EH)
Calculate the adaptive sub-optimal value of PS factor $\rho_{r_l,q}^{opt}$ for all relays and allocate optimal powers P_b, $P_{s,q}^{opt}$ and $P_{r_l,q}^{opt}$ for all transmitters using Sub-Algorithm 2 considering the overflow constraint in (15h).
Step 3: Relay selection strategies (SRM-RS and ETM-RS) according to Sub-Algorithm 3
for each relay l in $\mathbb{L}$ that lies in the RSC **do**
  if SRM-RS strategy is considered **then**
    Select relay l that achieves maximum sum-rate and then assign it as $R_{\psi}^{SM} \leftarrow R_l$.
  else if ETM-RS strategy is considered **then**
    Select relay l that achieves maximum sum of energy transferred and then assign it as $R_{\psi}^{ET} \leftarrow R_l$.
  end if
  Calculate $E_{r_l,q}^{h}$ and $E_{r_l,q}^{Res}$ according to (1) and (2), respectively considering overflow constraint in (15i).
end for

TABLE 2. Simumation parameters.

Parameter	Value
Cell radius	500 m
Number of cellular users (K)	10
Number of D2D links (M)	5
Number of relays (L)	200
Number of reused links (N)	5
Maximum power budget of the BS (P_b^{max})	46 dBm
Maximum power limit of subcarrier (P_{max})	24 dBm
SINR minimum requirements (γ_{min})	5 dB
Path loss exponent (ν)	3.5
Noise power (σ^2)	-174 dBm/Hz
Maximum amount of EH for relays	100 mJ
Initial residual energy of relays	0.1 J
Time slot duration	1 S
Total trasmission time (T_c)	10 s
RF conversion efficiency(η^{RF}) [62]	0.7

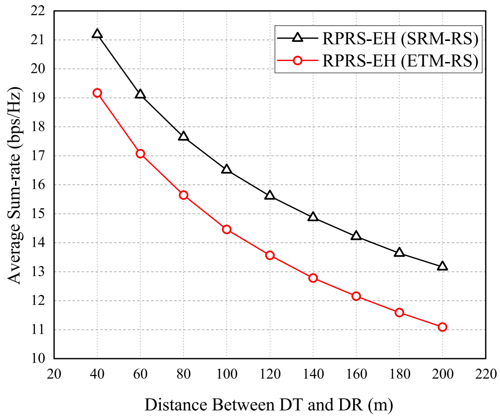

FIGURE 5. The impact of varying the distance between the D2D transmitter and receiver ($\mathcal{D}$) on the average sum-rate per time slot.

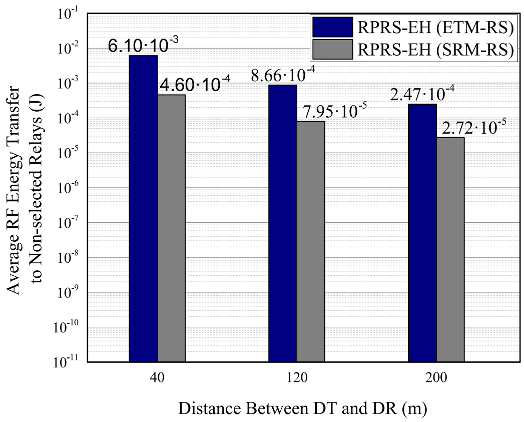

FIGURE 6. The average amount of RF energy transfer per time slot from the selected relay to its neighbors over different $\mathcal{D}$'s.

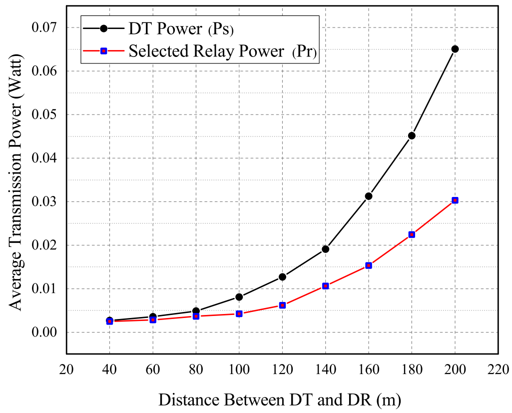

FIGURE 7. The effect of varying $\mathcal{D}$ on the average DT and selected relay transmission powers per time slot.

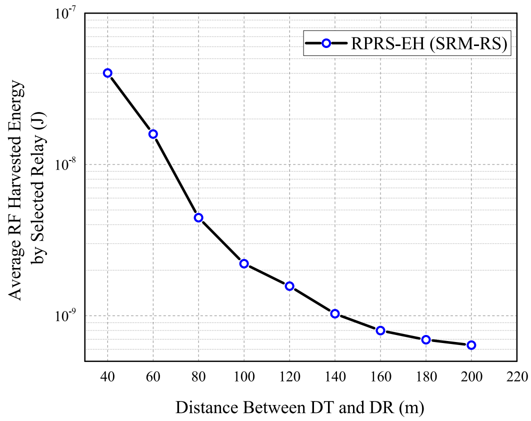

FIGURE 8. The effect of varying $\mathcal{D}$ on the average RF energy harvested per time slot by the selected relay.

In Fig. 6, the average amount of RF energy transfer from the selected relay $\mathcal{R}_\psi$ to the set of non-selected relays $\mathbb{R}_N$ for both the SRM-RS and ETM-RS strategies of the RPRS-EH algorithm is depicted. The shown results are over different distances between the DT and DR for $K = 10$, $M = 5$, $L = 200$, and $N = 5$. It is clear that the ETM-RS strategy achieves more energy transfer between the selected relay and its neighbors than that of the SRM-RS strategy. This gives more flexibility for selecting between the two strategies according to the application needs. During the current time slot, the non-selected relays store the harvested energy in their batteries for supporting their transmission in the next slots.

Fig. 7 illustrates the effect of the distance between the DT and DR on the average amount of transmission power of the DT and selected relay $\mathcal{R}_\psi$ considering the RPRS-EH algorithm with the SRM-RS strategy. Obviously, the more the $\mathcal{D}$, the more the value of P_s and P_r as the DT and $\mathcal{R}_\psi$ need to increase their transmission power to compensate the power loss due to the increased distance. For short distances (i.e. $\mathcal{D} \leq 40$), the transmission powers of the DT and $\mathcal{R}_\psi$ tend to be low and equal as the area of the RSC becomes small enough for a relay near the mid-point of the line between the DT and DR to be selected.

Fig. 8 depicts the average amount of RF energy harvested by the selected relay per time slot versus the distance variation between the DT and DR for the RPRS-EH algorithm with the SRM-RS strategy. Indeed, the more the $\mathcal{D}$, the less the energy harvested by $\mathcal{R}_\psi$ as the received power at the selected relay decays with long distances. Also, it is clear at long distances that the harvested energy is almost zero, which means that the selected relay cannot depend only on the RF harvested energy that comes from the DT. This shows the importance of the energy harvested by the non-selected relays during the current time slot to support their transmission when selected at the next slots as well as the important role that the RE harvested energy can play.

In Fig. 9, the effect of the number of CUs K on the average sum-rate of the RPRS-EH algorithm with its two relay selection strategies for $\mathcal{D} = 50$ and $L = 200$ is illustrated. Surely, increasing K gives more chance for the relay-aided D2D link to choose a favorable reuse partner and achieve better sum-rate as shown in the results of both the SRM-RS and ETM-RS strategies. It is also obvious that the RPRS-EH algorithm with the SRM-RS relay selection strategy still outperforms that of the ETM-RS strategy in terms of the average sum-rate.

Fig. 10 shows the impact of the number of the EHRs on the average sum-rate of both the links for the RPRS-EH

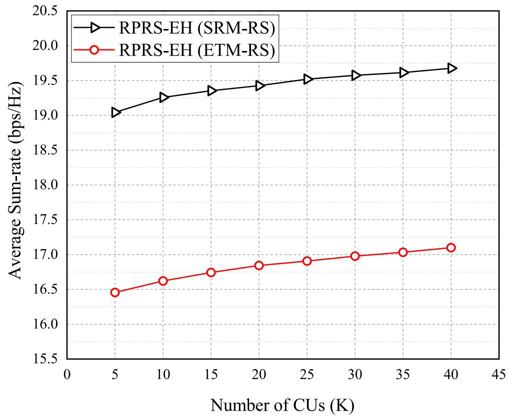

FIGURE 9. The impact of varying the number of cellular users (K) on the average sum-rate per time slot.

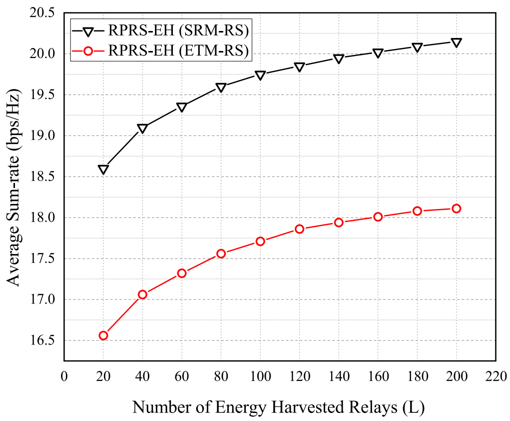

FIGURE 10. The impact of varying the number of EHRs (L) on the average sum-rate per time slot.

algorithm with the SRM-RS and ETM-RS strategies at $K = 10$ and $\mathcal{D} = 50$. Indeed, increasing the number of relays gives more chance for selecting an EHR that achieves higher sum-rate. As depicted in the results, the SRM-RS relay selection strategy achieves higher sum-rate than the ETM-RS strategy on average.

B. PERFORMANCE COMPARISON WITH UPLINK RA ALGORITHM

Here, the performance of the proposed algorithm is compared to the Uplink RA algorithm in terms of the average sum-rate and EE of the EHRs. We find that the Uplink RA with the relay-aided mode (R-relay) is the closest algorithm to compare our work with. The results show that the proposed algorithm not only achieves better sum-rate for both the links but also conserves the residual energy of the cooperative relays in order to motivate them for transmission participation. It is assumed that the mode selection feature of the Uplink RA algorithm is not considered as it is supposed that there is no direct link between the DT and DR.

In Fig. 11, the Uplink RA algorithm with the relay-aided mode is compared to the RPRS-EH algorithm considering the two relay selection strategies SRM-RS and ETM-RS. The shown results are for $K = 10$, $M = 5$, $L = 200$, and $N = 5$.

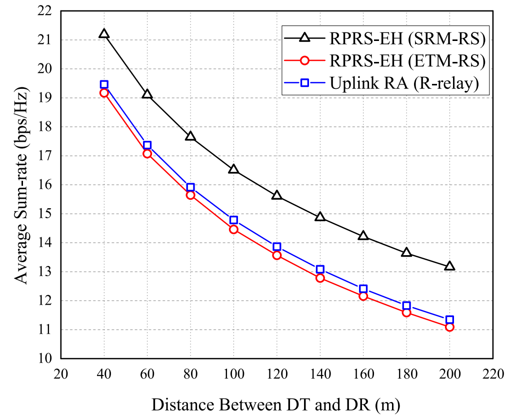

FIGURE 11. The effect of different $\mathcal{D}$'s on the average sum-rate per time slot for $K = 10$ and $L = 200$.

It is clear that the more the distance between the D2D transmitter and receiver, the less the sum-rate of the three curves. Also, the results depict that the RPRS-EH algorithm with the SRM-RS strategy outperforms the Uplink RA algorithm which is because of two reasons. First, the proposed algorithm uses the IMRA RA strategy that considers the channel gain including the effect of the channel attenuation coefficient and distance between the reuse partners. Whereas, the RA of the Uplink RA algorithm depends on the geographic locations of the nodes. Second, the SRM-RS strategy selects the EHRs such that the sum-rate of both the links is maximized, unlike the Uplink RA algorithm that selects them based on maximizing the relay-aided D2D link data rate only. It is important to notice that the performance of the RPRS-EH algorithm with the ETM-RS strategy is so close to that of the Uplink RA algorithm in terms of the average sum-rate. However, the proposed algorithm with the ETM-RS strategy shows EE advantages over the Uplink RA algorithm.

Table 3 shows the effect of the RF and RE harvested energies on the residual energy of the EHRs for the RPRS-EH algorithm with the SRM-RS strategy when compared to the Uplink RA algorithm. The results consider only one candidate relay for participation at $\mathcal{D} = 100$ m and different total transmission times. The table illustrates that the residual energy of the EHR always shows higher values for the proposed algorithm than that of the Uplink RA algorithm. This is because the EHR of the proposed algorithm not only depends on its battery like the Uplink RA algorithm but also harvests the energy from both the RF and RE sources to support each time-slot transmission. It is important to note that assuming only one EHR for participation does not give a chance for exchanging roles among the relays to be selected. Thus, it does not allow a number of non-selected relays to keep silent and perform EH without transmission during the current time slot, which is shown in the results of Table 3.

Table 4 illustrates the relationship between the residual energy of the EHRs and the duration of the total transmission time for the RPRS-EH algorithm with the SRM-RS strategy and the Uplink RA algorithm. The results consider

TABLE 3. Residual energy of $E_o = 0.1$ J, $\mathcal{D} = 100$ m, and $\mathbb{R}_C = 1$.

Algorithm	T_c	$2T_c$	$3T_c$
RPRS-EH (SRM-RS)	0.0962	0.0872	0.0785
Uplink RA(R-relay)	0.0956	0.0860	0.0767

TABLE 4. Residual Energy of $E_o = 0.1$ J, $\mathcal{D} = 60$ m, and $\mathbb{R}_C = 2$.

Algorithm	T_c		$2T_c$		$3T_c$	
	R_1	R_2	R_1	R_2	R_1	R_2
RPRS-EH (SRM-RS)	0.0994	0.1005	0.0993	0.1007	0.0997	0.1011
Uplink RA(R-relay)	0.0985	0.1000	0.0974	0.0996	0.0966	0.0969

two candidate relays for selection at $\mathcal{D} = 60$ m. The results show that the residual energy of R_1 and R_2 in the case of the RPRS-EH algorithm is always higher than that of the Uplink RA algorithm. This is due to the support of the RF and RE harvested energies for the relays during each time slot transmission. Also, it is clear that both the algorithms tend to choose R_1 more than R_2 for each time slot as R_1 achieves higher sum-rate. This allows R_2 to be idle most of the time, harvest an amount of energy, and store it for further transmission in the case of the RPRS-EH algorithm.

The computation complexity of the RPRS-EH and Uplink RA algorithms in terms of the number of candidate relays and CUs is shown in Table 5. It is clear from Table 5 that the number of candidate relays of the RPRS-EH algorithm is less than that of the Uplink RA, which gives less computation complexity to our proposed algorithm. Since the Uplink RA algorithm uses both the ILA and region partitioning schemes for determining reuse partners, its number of candidate CUs is less than that of the RPRS-EH algorithm. However, the RPRS-EH algorithm provides better performance in terms of the sum-rate maximization because of the IMRA strategy that considers all the CUs as candidates. In summary, the Uplink RA algorithm outperforms the proposed algorithm in terms of the computation complexity, however; the RPRS-EH algorithm achieves better performance in terms of the sum-rate maximization and EE. Furthermore, both algorithms achieve lower computation complexity than the conventional iterative algorithms aforementioned in [49].

TABLE 5. Computation complexity for $L = 500$ and $K = 50$.

Algorithm	Number of candidate relays	Number of candidate CUs
RPRS-EH	12	50
Uplink RA	14	12

V. CONCLUSIONS

In this paper, we studied a DL spectrum sharing system in the presence of relay-aided D2D communication links underlying conventional cellular links. It was assumed that the participating relays of the relay-aided D2D links are capable of harvesting both the RF and RE energy from the ambient environment. Aiming at maximizing the sum-rate of both the links with conserving the QoS, power, and EH constraints, an MINLP problem represented by a constrained objective function was introduced. A simple, non-iterative, and low complexity algorithm namely RPRS-EH was proposed. The algorithm determined the reuse partners, PS factor suboptimal value with optimal PA for links, and provided two different strategies for relay selection. The behavior of the proposed algorithm was investigated under different simulation scenarios, which showed consistent results over various parameters. Finally, the RPRS-EH algorithm was compared to one of the most recent relay-aided D2D communication algorithms namely the Uplink RA. The results illustrated that the proposed algorithm outperformed the Uplink RA algorithm in terms of the sum-rate maximization and EE for the participating relays. As part of the future work, the proposed model can be extended to investigate the performance of the EH relay-aided D2D communication assuming mobile D2D nodes in heterogeneous networks.

APPENDIX A

In order to show the convexity of (25), we first derive the direct transmission PA expression. Assuming that there is a direct link between the DT and DR as data transmission takes place within the whole time slot, the SINR at the CU and DR are respectively given as:

$$\gamma_{c,q}^{(Dir)} = \frac{P_{b,q}\alpha_{bc,q}}{P_{s,q}\alpha_{sc,q} + \sigma_{c,q}^2} \tag{28}$$

$$\gamma_{d,q}^{(Dir)} = \frac{P_{s,q}\alpha_{sd,q}}{P_{b,q}\alpha_{bd,q} + \sigma_{d,q}^2} \tag{29}$$

where $\alpha_{sd,q}$ is the channel gain between the DT and DR during time slot q. Thus, the sum-rate can be expressed as:

$$\begin{aligned} R_{Sum}^{(Dir)} &= R_{C,q}^{(Dir)} + R_{D,q}^{(Dir)} \\ &= B\log_2(1+\gamma_{c,q}^{(Dir)}) + B\log_2(1+\gamma_{d,q}^{(Dir)}) \end{aligned} \tag{30}$$

The DT power should be optimally allocated such that the sum-rate of both the links is maximized assuming that $P_b = P_{max}$. Therefore, the lower and higher bounds of the DT can be obtained respectively as:

$$P_{S_{Low},q}^{(Dir)} = \frac{\gamma_{min}(P_{b,q}\alpha_{bd,q} + \sigma_{d,q}^2)}{\alpha_{sd,q}} \tag{31}$$

$$P_{S_{High},q}^{(Dir)} = \min\left\{P_{max}, \frac{P_{b,q}\alpha_{bc,q} - \gamma_{min}\sigma_{c,q}^2}{\gamma_{min}\alpha_{sc,q}}\right\} \tag{32}$$

In agreement with the fact that $\arg\max_x B[\log_2(1+f(x)) + \log_2(1+g(x))]$ is equivalent to $\arg\max_x B(1+f(x))(1+g(x))$, (30) can be rewritten as:

$$\max_{P_{s,q}} \left(1 + \frac{P_{b,q}\alpha_{bc,q}}{P_{s,q}\alpha_{sc,q} + \sigma_{c,q}^2}\right)\left(1 + \frac{P_{s,q}\alpha_{sd,q}}{P_{b,q}\alpha_{bd,q} + \sigma_{d,q}^2}\right) \tag{33}$$

It is important to note that (33) is a convex function with a stationary point $P_{s,q}$ that represents its global maximum. Since the maximum value of any convex function is obtained at its boundary points, the optimal value of the PA maximization problem represented by (30) resides on one of the following points: $P^{(opt)} = \{(P_{max}, P^{(Dir)}_{S_{Low},q}), (P_{max}, P^{(Dir)}_{S_{High},q})\}$.

Because the structure of (25) is identical to that of (33), the optimal value of the PA problem represented by (25) is available at a boundary point of the constraints given by $P_{s,q}$ and $P_{r_l,q}$.

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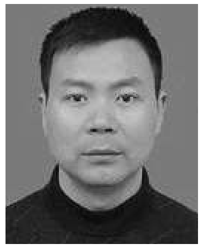

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