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Energy- and Spectral-Efficient Adaptive Forwarding Strategy for Multi-Hop Device-to-Device Communications Overlaying Cellular Networks [1]

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***Abstract*— Device-to-device (D2D) communications in cellular networks enable direct transmissions between user equipments (UEs). If the source UE (SUE) and the destination UE (DUE) are far away from each other or the channel between them is too weak for direct transmission, then multi-hop D2D communications, where relay UEs (RUEs) forward the SUE's data packets to the DUE, can be used. In this paper, we propose an energy-efficient optimal adaptive forwarding strategy (OAFS) for multi-hop D2D communications. OAFS adaptively chooses between the best relay forwarding (BRF) mode and the cooperative relay beamforming (CRB) mode with the optimal number of RUEs, depending on which of them provides the higher energy efficiency (EE). To reduce the computational complexity for selecting the optimal RUEs for CRB mode, we propose a low-complexity sub-optimal adaptive forwarding strategy (SAFS) that selects between the BRF and the CRB with two RUEs by comparing their EE. Furthermore, a distributed forwarding mode selection approach is proposed to reduce the overhead for forwarding mode selection. The analytical and simulation results show that OAFS and SAFS exhibit significantly higher EE and spectral efficiency (SE) than BRF, CRB, direct D2D communications and conventional cellular communications. SAFS is almost as energy- and spectral-efficient as OAFS.**

***Index Terms*—D2D communications, cellular networks, decode-and-forward relays, energy efficiency, spectral efficiency, multi-hop, cooperative beamforming, overhead.**

I. INTRODUCTION

Different from conventional cellular communications, where user equipments (UEs) communicate via the base station (BS), device-to-device (D2D) communications enable UE to communicate directly with other UEs in its vicinity using cellular resources [2]-[5]. D2D communications may potentially achieve three types of gains: proximity gain, reuse gain and hop gain [6]. D2D was first proposed for relaying user traffic [7]. Nowadays, new use cases have been introduced such as peer-to-peer (P2P) communications [8], cellular offloading [9], machine-to-machine (M2M) communications [10], and so on.

Direct communications between UEs can be realized using cellular spectrum (in-band [11][12]) or unlicensed spectrum (out-of-band [13][14]). For in-band communications, D2D links can share the radio resources with cellular links (underlay [11]) or use dedicated cellular resources (overlay [12]). In underlay D2D, uplink [15] and downlink [16] spectrum resources can be deployed, leading to high spectral efficiency (SE). However, reusing spectral resources incurs mutual interference that is especially severe when downlink spectrum resources are used for D2D [17]. Many works have investigated interference reduction for D2D underlaying cellular networks [18]-[21]. Based on the game theory, a spectrum resource allocation scheme for D2D underlaying downlink cellular networks was proposed in [18]. An interference management method to increase the overall system capacity of D2D underlaying uplink cellular networks was presented in [21]. Interference limited areas are defined to forbid sharing resources between D2D pairs and cellular users [12]. Besides, mode selection among overlay, underlay and cellular communications is another critical issue in D2D communications [22]-[26]. In [22], a communication mode was selected according to the distance between involved devices, where an optimal mode selection threshold that minimizes the transmit power was used. Dynamic mode selection on a slot-by-slot basis was proposed in [24], where it was shown that dynamic mode selection outperforms semi-static method. For D2D underlaying a two-tier cellular network, a centralized mode selection mechanism was proposed in [26]. When orthogonal resources are available, the D2D overlay mode is selected if D2D pairs are close to each other. Otherwise, the D2D underlay mode is selected if distance and interference criteria are fulfilled.

The above works mainly focus on improving the SE of D2D communications, while the energy efficiency (EE) has been widely ignored. Typical wireless devices are battery-powered equipment with limited energy capacity that makes energy-efficient D2D communications imperative [27]-[31]. An energy-efficient resource sharing scheme for D2D multimedia communications that rely on a coalition formation game was presented in [27]. It addressed jointly mode selection and resource allocation, and considered both transmission power consumption and circuit power consumption. The EE of mode switching under quality of service (QoS) constraints for D2D pairs and cellular UEs was studied in [30]. The simulation results show that the underlay mode is preferable if EE is the optimization objective, while the overlay mode is selected if user capacity has to be maximized. Moreover, the overlay mode will be chosen more often if D2D distance increases. Energy savings for D2D underlaying cellular networks were investigated in [31]. It was demonstrated that D2D com-

[1]Part of this work has been presented at IEEE Globecom'17, Singapore [1].

munications can reduce the energy consumption by 65% as compared to the conventional cellular transmissions.

In practice, D2D UEs might not be close enough to each other or the channel conditions between them could be so poor that direct D2D communications become impossible. Under these circumstances, relays could assist the communication between D2D UEs [32]-[38]. In [32], a distributed best relay selection method for D2D communications underlaying cellular networks was proposed, where the best relay among the ones that will not cause harmful interference to the cellular network was selected. Multi-hop UE relaying for sending emergency messages from disconnected areas was studied in [33]. For Layer 3 relay assisted D2D communications underlaying LTE-A cellular networks, a gradient-based distributed resource allocation scheme was proposed in [34]. This work was extended to consider also the uncertainties in useful and interference channels in [35], where a distributed resource allocation algorithm that relies on stable matching theory was proposed. A distributed resource allocation scheme for Layer 3 relay aided D2D communications that utilize a message passing approach on a factor graph was proposed in [36]. Joint relay selection and sub-channel and power allocation for relay aided D2D communications was investigated in [37]. An iterative Hungarian method was proposed as a suboptimal solution with a low complexity and near-optimal throughput performance. The EE and SE of multi-hop overlay D2D communications based on a two-time-slot physical-layer network coding scheme was analysed in [38].

However, in the works mentioned above, the overhead for obtaining channel state information (CSI) and for performing relay selection in multi-hop D2D communications has been neglected. D2D communications have not been considered in the existing works that analyze the overhead costs and the related energy consumption for implementing cooperative relaying [39]-[43]. Nevertheless, these schemes select a number of relays based on the size of the decoding relay set, which requires the knowledge of the decoding set size and the availability of a lookup table (containing the optimal number of selected relays for any possible size of the decoding set and the location of cooperating relays) at the source [39][41][43] or the destination [40]. In [42], no relay selection was considered.

In this paper, we analyse the EE and SE of multi-hop D2D communications overlaying cellular networks under the maximum transmit power constraint. We consider the overhead for obtaining CSI, forwarding mode selection and cooperative beamforming, as well as the circuit power consumption. The main contributions of this work can be summarized as follows:

- We propose a new energy-efficient optimal adaptive forwarding strategy (OAFS) for multi-hop D2D communications that dynamically switches between the best relay forwarding (BRF) mode [44] and the cooperative relays beamforming (CRB) mode with an optimal number of RUEs [43], depending on which of them exhibits the higher EE. OAFS consists of two main steps. In the first step, all correctly decoding RUEs form a main cluster, and the RUE with the strongest second-hop channel in the main-cluster is selected using timers at RUEs. In the second step, the remaining RUEs with their first-hop channels no weaker than that of any selected RUE, if any, form a sub-cluster; the RUE with the strongest second-hop channel in the sub-cluster is selected to perform cooperative beamforming with the selected RUE(s) if it improves the EE; otherwise, BRF is performed. The second step repeats until the best RUE selected from the sub-cluster cannot improve the EE anymore or all RUEs in the sub-cluster have been selected for cooperative beamforming. OAFS is also spectral-efficient as it leverages cooperative gains through CRB that lower outage probability.
- In order to reduce the computational complexity for identifying the optimal RUEs for CRB mode, we propose a low-complexity sub-optimal adaptive forwarding strategy (SAFS), where at most two RUEs, i.e., the best RUE in the main-cluster and the best RUE in the sub-cluster, are selected using timers at RUEs to perform CRB if CRB shows a higher EE than BRF; otherwise, BRF is performed.
- A distributed forwarding mode selection approach is proposed to reduce the overhead for mode selection, thus improving EE and SE of OAFS and SAFS. This approach enables RUEs of sub-cluster to autonomously decide whether to forward the received data from SUE to DUE or not, without the knowledge of main-cluster and sub-cluster sizes.
- We perform theoretical analysis of average EE and SE for multi-hop D2D communications utilizing the proposed optimal and sub-optimal adaptive forwarding strategies. The performance of the proposed forwarding strategies is compared to BRF, CRB with the optimal number of RUEs, direct D2D communications, and conventional cellular communications.

The remainder of the paper is organized as follows. The system model is presented in Section II. The proposed optimal and sub-optimal adaptive forwarding strategies for multi-hop D2D communications are described in Section III. Section IV presents the proposed approach for distributed forwarding mode selection. Complexity analysis is provided in Section V. Section VI analyses the average EE and SE for multi-hop D2D communications utilizing the proposed forwarding strategies, direct D2D communications, and cellular communications. The simulation results are shown in Section VII. Finally, the paper is concluded in Section VIII.

II. System Model

We consider D2D communications overlaying a cellular network as depicted in Fig. 1, where cellular and D2D communications are allocated with orthogonal channels [38]. The source UE (SUE) intends to transmit data packets to the destination UE (DUE). The data transmission from SUE to DUE can be realized in three different ways:

1) Cellular communications via the BS,
2) Direct D2D communications between SUE and DUE,
3) Multi-hop D2D communications through half-duplex decode-and-forward (DF) relay UEs (RUEs).

The channel power gains between any two nodes are exponentially distributed and are represented as follows: h_B

is the channel power gain between SUE and BS; h_0 is the channel power gain between SUE and DUE; h_i (i=1,. . .,N) denotes the channel power gain from SUE to RUE_i; g_B is the channel power gain between BS and DUE; and g_i (i=1,. . .,N) denotes the channel power gain from RUE_i to DUE. BS

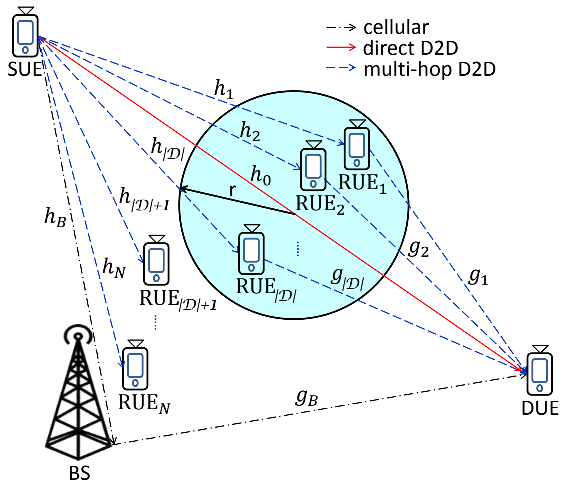


Fig. 1: Different communication modes between SUE and DUE.

is located at the center of the cell. It is assumed that only $RUE_{1\leq i\leq|\mathcal{D}|}$ located within the main-cluster $\mathcal{D}$ with radius r can correctly decode the received data from SUE and are eligible for forwarding the data to the DUE. Furthermore, we assume that $RUE_{1\leq i\leq|\mathcal{D}|}$ are relatively close to each other, resulting in approximately the same distances to SUE (d_{SR}) and to DUE (d_{RD}), respectively [41][42]. We assume reciprocal channels and single-antenna nodes that are subject to the additive white Gaussian noise (AWGN) with power spectral density of N_0. Perfect channel estimation at each node is assumed. The communication between each pair of nodes is performed with fixed rate R (bits/symbol) and bandwidth B (Hz). We account for both transmission power and circuit power consumption. Each UE has the same circuit power consumption P_C^{UE}, while the BS circuit power consumption is P_C^{BS}. We assume that P_C^{UE} and P_C^{BS} are constant and are the same for both transmitter and receiver. All UEs and the BS are constrained by the maximum transmission power P_{MAX}^{UE} and P_{MAX}^{BS}, respectively. The main notations used in this work with the related explanations are listed in Table I.

We propose two adaptive forwarding strategies for multi-hop D2D communications: an optimal adaptive forwarding strategy (OAFS) and a sub-optimal adaptive forwarding strategy (SAFS) with a reduced complexity. Both OAFS and SAFS select adaptively between two forwarding modes: BRF and CRB depending on which of them has the higher instantaneous EE.

III. Multi-Hop D2D Communications with the Proposed Forwarding Strategies

A. Optimal Adaptive Forwarding Strategy (OAFS)

As shown in Fig.2, multi-hop D2D communications with the proposed OAFS consists of three main activities: training to obtain CSI for both hops at each RUE, forwarding mode selection, and data transmission. The proposed OAFS is summarized in Algorithm 1 and is explained in the following.

TABLE I: LIST OF NOTATIONS

Notation	Description
$\mathcal{D}$	Main-cluster that contains correctly decoding RUEs.
$\mathcal{S}$	Sub-cluster that contains RUEs, which can correctly decode the data transmitted to the best RUE in $\mathcal{D}$.
$\mathcal{F}$	Forwarding set, which encompasses RUEs selected for forwarding the received data.
$\lvert.\rvert$	Cardinality of a set.
E_T^M	Energy consumption for training for multi-hop D2D communications.
$P_T^{S,M}$	Transmission power for training from SUE to RUEs for multi-hop D2D communications.
$P_T^{D,M}$	Transmission power for training from DUE to RUEs for multi-hop D2D communications.
δ_{out}	Outage probability for training symbols transmission.
$E_{S,\mathcal{F}}^M$	Energy consumed for forwarding mode selection.
$E_{D,\mathcal{F}}^M$	Energy consumption for data transmission for multi-hop D2D communications.
$EE_{\mathcal{F}}^M$	Instantaneous EE for multi-hop D2D communications.
$SE_{\mathcal{F}}^M$	Instantaneous SE for multi-hop D2D communications.
$\lceil.\rceil$	The ceiling function.
$\overline{X}=\mathbb{E}\{X\}$	The expected value of a random variable X.
$\lvert\mathcal{F}\rvert_{A1}$	Optimal number of forwarding RUEs for Algorithm 1 (OAFS).
$\lvert\mathcal{F}\rvert_{A2}$	Optimal number of forwarding RUEs for Algorithm 2 (SAFS).
E_T^D	Energy consumption for training for direct D2D communications.
$P_T^{S,D}$	Transmission power for training from SUE to DUE for direct D2D communications.
E_{FB}^D	Energy consumed for CSI feedback for direct D2D communications.
E_D^D	Energy consumption for data transmission for direct D2D communications.
E_T^C	Energy consumed for training for cellular communications.
$P_T^{S,C}$	Transmission power for training from SUE to BS for cellular communications.
$P_T^{D,C}$	Transmission power for training from DUE to BS for cellular communications.
E_{FB}^C	Energy consumption for CSI feedback for cellular communications.
E_D^C	Energy consumed for data transmission for cellular communications.

1) Training: At time instants t_0 and $t_1(>t_0)$, N_T training symbols are transmitted from SUE to RUEs and from DUE to RUEs, respectively, using the following powers to satisfy target rate R with outage probability δ_{out}

$$P_T^{S,M}=\frac{1-2^{R/B}}{\bar{h}_M\ln(1-\delta_{out})}P_N,\quad \bar{h}_M=1/\left(\mathcal{PL}_D d_{SR}^{\xi_d}\right), \quad (1)$$

$$P_T^{D,M} = \frac{1-2^{R/B}}{\bar{g}_M \ln(1-\delta_{out})} P_N, \quad \bar{g}_M = 1/\left(\mathcal{PL}_D d_{RD}^{\xi_d}\right). \quad (2)$$

$P_N = N_0 B$ is the noise power; $\bar{h}_M$ and $\bar{g}_M$ denote the mean channel power gains of the first hop and the second hop, respectively; $\mathcal{PL}_D$ is a path loss constant for D2D communications; and ξ_d is the path loss exponent. The N

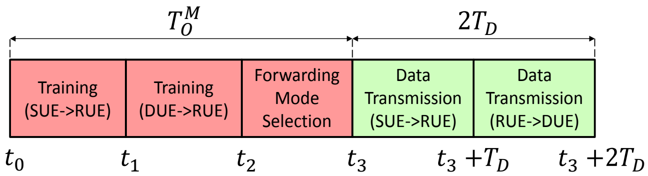


Fig. 2: Timing diagram for multi-hop D2D communications with the proposed OAFS.

available RUEs estimate the corresponding channels. The energy consumed for the training can be calculated as follows

$$E_T^M = \left(2(N+1)P_C^{UE} + P_T^{S,M} + P_T^{D,M}\right) N_T T_S, \quad (3)$$

where $T_S = 1/B$ denotes the symbol duration. E_T^M consists of two key parts. The first part is the circuit energy consumption for SUE transmitting and N RUEs receiving N_T training symbols as well as for DUE transmitting and N RUEs receiving N_T training symbols. The second part comprises the energy consumed for transmission of N_T training symbols from SUE to RUEs and from DUE to RUEs.

All RUE_i (i=1,...,N) with the channel power gains h_i no less than the threshold for successful decoding, $\theta_{th} = (2^{R/B}-1)P_N/P_{MAX}^{UE}$, become part of the main-cluster

$$\mathcal{D} = \{RUE_{1\le i \le N} : h_i \ge \theta_{th}\}.$$

2) Adaptive Forwarding Mode Selection: At time $t_2 (> t_1)$, the procedure for forwarding mode selection is initiated, and each UE belonging to the main-cluster $\mathcal{D}$ starts a timer $\tau_j = \lambda/g_j$, where λ is a constant parameter in unit of time [44]. The $RUE_{1:|\mathcal{D}|}$ with the shortest timer $\tau_{1:|\mathcal{D}|}$, i.e., the strongest channel to DUE, becomes part of the forwarding set $\mathcal{F} = \{RUE_{1:|\mathcal{D}|}\}$ and transmits N_T training symbol to SUE with transmission power $P_T^{R,M} = P_T^{S,M}$. All $RUE_j \in \mathcal{D} \setminus \{RUE_{1:|\mathcal{D}|}\}$ put their timers on hold when they overhear the transmission of training symbols from $RUE_{1:|\mathcal{D}|}$. SUE performs channel estimation to obtain the first-hop CSI of $RUE_{1:|\mathcal{D}|}$ and calculates the minimum transmit power to reach $RUE_{1:|\mathcal{D}|}$, $P_{D,1:|\mathcal{D}|}^I = \left(2^{R/B}-1\right) P_N/h_1$.

Due to the broadcast property of wireless channels, the other $RUE_j \in \mathcal{D} \setminus \{RUE_{1:|\mathcal{D}|}\}$ may still correctly decode the data transmitted with power $P_{D,1:|\mathcal{D}|}^I$ and can potentially improve the EE through CRB. Since $RUE_j \in \mathcal{D} \setminus \{RUE_{1:|\mathcal{D}|}\}$ do not know $P_{D,1:|\mathcal{D}|}^I$ and hence do not know whether they can improve EE or not, SUE broadcasts a triggering symbol with power $P_{D,1:|\mathcal{D}|}^I$. All $RUE_j \in \mathcal{D} \setminus \{RUE_{1:|\mathcal{D}|}\}$ that can correctly decode this symbol constitute the RUE sub-cluster $\mathcal{S} = \left\{RUE_j \in \mathcal{D} \setminus \{RUE_{1:|\mathcal{D}|}\} : h_j \ge \frac{(2^{R/B}-1)P_N}{P_{D,1:|\mathcal{D}|}^I}\right\}$ and resume their timers.

The best RUE in the sub-cluster $\mathcal{S}$, $RUE_{1:|\mathcal{S}|}$, with the shortest timer $\tau_{1:|\mathcal{S}|}$ becomes part of $\mathcal{F}$ and it is removed from $\mathcal{S}$, thus CRB is selected as the forwarding mode, if $RUE_{1:|\mathcal{D}|}$ cannot support target rate R with P_{MAX}^{UE}, i.e., outage occurred or $RUE_{1:|\mathcal{S}|}$ improves the instantaneous EE (lines 26-29 in Algorithm 1), otherwise BRF is chosen as the forwarding mode. Section IV explains in more details how $RUE_{1:|\mathcal{S}|}$ finds out whether one of the conditions mentioned above is satisfied or not. In the case that CRB is selected as forwarding mode, $RUE_{1:|\mathcal{S}|}$ broadcasts a notification symbol with power

$$P_N^{R,M} = \frac{1-2^{R/B}}{\ln(1-\delta_{out})} \mathcal{PL}_D (2r)^{\xi_d} P_N, \quad (4)$$

which satisfies the target rate R with outage probability δ_{out} at the maximum distance $2r$, where r is the radius of main cluster $\mathcal{D}$. As soon as receiving the notification symbol from $RUE_{1:|\mathcal{S}|}$, $RUE_j \in \mathcal{S} \setminus \{RUE_{1:|\mathcal{S}|}\}$ with still unexpired timers will update their timers to $\tau_j = \tau_j + T_S$, in order to avoid possible collisions between RUEs transmissions. The procedure of RUEs joining $\mathcal{F}$ from $\mathcal{S}$, transmitting a notification symbol and remaining RUEs in $\mathcal{S}$ updating their timers (line 28-31) continues with second best, then third best RUEs in $\mathcal{S}$ and so on until all RUEs from $\mathcal{S}$ become part of $\mathcal{F}$ (line 25) or none of the conditions in line 27 is satisfied.

The energy consumption for the forwarding mode selection is given by

$$E_{S,\mathcal{F}}^M = \Bigg(\Big((N_T+1)(|\mathcal{D}|+1) + (|\mathcal{F}|-1)(|\mathcal{S}|+1)\Big)P_C^{UE} + N_T P_T^{R,M} + P_{D,1:|D|}^I + (|\mathcal{F}|-1)P_N^{R,M}\Bigg)T_S. \quad (5)$$

It is composed of two main parts. The first part is the circuit energy consumption consisting of the following three components:

- The circuit energy consumed when $RUE_{1:|\mathcal{D}|}$ transmits N_T training symbols and $(|\mathcal{D}|-1)$ RUEs and the SUE receive them.
- The circuit energy consumed when the SUE broadcasts a triggering symbol and when the $|\mathcal{D}|$ RUEs receive it.
- The circuit energy consumed when the $(|\mathcal{F}|-1)$ RUEs transmit a notification symbol and when the $|\mathcal{S}|$ RUEs receive them.

The second part represents the related transmission energy consumption for N_T training symbols, a triggering symbol, and $|\mathcal{F}|-1$ notification symbols.

3) Data Transmission: At time instant $t_3 (> t_2)$, the data transmission stage (composed of two equally long time intervals) starts. In the first time interval, SUE transmits data packets with transmission power $P_{D,1:|\mathcal{D}|}^I$ that are decoded only by $RUE_i \in \mathcal{F}$. In the second time interval, all $RUE_i \in \mathcal{F}$ forward the decoded data packets.

***Lemma** 1:* The optimal transmission power for forwarding the data is given by

$$P_{D,i}^{II} = \begin{cases} (2^{R/B}-1)P_N/g_{1:|\mathcal{D}|}, \ BRF \\ (2^{R/B}-1)P_N \left(\sum_{j=1}^{|\mathcal{F}|} g_j/\sqrt{g_i}\right)^{-2}, \ CRB \end{cases}, \quad (6)$$

where for CRB mode maximum ratio transmission (MRT) beamforming is used [45].

Algorithm 1: Multi-hop D2D communications with OAFS.

$i = 1$, $l = 1$, $\mathcal{D} = \emptyset$, $\mathcal{S} = \emptyset$;
SUE and DUE transmit N_T training symbols with powers $P_T^{S,M}$ and $P_T^{D,M}$, respectively. Each $RUE_{1 \le i \le N}$, estimates the corresponding h_i and g_i;
$\theta_{th} = (2^{R/B} - 1)P_N / P_{MAX}^{UE}$;
while $i \le N$ **do**
  if $h_i \ge \theta_{th}$ **then**
    $\mathcal{D} = \mathcal{D} \cup \{RUE_i\}$;
  end
  $i = i + 1$;
end
All $RUE_j \in \mathcal{D}$, start timers $\tau_j = \lambda / g_j$;
$RUE_{1:|\mathcal{D}|}$ transmits N_T symbols to SUE with power $P_T^{R,M} = P_T^{S,M}$;
$\mathcal{D}_{RES} = \mathcal{D} \setminus \{RUE_{1:|\mathcal{D}|}\}$;
Each $RUE_l \in \mathcal{D}_{RES}$ puts its timer on hold if it overhears transmission from $RUE_{1:|\mathcal{D}|}$;
SUE transmits a triggering symbol with minimum power to reach $RUE_{1:|\mathcal{D}|}$, $P_{D,1:|\mathcal{D}|}^I$;
while $l \le |\mathcal{D}|$ **do**
  if $RUE_l \in \mathcal{D}_{RES}$ && $h_l \ge (2^{R/B} - 1)P_N / P_{D,1:|\mathcal{D}|}^I$ **then**
    $\mathcal{S} = \mathcal{S} \cup \{RUE_l\}$;
  end
  $l = l + 1$;
end
$\mathcal{F} = \{RUE_{1:|\mathcal{D}|}\}$;
if $|\mathcal{S}| > 0$ **then**
  All $RUE_i \in \mathcal{S}$ resume their timers τ_i;
  $\mathcal{S}_{RES} = \mathcal{S}$;
  while $|\mathcal{S}_{RES}| > 0$ **do**
    $\mathcal{F}^+ = \mathcal{F} \cup \{RUE_{1:|\mathcal{S}_{RES}|}\}$;
    if $EE_{\mathcal{F}}^M == 0 \;||\; EE_{\mathcal{F}^+}^M > EE_{\mathcal{F}}^M$ **then**
      $\mathcal{F} = \mathcal{F}^+$;
      $RUE_{1:|\mathcal{S}_{RES}|}$ transmits a notification symbol with power $P_N^{R,M}$;
      $\mathcal{S}_{RES} = \mathcal{S}_{RES} \setminus \{RUE_{1:|\mathcal{S}_{RES}|}\}$;
      All $RUE_i \in \mathcal{S}_{RES}$ update their timers $\tau_i = \tau_i + T_S$;
    else
      break;
    end
  end
end
SUE transmits data with power $P_{D,1:|\mathcal{D}|}^I$;
if $|\mathcal{F}| == 1$ **then**
  $RUE_{1:|\mathcal{D}|}$ forwards data to DUE with power $P_{D,1:|\mathcal{D}|}^{II}$;
else
  All $RUE_i \in \mathcal{F}$ cooperatively beamform data towards DUE with powers $P_{D,i}^{II}$;
end

Proof: The proof is given in Appendix A.

The overall energy consumed for data transmission is given by

$$E_{D,\mathcal{F}}^M = \left(2(1 + |\mathcal{F}|)P_C^{UE} + P_{D,1:|\mathcal{D}|}^I + \sum_{i=1}^{|\mathcal{F}|} P_{D,i}^{II}\right)T_D, \quad (7)$$

where $T_D = N_D T_S$, and N_D is the number of symbols per data packet. $E_{D,\mathcal{F}}^M$ consists of two main components. The first component encompasses circuit energy consumption for source transmitting a data packet and $|\mathcal{F}|$ selected RUEs receiving it as well as $|\mathcal{F}|$ selected RUEs forwarding data packet and destination receiving it. The second component represents the energy consumed for data transmission from the source to the destination over $|\mathcal{F}|$ selected RUEs.

From (6) it can be seen that for CRB each $RUE_i \in \mathcal{F}$ needs to know the second-hop channel power gains of all the other $RUE_j \in \mathcal{F} \setminus \{RUE_i\}$, in order to calculate the optimal transmission power. $RUE_i \in \mathcal{F}$ can obtain each others second-hop channel power gains in a distributed way through overhearing the notification symbols sent upon the expiration of their timers. For illustrative purposes it is assumed that at time t_k, $RUE_k \in \mathcal{S} \setminus \{RUE_{j:|\mathcal{S}|}\}$ overhears the notification symbol sent from $RUE_{j:|\mathcal{S}|}$, then $RUE_k \in \mathcal{S} \setminus \{RUE_{j:|\mathcal{S}|}\}$ can acquire $g_{j:|\mathcal{S}|}$ as follows [43]

$$g_{j:|\mathcal{S}|} = \frac{\lambda}{t_k - t_2 - (j+1)T_S}, \quad (8)$$

where t_2 is the time instant when all $RUE_j \in \mathcal{D}$ start their timers. It is assumed that the propagation delay within the main cluster $\mathcal{D}$ is negligible compared to the RUE selection time.

4) Instantaneous EE and SE: The instantaneous EE and SE for multi-hop D2D communications with OAFS are given by

$$EE_{\mathcal{F}}^M = \begin{cases} \frac{RN_D}{E_T^M + E_{S,\mathcal{F}}^M + E_{D,\mathcal{F}}^M}, & \sum_{i=1}^{|\mathcal{F}|} g_i \ge \theta_{th} \\ 0, & otherwise \end{cases}, \quad (9)$$

$$SE_{\mathcal{F}}^M = \begin{cases} \frac{1}{2}\frac{R}{B}\frac{T_D}{T_D + T_{O,\mathcal{F}}^M}, & \sum_{i=1}^{|\mathcal{F}|} g_i \ge \theta_{th} \\ 0, & otherwise \end{cases}, \quad (10)$$

where

$$T_O^M = (3N_T + |\mathcal{F}|)\,T_S + \begin{cases} \lambda / g_{1:|\mathcal{D}|}, & |\mathcal{F}| = 1 \\ \lambda / g_{|\mathcal{F}|-1:|\mathcal{S}|}, & |\mathcal{F}| > 1 \end{cases},$$

is the time consumed for the related overhead. Outage $\left(EE_{\mathcal{F}}^M = 0, SE_{\mathcal{F}}^M = 0\right)$ occurs when the RUEs in the forwarding set $\mathcal{F}$ cannot support target rate R in the second-hop with P_{MAX}^{UE}.

B. Sub-Optimal Adaptive Forwarding Strategy (SAFS)

To reduce the computational complexity required for selecting optimal number of RUEs for CRB mode, we propose a low-complexity sub-optimal adaptive forwarding strategy (SAFS) as shown in Algorithm 2. SAFS dynamically switches between BRF and CRB with two RUEs depending on which of them exhibits higher $EE_{\mathcal{F}}^{M}$ (condition in line 5). If this condition is satisfied, then CRB with $\mathcal{F} = \{RUE_{1:|\mathcal{D}|}, RUE_{1:|\mathcal{S}|}\}$ is selected as forwarding mode, where $RUE_{1:|\mathcal{D}|}$ and $RUE_{1:|\mathcal{S}|}$ cooperatively forward the received data using the optimal transmission powers given in (6). Otherwise, BRF with $\mathcal{F} = \{RUE_{1:|\mathcal{D}|}\}$ is chosen as the forwarding mode, where only $RUE_{1:|\mathcal{D}|}$ forwards the received data to DUE. In comparison to OAFS, SAFS recruits at most two RUEs for forwarding the data.

Algorithm 2: Multi-hop D2D communications with SAFS.

```
1  F = {RUE_{1:|D|}};
2  if |S| > 0 then
3      All RUE_i ∈ S resume their corresponding timers τ_i;
4      F+ = F ∪ {RUE_{1:|S|}};
5      if EE^M_{F+} > EE^M_F then
6          F = F+;
7          RUE_{1:|S|} transmits a notification symbol with
             power P_N^{R,M};
8          All RUE_i ∈ S \ {RUE_{1:|S|}} reset their timers;
9      end
10 end
11 SUE transmits data with power P^I_{D,1:|D|};
12 if |F| == 1 then
13     RUE_{1:|D|} forwards data to DUE with power
         P^{II}_{D,1:|D|};
14 else
15     RUE_{1:|D|} and RUE_{1:|S|} cooperatively beamform
         data towards DUE with powers P^{II}_{D,1:|D|} and
         P^{II}_{D,1:|S|}, respectively;
16 end
```

Besides the number of selected RUEs $|\mathcal{F}|$, how RUEs obtain the necessary information to decide whether to join $\mathcal{F}$ or not, also plays a crucial role in the practical implementation of multi-hop D2D communications. A central entity can be used to collect the first-hop CSI for all RUEs and then signal the values of $|\mathcal{D}|$ and $|\mathcal{S}|$ to $RUE_j \in \mathcal{S}$. However, this centralized solution is less practical and increases the energy consumption and reduces SE.

In the next section, we will propose an approach that enables the RUEs to autonomously decide whether to participate or not in data forwarding using solely the information that is locally available to them.

IV. Distributed Forwarding Mode Selection

We propose that $RUE_j (\in \mathcal{S})$ joins forwarding set $\mathcal{F}$ only if either the RUEs in $\mathcal{F}$ are in outage or it improves instantaneous EE, i.e.,

$$\left(EE_{\mathcal{F}}^{M} = 0\right) \vee \left(EE_{F^+}^{M} > EE_{\mathcal{F}}^{M}\right), \tag{11}$$

where $\mathcal{F}^+ = \mathcal{F} \cup \{RUE_j\}$.

RUE_j possesses all necessary information to evaluate locally the first condition from (11) using (8) and (9). Nevertheless, due to the dependency of second condition in (11) on $|\mathcal{D}|$ and $|\mathcal{S}|$, if $EE_{\mathcal{F}}^{M} > 0$, $RUE_j \in \mathcal{S}$ does not have all the information to decide autonomously whether to join $\mathcal{F}$ or remain silent.

Lemma 2: Independent on $|\mathcal{D}|$ and $|\mathcal{S}|$, for $EE_{\mathcal{F}}^{M} > 0$ and N known at RUEs, $RUE_j \in \mathcal{S}$ improves instantaneous EE and hence can become part of $\mathcal{F}$ if the associated energy saving for data transmission is higher than the additional energy consumption for forwarding mode selection, i.e.,

$$\Delta E_D^M > \Delta E_S^M, \tag{12}$$

where

$$\Delta E_S^M = E_{S,\mathcal{F}^+}^M - E_{S,\mathcal{F}}^M = \left((N+1)P_C^{UE} + P_N^{R,M}\right) T_S, \tag{13}$$

$$\Delta E_D^M = E_{D,\mathcal{F}}^M - E_{D,\mathcal{F}^+}^M = \Bigg(\left(2^{R/B} - 1\right) P_N \left(\left(\sum_{i=1}^{|\mathcal{F}|} g_i \right)^{-1} - \left(\sum_{j=1}^{|\mathcal{F}^+|} g_j \right)^{-1} \right) - 2P_C^{UE} \Bigg) T_D, \tag{14}$$

is fulfilled.

Proof: The proof is given in Appendix B.

Each RUE can calculate (13) as it knows N and $P_N^{R,M}$. Furthermore, RUEs can obtain each others second-hop channel power gains through (8) and hence are able to calculate (14). Therefore, RUEs can in distributed manner by means of (12) evaluate their suitability for improving instantaneous EE.

V. Complexity Analysis

The reduction of computational complexity in terms of floating point operations (FLOPS) achieved by SAFS with respect to OAFS is given by

$$\Delta\mathcal{C} = \mathcal{C}_{OAFS} - \mathcal{C}_{SAFS}, \tag{15}$$

where $\mathcal{C}_{OAFS}$ and $\mathcal{C}_{SAFS}$ are computational complexity of OAFS and SAFS, respectively.

Four main factors contribute to the higher computational complexity of OAFS employing $|\mathcal{S}| + 1$ RUEs as compared with SAFS employing 2 RUEs:

- Evaluation of condition in (12) for additional $|\mathcal{S}| - 1$ RUEs, i.e.,
$$\Delta\mathcal{C}_1 = \left(|\mathcal{S}| + 2\left(\frac{R}{B} + \xi_d\right) + 21\right)(|\mathcal{S}| - 1).$$
- $|\mathcal{S}| - 1$ RUEs need to calculate $P_N^{R,M}$, leading to
$$\Delta\mathcal{C}_2 = \left(\frac{R}{B} + 2\xi_d + 4\right)(|\mathcal{S}| - 1).$$
- Computation of $g_{1:|\mathcal{S}|}$ and $g_{2:|\mathcal{S}|}, \ldots, g_{|\mathcal{S}|:|\mathcal{S}|}$ from $|\mathcal{S}| - 1$ and $|\mathcal{S}|$ RUEs, respectively, using (8) that yields
$$\Delta\mathcal{C}_3 = 5(|\mathcal{S}| - 1)(|\mathcal{S}| + 1).$$
- Calculation of the optimal transmission power for $|\mathcal{S}| + 1$ RUEs using (6) as compared to 2 RUEs for SAFS with the complexity of
$$\Delta\mathcal{C}_4 = \left(2|\mathcal{S}| + \frac{R}{B} + 5\right)(|\mathcal{S}| + 1) - 2\left(\frac{R}{B} + 7\right).$$

The computational complexity reduction of SAFS compared to OAFS is given by

$$\Delta\mathcal{C} = \Delta\mathcal{C}_1 + \Delta\mathcal{C}_2 + \Delta\mathcal{C}_3 + \Delta\mathcal{C}_4. \quad (16)$$

VI. Analysis of Average Energy- and Spectral-Efficiency

In this section, we analyze the average EE and SE under the maximum transmit power constraint for the two proposed adaptive forwarding strategies OAFS and SAFS, direct D2D communications, and conventional cellular communications.

A. Multi-Hop D2D Communications with the Proposed Adaptive Forwarding Strategies

Without loss of generality, we assume a non-empty subcluster set $\mathcal{S}$, i.e., $|\mathcal{S}| > 0$. The average EE for multi-hop D2D communications is given by

$$\mathcal{EE} = \mathbb{E}\Big\{ \left(1 - p_{out}^{M}(|\mathcal{F}|)\right) EE_{\mathcal{F}}^{M}\left(|\mathcal{F}|\right) \Big\}, \quad (17)$$

where $p_{out}^{M}(|\mathcal{F}|) = Prob\Big\{\sum_{i=1}^{|\mathcal{F}|} g_i < \theta_{th}\Big\}$ is the outage probability in the second-hop of multi-hop D2D communications. It is very difficult to obtain the exact expression for the expectation in (17).

***Proposition** 1:* For given $|\mathcal{S}| > 0$, $\mathcal{EE}$ can be approximated as follows

$$\mathcal{EE} \approx \frac{\left(1 - p_{out}^{M}(|\mathcal{F}|)\right) R N_D}{E_T^M + \overline{E}_{S,\mathcal{F}}^M(|\mathcal{F}|) + \overline{E}_{D,\mathcal{F}}^M(|\mathcal{F}|)}, \quad (18)$$

where

$$\begin{aligned} p_{out}^{M}(|\mathcal{F}|) \approx& \frac{|\mathcal{D}|!}{(|\mathcal{D}|-|\mathcal{F}|)!|\mathcal{F}|!}\Bigg(\frac{\gamma\left(|\mathcal{F}|, \theta_{th}/\overline{g}\right)}{(|\mathcal{F}|-1)!} \\ &+ \sum_{l=1}^{|\mathcal{D}|-|\mathcal{F}|} \frac{(-1)^{|\mathcal{F}|+l-1}(|\mathcal{D}|-|\mathcal{F}|)!}{(|\mathcal{D}|-|\mathcal{F}|-l)!l!}\left(\frac{|\mathcal{F}|}{l}\right)^{|\mathcal{F}|-1} \\ &\Bigg(\frac{|\mathcal{F}|}{|\mathcal{F}|+l}\Big(1 - \exp(-\left(1 + l/|\mathcal{F}|\right)\theta_{th}/\overline{g})\Big) \\ &- \sum_{m=0}^{|\mathcal{F}|-2}\left(-\frac{l}{|\mathcal{F}|}\right)^m \frac{\gamma\left(m+1, \theta_{th}/\overline{g}\right)}{m!}\Bigg)\Bigg), \end{aligned} \quad (19)$$

with $\gamma(\alpha, x) = \int_0^x t^{\alpha-1}\exp(-t)dt$ being the lower incomplete gamma functions. $\overline{E}_{S,\mathcal{F}}^M(|\mathcal{F}|)$, $\overline{E}_{D,\mathcal{F}}^M(|\mathcal{F}|)$, and $|\mathcal{F}|$ are average energy consumption for forwarding mode selection, average energy consumed for data transmission, and the optimal number of selected RUEs, respectively, and are given by

$$\begin{aligned} &\overline{E}_{S,\mathcal{F}}^M(|\mathcal{F}|) \\ &= \Bigg(\Big((N_T+1)(|\mathcal{D}|+1) + (|\mathcal{F}|-1)(|\mathcal{S}|+1)\Big)P_C^{UE} \\ &+ N_T P_T^{R,M} + (|\mathcal{F}|-1)P_N^{R,M} \\ &- \left(\frac{2^{R/B}-1}{\overline{h}}\right)\exp(\theta_{th}/\overline{h})Ei(-\theta_{th}/\overline{h})P_N\Bigg)T_S, \end{aligned} \quad (20)$$

$$\begin{aligned} &\overline{E}_{D,\mathcal{F}}^M(|\mathcal{F}|) = \Bigg(2\left(|\mathcal{F}|+1\right)P_C^{UE} \\ &- \frac{\left(2^{R/B}-1\right)\exp(\theta_{th}/\overline{h})Ei(-\theta_{th}/\overline{h})}{\overline{h}}P_N \\ &+ \frac{\left(2^{R/B}-1\right)|\mathcal{D}|!}{(|\mathcal{D}|-|\mathcal{F}|)!|\mathcal{F}|!\overline{g}}\Bigg(\frac{\Gamma\left(|\mathcal{F}|-1, \theta_{th}/\overline{g}\right)}{(|\mathcal{F}|-1)!} \\ &- \sum_{l=1}^{|\mathcal{D}|-|\mathcal{F}|} \frac{(-1)^{|\mathcal{F}|+l-1}(|\mathcal{D}|-|\mathcal{F}|)!}{(|\mathcal{D}|-|\mathcal{F}|-l)!l!}\left(\frac{|\mathcal{F}|}{l}\right)^{|\mathcal{F}|-1} \\ &\Bigg(Ei(-\left(1+l/|\mathcal{F}|\right)\theta_{th}/\overline{g}) - Ei(-\theta_{th}/\overline{g}) \\ &+ \sum_{m=1}^{|\mathcal{F}|-2}\left(-\frac{l}{|\mathcal{F}|}\right)^m \frac{\Gamma\left(m, \theta_{th}/\overline{g}\right)}{m!}\Bigg)\Bigg) \\ &\Bigg(1 - \frac{|\mathcal{D}|!}{(|\mathcal{D}|-|\mathcal{F}|)!|\mathcal{F}|!}\Bigg(\frac{\gamma\left(|\mathcal{F}|, \theta_{th}/\overline{g}\right)}{(|\mathcal{F}|-1)!} \\ &+ \sum_{l=1}^{|\mathcal{D}|-|\mathcal{F}|} \frac{(-1)^{|\mathcal{F}|+l-1}(|\mathcal{D}|-|\mathcal{F}|)!}{(|\mathcal{D}|-|\mathcal{F}|-l)!l!}\left(\frac{|\mathcal{F}|}{l}\right)^{|\mathcal{F}|-1} \\ &\Bigg(\frac{|\mathcal{F}|}{|\mathcal{F}|+l}\Big(1 - \exp(-\left(1+l/|\mathcal{F}|\right)\theta_{th}/\overline{g})\Big) \\ &- \sum_{m=0}^{|\mathcal{F}|-2}\left(-\frac{l}{|\mathcal{F}|}\right)^m \frac{\gamma\left(m+1, \theta_{th}/\overline{g}\right)}{m!}\Bigg)\Bigg)\Bigg)^{-1} P_N\Bigg)T_D. \end{aligned} \quad (21)$$

$Ei(x) = \int_{-\infty}^{x}\exp(t)/t dt$ and $\Gamma(\alpha, x) = \int_x^\infty t^{\alpha-1}\exp(-t)dt$ are the exponential integral function and the upper incomplete gamma function, respectively [46].

Proof: The proof is given in Appendix C.

The average SE for multi-hop D2D communications is given by

$$\mathcal{SE} \approx \frac{1}{2}\left(1 - p_{out}^{M}(|\mathcal{F}|)\right)\frac{R}{B}\frac{T_D}{T_D + \overline{T}_O^M\left(|\mathcal{F}|\right)}, \quad (22)$$

where following [47] the average time consumed for overhead when $|\mathcal{F}|$ RUEs are selected, is given by

$$\begin{aligned} \overline{T}_O^M\left(|\mathcal{F}|\right) \approx& \left(3N_T + |\mathcal{F}|\right)T_S - \lambda\frac{|\mathcal{D}|!}{\overline{g}\left(|\mathcal{F}|-1\right)!} \\ &\sum_{i=0}^{|\mathcal{D}|-|\mathcal{F}|}\frac{(-1)^i}{(|\mathcal{D}|-|\mathcal{F}|-i)!i!}\int_0^\infty \frac{\exp\left(-\left(i+|\mathcal{F}|\right)x\right)}{x}dx, \end{aligned} \quad (23)$$

1) Average EE and SE for OAFS: The average EE for OAFS is given by

$$\mathcal{EE}_{A1} = \mathbb{E}\Big\{\max_{|\mathcal{F}| \in \{1,\ldots,|\mathcal{S}|+1\}}\left(1 - p_{out}^{M}(|\mathcal{F}|)\right)EE_{\mathcal{F}}^{M}\left(|\mathcal{F}|\right)\Big\}. \quad (24)$$

***Proposition** 2:* $\mathcal{EE}_{A1}$ can be lower bounded as follows

$$\mathcal{EE}_{A1} \geq \frac{\left(1 - p_{out}^{M}(|\mathcal{F}|_{A1})\right)RN_D}{E_T^M + \overline{E}_{S,\mathcal{F}}^M(|\mathcal{F}|_{A1}) + \overline{E}_{D,\mathcal{F}}^M(|\mathcal{F}|_{A1})}, \quad (25)$$

where

$$|\mathcal{F}|_{A1} = \min\left(\left\lceil\sqrt{\frac{(2^{R/B}-1)N_D P_N}{\left((2N_D+|\mathcal{S}|+1)P_C^{UE}+P_N^{R,M}\right)\overline{g}}}\right\rceil, |\mathcal{S}|+1\right), \tag{26}$$

is obtained from the following integer optimizations problem

$$\begin{aligned}&\min_{|\mathcal{F}|}\left(\overline{E}_{S,\mathcal{F}}^{M}(|\mathcal{F}|)+\overline{E}_{D,\mathcal{F}}^{M}(|\mathcal{F}|)\right)\\ &s.t.\\ &|\mathcal{F}|\le|\mathcal{S}|+1, |\mathcal{F}|\in\mathbb{N}.\end{aligned} \tag{27}$$

Proof: The proof is given in Appendix D.

2) Average EE and SE for SAFS: In SAFS, at most two RUEs are selected to forward the data from SUE to DUE.

Using Proposition 1, a lower bound of the average EE for SAFS can be calculated as follows

$$\mathcal{EE}_{A2}\ge\mathcal{EE}_{A1}^{L}\left(|\mathcal{F}|_{A2}\right), \tag{28}$$

where

$$|\mathcal{F}|_{A2}=\underset{|\mathcal{F}|=1,2}{\operatorname{argmax}}\left(\mathcal{EE}_{A1}^{L}\left(|\mathcal{F}|\right)\right). \tag{29}$$

The average SE for SAFS is given by

$$\mathcal{SE}_{A2}\approx\frac{1}{2}\left(1-p_{out}^{M}(|\mathcal{F}|_{A2})\right)\frac{R}{B}\frac{T_D}{T_D+\overline{T}_O^{M}\left(|\mathcal{F}|_{A2}\right)}. \tag{30}$$

B. Direct D2D Communications

In direct D2D communications, SUE directly transmits data to DUE. First, SUE transmits N_T training symbols to DUE with the power

$$P_T^{S,D}=\frac{1-2^{R/B}}{\bar{h}_0\ln(1-\delta_{out})}P_N,\quad \bar{h}_0=1/\left(\mathcal{PL}_D d_{SD}^{\xi_d}\right). \tag{31}$$

$\bar{h}_0$ is the mean channel power gain between SUE and DUE; d_{SD} denotes the distance from SUE to DUE.

The energy consumption for training can be calculated as

$$E_T^D=\left(2P_C^{UE}+P_T^{S,D}\right)N_T T_S, \tag{32}$$

where $2P_C^{UE}$ is circuit power consumption for SUE transmitting and DUE receiving training symbols.

Then, DUE performs channel estimation and uses N_{FB} symbols to feed back CSI to SUE with power $P_{FB}^{D,D}=\left(2^{R/B}-1\right)P_N/h_0$.

The energy consumption for the CSI feedback is given by

$$E_{FB}^D=\left(2P_C^{UE}+P_{FB}^{D,D}\right)N_{FB}T_S. \tag{33}$$

After reception of CSI, SUE is able to adapt its data transmission power to the minimum level required to support target rate R, $P_D^{S,D}=P_{FB}^{D,D}$, leading to the following energy consumption for data transmission:

$$E_D^D=\left(2P_C^{UE}+P_D^{S,D}\right)T_D. \tag{34}$$

The average EE and SE for direct D2D communications are given respectively by

$$\mathcal{EE}_D\approx(1-p_{out}^D)\frac{RN_D}{E_T^D+\overline{E}_{FB}^D+\overline{E}_D^D}, \tag{35}$$

$$\mathcal{SE}_D=(1-p_{out}^D)\frac{R}{B}\frac{T_D}{T_D+T_O^D}, \tag{36}$$

where p_{out}^D is the outage probability, i.e., the probability that the direct D2D link cannot support target rate R with maximum transmission power P_{MAX}^{UE}, and is given by

$$p_{out}^D=Prob\{h_0<\theta_{th}\}=1-\exp\left(-\theta_{th}/\overline{h}_0\right); \tag{37}$$

$\overline{E}_{FB}^D$ and $\overline{E}_D^D$ are the average energy consumptions for CSI feedback and for data transmission, respectively, and can be calculated as follows

$$\begin{aligned}\overline{E}_{FB}^D=&\Bigg(2P_C^{UE}-\left(\frac{2^{R/B}-1}{\overline{h}_0}\right)\exp(\theta_{th}/\overline{h}_0)\\ &Ei(-\theta_{th}/\overline{h}_0)P_N\Bigg)N_{FB}T_S,\end{aligned} \tag{38}$$

$$\begin{aligned}\overline{E}_{D}^D=&\Bigg(2P_C^{UE}-\left(\frac{2^{R/B}-1}{\overline{h}_0}\right)\exp(\theta_{th}/\overline{h}_0)\\ &Ei(-\theta_{th}/\overline{h}_0)P_N\Bigg)T_D;\end{aligned} \tag{39}$$

and $T_O^D=(N_T+N_{FB})T_S$ is the overhead time consumption for direct D2D communications.

C. Cellular Communications

In conventional cellular communications, SUE transmits data to DUE via the BS. In general case, CSI is neither readily available at SUE nor at DUE. For this reason, N_T training symbols are broadcast from the BS to enable SUE and DUE to estimate their channels to the BS.

The required training transmit power levels from BS to SUE ($P_T^{S,C}$) and from BS to DUE ($P_T^{D,C}$) to satisfy target rate R with outage probability δ_{out} are given by

$$P_T^{S,C}=\frac{1-2^{R/B}}{\bar{h}_B\ln(1-\delta_{out})}P_N,\quad \bar{h}_B=1/\left(\mathcal{PL}_C d_{SB}^{\xi_c}\right), \tag{40}$$

$$P_T^{D,C}=\frac{1-2^{R/B}}{\bar{g}_B\ln(1-\delta_{out})}P_N,\quad \bar{g}_B=1/\left(\mathcal{PL}_C d_{BD}^{\xi_c}\right). \tag{41}$$

$\bar{h}_B$ and $\bar{g}_B$ are the mean channel power gains from SUE to BS and from BS to DUE, respectively; $\mathcal{PL}_C$ is a path loss constant for cellular communications and ξ_c is the corresponding path loss exponent; d_{SB} and d_{BD} denote the distances from SUE to BS and from BS to DUE, respectively.

The training broadcasting energy for reaching both SUE and DUE is given by

$$E_T^C=\left(P_C^{BS}+2P_C^{UE}+\max\left\{P_T^{S,C},P_T^{D,C}\right\}\right)N_T T_S, \tag{42}$$

where $P_C^{BS}+2P_C^{UE}$ is circuit power consumption for BS transmitting and SUE as well as DUE receiving training symbols.

Once DUE has estimated its channel to the BS, it feeds back the estimated CSI to BS using N_{FB} symbols with the minimum transmission power that supports target rate R, $P_{FB}^{D,C} = \left(2^{R/B} - 1\right) P_N / g_B$.

The energy consumption for the CSI feedback is given by

$$E_{FB}^{C} = \left(P_C^{UE} + P_C^{BS} + P_{FB}^{D,C}\right) N_{FB} T_S, \quad (43)$$

where $P_C^{UE} + P_C^{BS}$ is circuit power consumption for DUE transmitting CSI and BS receiving it.

During data transmission, SUE transmits data to BS with the adaptive power, $P_D^{S,C} = \left(2^{R/B} - 1\right) P_N / h_B$. BS forwards the received data to DUE with transmission power $P_D^{BS} = \left(2^{R/B} - 1\right) P_N / g_B$.

The overall energy consumption for the data transmission is given by

$$E_D^{C} = \left(2\left(P_C^{BS} + P_C^{UE}\right) + P_D^{S,C} + P_D^{BS}\right) T_D, \quad (44)$$

where $2\left(P_C^{BS} + P_C^{UE}\right)$ is circuit power consumption for the two-hop data transmission through BS.

The average EE and SE for cellular communications are given respectively by

$$\mathcal{EE}_C \approx (1 - p_{out}^{C,I})(1 - p_{out}^{C,II}) \frac{R N_D}{E_T^C + \overline{E}_{FB}^C + \overline{E}_D^C}, \quad (45)$$

$$\mathcal{SE}_C = \frac{1}{2}(1 - p_{out}^{C,I})(1 - p_{out}^{C,II}) \frac{R}{B} \frac{T_D}{T_D + T_O^C}, \quad (46)$$

where $T_O^C = (N_T + N_{FB}) T_S$ denotes the overhead time consumption for cellular communications; The factor 1/2 in (46) is due to the two-hop half-duplex transmissions; $p_{out}^{C,I}$ and $p_{out}^{C,II}$ are the outage probabilities for the uplink and downlink transmissions, respectively, and can be calculated as follows

$$p_{out}^{C,I} = Prob\{h_B < \theta_{th}\} = 1 - \exp\left(-\theta_{th}/\overline{h}_B\right), \quad (47)$$

$$p_{out}^{C,II} = Prob\{g_B < \theta_{th}\} = 1 - \exp\left(-\theta_{th}/\overline{g}_B\right); \quad (48)$$

and the average energy consumptions for CSI feedback ($\overline{E}_{FB}^C$) and for data transmission ($\overline{E}_D^C$) are given by

$$\overline{E}_{FB}^C = \Bigg(P_C^{UE} + P_C^{BS} - \left(\frac{2^{R/B} - 1}{\overline{g}_B}\right) \exp(\theta_{th}/\overline{g}_B) \, Ei(-\theta_{th}/\overline{g}_B) P_N\Bigg) N_{FB} T_S, \quad (49)$$

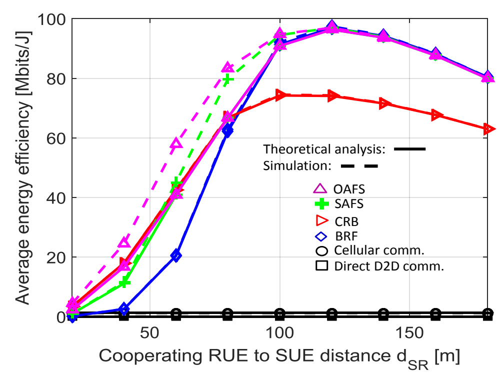
$$\overline{E}_D^C = \Bigg(2\left(P_C^{BS} + P_C^{UE}\right) - \left(2^{R/B} - 1\right)\left(\frac{\exp(\theta_{th}/\overline{h}_B) Ei(-\theta_{th}/\overline{h}_B)}{\overline{h}_B} + \frac{\exp(\theta_{th}/\overline{g}_B) Ei(-\theta_{th}/\overline{g}_B)}{\overline{g}_B}\right) P_N\Bigg) T_D. \quad (50)$$

VII. Simulation Results

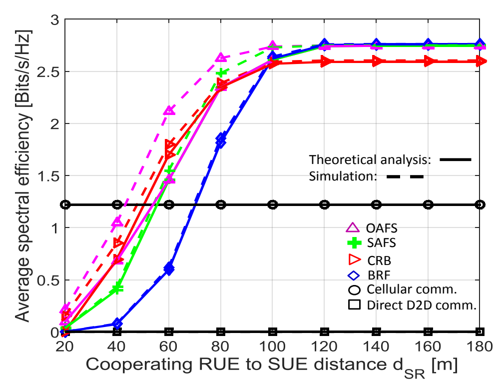
The performance of the proposed adaptive forwarding strategies for multi-hop D2D communications and the accuracy of the theoretical analysis are evaluated through simulation. Main system parameters are listed in Table II [38]. During training, $N_T = 1$ symbol is transmitted with the power to satisfy the target rate R with outage probability $\delta_{out} = 0.1$ [40]. We consider 64-QAM modulation ($R = 6$) and data packet length of $N_D = 200$ symbols. A DUE uses $N_{FB} = 2$ symbols to feedback CSI to BS and to SUE. The radius of main-cluster $\mathcal{D}$ is set as $r = 5m$.

TABLE II: System Parameters

Bandwidth, B	10 MHz
Noise power spectral density, N_0	-174 dBm/Hz
Maximum BS Tx power, P_{MAX}^{BS}	43 dBm
Maximum UE Tx power, P_{MAX}^{UE}	23 dBm
BS circuit power, P_C^{BS}	10 W
UE circuit power, P_C^{UE}	100 mW
Path-loss for cellular communications	128.1 + 37.6 $\log_{10}[d(km)]$ dB
Path-loss for D2D communications	148 + 40 $\log_{10}[d(km)]$ dB



(a) Average energy efficiency



(b) Average spectral efficiency

Fig. 3: Average energy and spectral efficiency versus cooperating RUE to SUE distance (d_{SR}) for the proposed forwarding strategies and different communication modes with $d_{SD} = 200m, d_{SB} = d_{BD} = 250m, |\mathcal{D}| = 5$, and $|\mathcal{S}| = 4$.

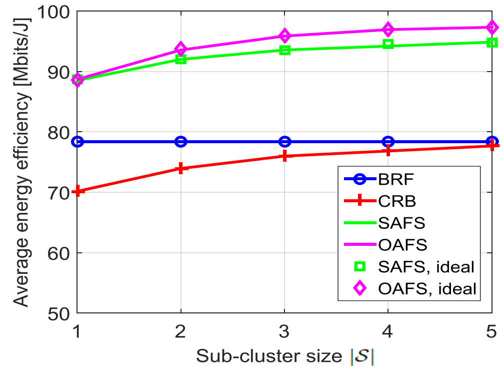
Fig. 3(a) plots the average EE versus d_{SR} for the proposed adaptive forwarding strategies, conventional cellular communications, direct D2D communications, BRF [44], and CRB [43] with the optimal number of RUEs, for $d_{SD} = 200m$ and $d_{SB} = d_{BD} = 250m$. Both the simulation and theoretical results are shown. We can see that the theoretical lower bounds of average EE for OAFS and SAFS are reasonably tight, while for the other considered communication modes the theoretical results closely match the simulation results. OAFS exhibits the highest average EE when the cooperating RUEs are located closer to SUE. This is because OAFS selects optimally between BRF and CRB. For OAFS, SAFS, BRF and CRB, the average EE initially increases with increasing d_{SR} due to the reduction of transmission power and outage probability in the second-hop; after reaching the maximum, the average EE decreases because the energy consumption in the first hop increases with increasing d_{SR} and dominates the overall energy consumption. For $d_{SR} \geq 80m$, SAFS achieves almost the same average EE as OAFS. Cellular communications is more energy-efficient than direct D2D communications due to lower path-loss [38] (as given in Table II) resulting in lower transmission power required to satisfy target rate R and lower outage probability. To the best of our knowledge, no overhead-aware adaptive forwarding methods exist in the literature that could be included in performance comparison with the proposed OAFS and SAFS. Only a few works have considered the related overhead for implementing multi-hop communications [40]-[44], but none of them has proposed or considered adaptive methods. For overhead-aware multi-hop communications, it was shown in [43] that cooperative beamforming achieves the higher average EE than best relay selection for relays located close to the source, while for other relay locations, best relay selection [44] outperforms cooperative beamforming.

Fig. 3(b) plots the average SE versus d_{SR}. We can observe that OAFS and SAFS are more spectral-efficient than BRF for RUEs located closer to SUE. The average SE for OAFS, SAFS, BRF and CRB first increases with increasing d_{SR} due to the reduction of outage probability in the second-hop and then at certain d_{SR} it saturates as no further noticeable reduction of outage probability can be achieved. CRB saturates to the lowest average SE as it needs more overhead that lowers its SE. Cellular communications show the highest average SE for $d_{SR} \leq 50m$ due to the smaller path-loss compared to D2D links resulting in a lower outage probability.

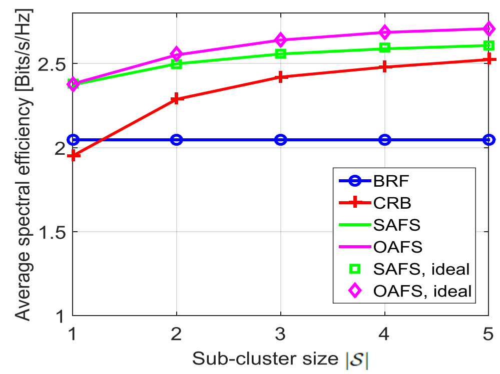
Fig. 4(a) plots the average EE versus sub-cluster size $|\mathcal{S}|$ for OAFS, SAFS, BRF and CRB, for $d_{SD} = 150m$. For OAFS and SAFS, the performance under the ideal case, where each RUE knows $|\mathcal{D}|$ and $|\mathcal{S}|$ is also shown. We can see that for more realistic cases, where $|\mathcal{D}|$ and $|\mathcal{S}|$ are unknown to RUEs, OAFS and SAFS using the distributed forwarding mode selection proposed in Section IV, perform closely to the corresponding ideal cases. With increasing $|\mathcal{S}|$, the average EE of OAFS, SAFS and CRB increases due to increasing diversity gains. OAFS achieves the highest average EE among the four strategies, closely followed by SAFS. CRB exhibits the lowest average EE as it performs cooperative beamforming without considering the associated overhead.

Table III shows the reduction of computational complexity ΔC using (16) achieved by SAFS compared to OAFS for three different sub-cluster sizes ($|\mathcal{S}|$). ΔC increases significantly with $|\mathcal{S}|$. For example, doubling the sub-cluster size from $|\mathcal{S}| = 5$ to $|\mathcal{S}| = 10$ leads to increase of computational complexity reduction from $\Delta C = 476$ FLOPS to $\Delta C = 1431$ FLOPS.

The average SE of OAFS, SAFS, BRF and CRB versus sub-



(a) Average energy efficiency



(b) Average spectral efficiency

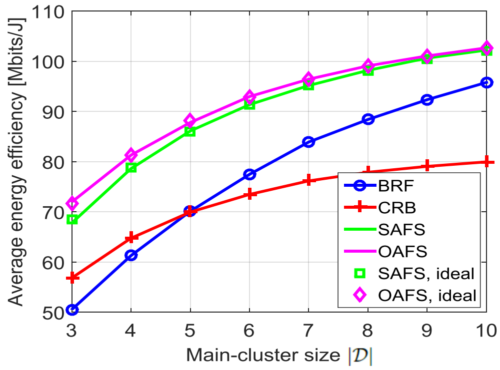
Fig. 4: Average energy and spectral efficiency comparison between the proposed forwarding strategies, BRF and CRB for different sub-cluster size ($|\mathcal{S}|$) with $d_{SD} = 150m, d_{SR} = 0.2d_{SD}$, and $|\mathcal{D}| = 6$.

TABLE III: Computational complexity reduction offered by SAFS compared to OAFS, ΔC, for $|\mathcal{S}| = 5, 10, 15$.

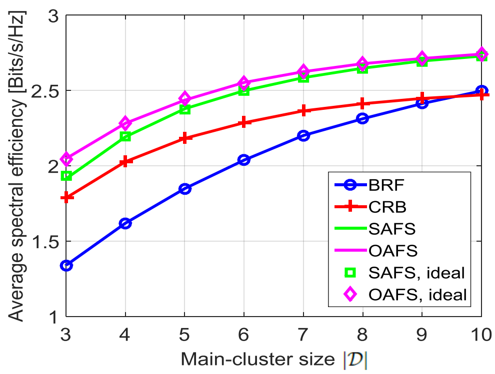
Sub-cluster size ($\lvert\mathcal{S}\rvert$)	$\lvert\mathcal{S}\rvert = 5$	$\lvert\mathcal{S}\rvert = 10$	$\lvert\mathcal{S}\rvert = 15$
ΔC in FLOPS	476	1431	2786

cluster size $|\mathcal{S}|$ for $d_{SD} = 150m$ is depicted in Fig. 4(b). With increasing $|\mathcal{S}|$, the average SE of these forwarding strategies increases because of higher diversity gains. For $|\mathcal{S}| \geq 2$, different from Fig. 4(a), CRB is more spectral efficient than BRF. This is because the overhead has a much less impact on SE than on EE and recruiting more than one RUE for forwarding data to DUE reduces outage probability due to cooperative gains.

Fig. 5(a) plots the average EE versus main-cluster size $|\mathcal{D}|$ for $|\mathcal{S}| = 2$. For all considered forwarding strategies, increasing $|\mathcal{D}|$ leads to higher average EE due to higher diversity gains. We can see that the average EE of the proposed forwarding strategies and CRB saturate at lower values of $|\mathcal{D}|$ than BRF. This is because the overhead of the proposed forwarding strategies and CRB increases with increasing $|\mathcal{D}|$. OAFS and SAFS are more energy-efficient than CRB and BRF independent of $|\mathcal{D}|$ ($3 \leq |\mathcal{D}| \leq 10$). SAFS performs almost as well as OAFS, but at a much lower computational complexity. CRB shows higher average EE than BRF for $3 \leq |\mathcal{D}| < 5$,

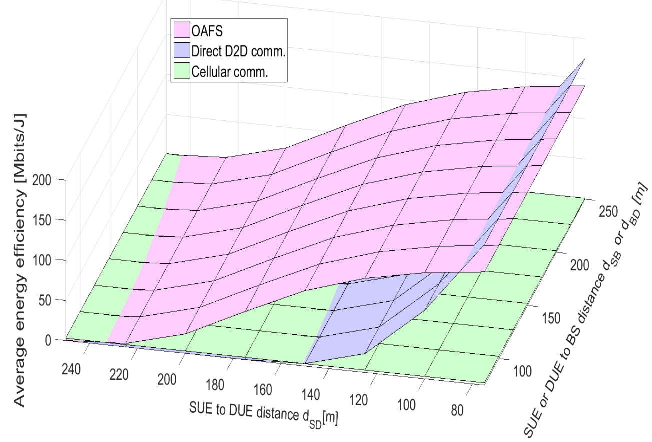


(a) Average energy efficiency

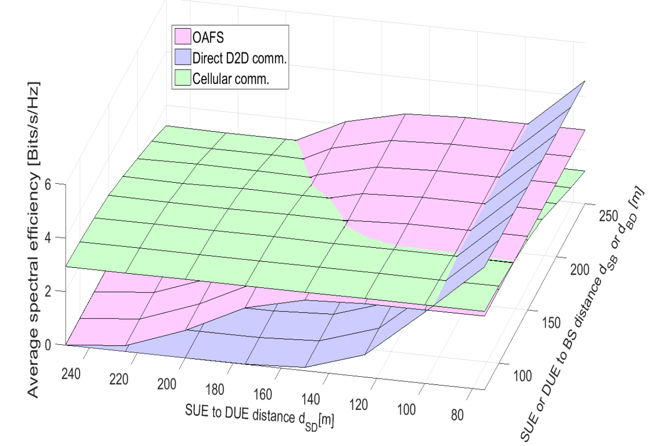


(b) Average spectral efficiency

Fig. 5: Average energy and spectral efficiency comparison between the proposed forwarding strategies, BRF and CRB for different main-cluster size ($|\mathcal{D}|$) with $d_{SD} = 150m, d_{SR} = 0.2d_{SD}$, and $|\mathcal{S}| = 2$.



(a) Average energy efficiency



(b) Average spectral efficiency

Fig. 6: Average energy and spectral efficiency versus SUE to DUE distance (d_{SD}) and SUE or DUE to BS distance (d_{SB} or d_{BD}) for OAFS, direct D2D and cellular communications with $d_{SR} = 0.2d_{SD}, |\mathcal{D}| = 5$, and $|\mathcal{S}| = 4$.

due to cooperative gains that reduce transmission power and outage probability. For $|\mathcal{D}| > 5$, BRF outperforms CRB due to weaker dependency of its overhead energy consumption on $|\mathcal{D}|$.

Fig. 5(b) shows the average SE versus $|\mathcal{D}|$ for $|\mathcal{S}| = 2$. Due to the same reasons as for Fig. 5(a), the average SE of the considered forwarding strategies increases with increasing $|\mathcal{D}|$ and saturates at different values of $|\mathcal{D}|$. The performance gap between SAFS and OAFS is practically negligible.

Fig. 6(a) plots the average EE of OAFS, direct D2D, and cellular communications versus d_{SD} and d_{SB} (or d_{BD}) for $d_{SR} = 0.2d_{SD}$, $|\mathcal{D}| = 5$, and $|\mathcal{S}| = 4$. For $d_{SD} < 87$m, independent of d_{SB} or d_{BD}, direct D2D communications exhibit the highest average EE because of the lowest circuit energy consumption that dominates the overall energy consumption for short SUE to DUE distances. For higher d_{SD}, OAFS outperforms direct D2D communications. Moreover, for $d_{SD} \leq 230$m, OAFS achieves higher EE than cellular communications due to lower outage probability and reduced transmission power.

Fig. 6(b) plots the average SE versus d_{SD} and d_{SB} (or d_{BD}). We can observe that direct D2D communication is the most spectral-efficient mode for $d_{SD} < 100$m, as the OAFS and cellular communications suffer from 1/2 loss of SE due to half-duplex forwarding and need more overhead. For 100m$\leq d_{SD} \leq 195$m and d_{SB} or ($d_{BD} \geq 125$m), OAFS is the most spectral-efficient among all communication modes under comparison.

Fig. 7 plots the average EE versus the average SE of OAFS for two different values of d_{SD}, $d_{SR} = 0.2d_{SD}$, $|\mathcal{D}| = 10$, $|\mathcal{S}| = 5$, and $\delta_{out} = 10^{-3}$. Each curve is plotted for seven different target rates $R = 1, 2, ..., 7$ bits/symbol. We can observe that both EE and SE increase initially with increasing R. After reaching a peak (at $R = 3$ bits/symbol for $d_{SD} = 150$m and at $R = 5$ bits/symbol for $d_{SD} = 100$m), EE starts to decrease with increasing R and increasing SE. For a given SE, the EE decreases with d_{SD}, as higher transmission power is required to satisfy the target rate R, thus reducing EE.

In the following, in order to evaluate the performance of the proposed forwarding strategies under a more realistic setup, we consider a multi-cell network with multiple D2D pairs per cell

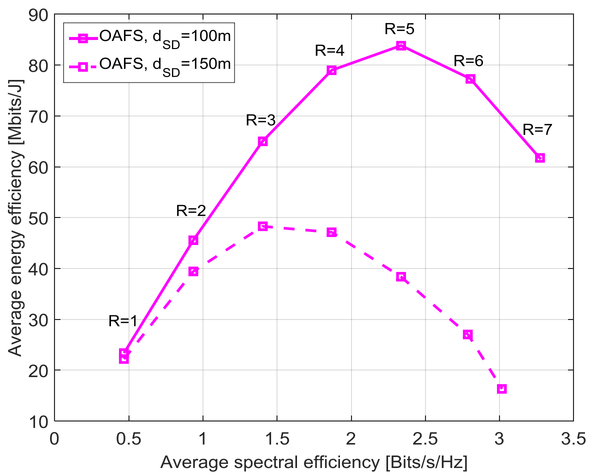


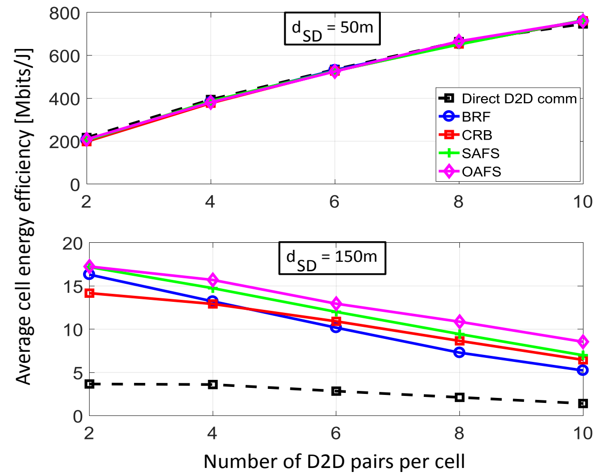
Fig. 7: Average EE versus average SE of OAFS for two different d_{SD}, $d_{SR} = 0.2d_{SD}$, $|\mathcal{D}| = 10$, $|\mathcal{S}| = 5$, and $\delta_{out} = 10^{-3}$.

that interfere with each other. More specifically, we simulate a network consisting of seven hexagonal cells each with a radius of 1km and take into account both intra- and inter-cell interference between D2D pairs [48]. D2D pairs are uniformly distributed in the network area. Furthermore, $RUE_{1\leq i\leq|\mathcal{D}|}$ are uniformly distributed within the main-cluster $\mathcal{D}$ of radius $r = 10$m. Among all D2D pairs, one pair utilizes one of the communication modes such as direct D2D, OAFS, SAFS, BRF or CRB, while the other D2D pairs deploy direct D2D communications and use 3GPP LTE uplink open loop power control with compensation factor $\alpha = 1$ [49]. For SUE to DUE distance d_{SD} and under maximum transmission power constraint P_{UE}^{MAX}, each UE transmits with the following power

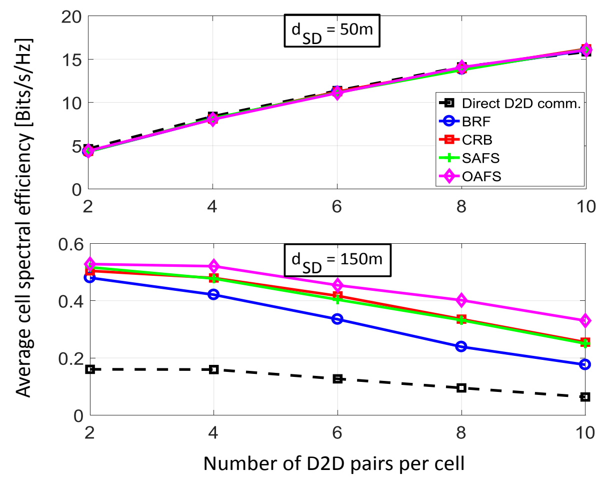
$$P[dB] = \min\left\{P_{UE}^{MAX}, 10log_{10}\left(\mathcal{PL}_D d_{SD}^{\xi_d}\left(2^{R/B}-1\right)P_N\right)\right\},$$

where $\mathcal{PL}_D$, ξ_d, R, B, and P_N denote the path loss constant for D2D communications, the path loss exponent, the target rate, the bandwidth, and the AWGN power, respectively. An outage occurs when a D2D pair fails to achieve target rate R with transmission power P.

Fig. 8(a) plots the average cell energy efficiency (EE) of OAFS, SAFS, direct D2D communications, BRF, and CRB versus the number of D2D pairs per cell for $d_{SD} = 50$m and $d_{SD} = 150$m. We can see that for $d_{SD} = 50$m all communication modes achieve the same cell EE, which increases with the number of D2D pairs. This is because for a relatively short d_{SD}, the interference between D2D pairs is negligible. For $d_{SD} = 150$m, D2D pairs need to transmit with a much higher power level to satisfy their target rate R and hence the interference level between D2D pairs increases significantly, so does the outage probability. Consequently, with the increasing number of D2D pairs, the interference increases, thus reducing the cell EE. OAFS exhibits the highest cell EE as it reduces energy consumption and generates less interference towards other D2D pairs due to the lower transmission power used.



(a) Average cell energy efficiency



(b) Average cell spectral efficiency

Fig. 8: Average cell energy and spectral efficiency versus number of D2D pairs per cell for the proposed forwarding strategies, direct D2D communications, BRF, and CRB for $|\mathcal{D}| = 10$ and $|\mathcal{S}| = |\mathcal{D}| - 1$.

Fig. 8(b) plots the average cell spectral efficiency (SE) of OAFS, SAFS, direct D2D communications, BRF, and CRB versus number of D2D pairs per cell for $d_{SD} = 50$m and $d_{SD} = 150$m. For $d_{SD} = 50$m, all the considered communication modes achieve the same average cell SE, which increases with the increasing number of D2D pairs. For $d_{SD} = 150$m, the average cell SE decreases with the increasing number of D2D pairs due to increasing interference between D2D pairs leading to a higher outage probability. We can observe that OAFS is the most spectral-efficient communication mode as it has the lowest outage probability among the communication modes under comparison.

VIII. Conclusions

In this paper, an energy- and spectral-efficient optimal adaptive forwarding strategy (OAFS) for multi-hop D2D communications is proposed, where RUEs dynamically choose between BRF and CRB (with the optimal number of RUEs) depending on which of them provides the higher instantaneous EE. In order to reduce the computational complexity for determining the optimal number of RUEs for CRB mode, a low-complexity sub-optimal adaptive forwarding strategy (SAFS) is proposed to select between BRF and CRB with two RUEs. Furthermore, a distributed forwarding mode selection approach is proposed to reduce the overhead for mode selection. We have analyzed the average EE and SE for the proposed forwarding strategies under maximum transmission power constraint, considering circuit power consumption and the overhead for obtaining CSI, forwarding mode selection, and cooperative beamforming. The theoretical and simulation results have shown that the proposed OAFS and SAFS are more energy-and spectral-efficient than BRF, CRB, direct D2D communications, and conventional cellular communications, especially for RUEs located closer to the SUE. Moreover, the performance of SAFS is close to that of OAFS for short to moderate SUE-to-DUE distances. OAFS and SAFS with the proposed distributed forwarding mode selection approach exhibit practically the same EE and SE as for the ideal case where main- and sub-cluster sizes are known at RUEs.

Appendix A
Proof of Lemma 1

For calculation of optimal transmission power for RUEs, two different modes need to be considered: BRF and CRB.

The optimal transmission power for BRF mode ($|\mathcal{F}| = 1$) can be easily obtained from Shannon's capacity formula.

The received signal at DUE for cooperative MRT beamforming for $|\mathcal{F}| > 1$ transmitting RUEs is given by

$$y_d = \left(\sum_{i=1}^{|\mathcal{F}|} f_i w_i \right) s + n_d, \tag{51}$$

where f_i, s, and n_d denote the channel coefficient between RUE_i and DUE, the transmitted signal with $E\{|s|^2\} = 1$, and the additive white Gaussian noise at DUE, respectively, and the MRT beamforming weights w_i $(i = 1, \ldots, |\mathcal{F}|)$ are obtained as follows [45]

$$w_i = \sqrt{P_{D,i}^{II}} \frac{f_i^*}{|f_i|}, \tag{52}$$

where $P_{D,i}^{II}$ denotes the transmission power for RUE_i.

In order to find the optimal transmission power of RUEs ($P_{D,i}^{II}$) for CRB mode with MRT beamforming, the following constrained optimization problem needs to be solved [50]

$$\begin{aligned} &\min_{w_1,\ldots,w_{|\mathcal{F}|}} \sum_{i=1}^{|\mathcal{F}|} |w_i|^2 \\ &s.t. \\ &\frac{\left| \sum_{i=1}^{|\mathcal{F}|} f_i w_i \right|^2}{P_N} \geq 2^{R/B} - 1. \end{aligned} \tag{53}$$

Using Cauchy-Schwarz inequality [46]

$$\left| \sum_{i=1}^{|\mathcal{F}|} f_i w_i \right|^2 \leq \sum_{j=1}^{|\mathcal{F}|} |f_j|^2 \sum_{i=1}^{|\mathcal{F}|} |w_i|^2, \tag{54}$$

where for $w_i = c f_i^*$, $c = \sqrt{P_{D,i}^{II}}/|f_i|$, (54) holds with equality, we can rewrite the optimization problem in (53) as follows,

$$\begin{aligned} &\min_{w_1,\ldots,w_{|\mathcal{F}|}} \sum_{i=1}^{|\mathcal{F}|} |w_i|^2 \\ &s.t. \\ &\frac{\sum_{j=1}^{|\mathcal{F}|} |f_j|^2 \sum_{i=1}^{|\mathcal{F}|} |w_i|^2}{P_N} \geq 2^{R/B} - 1. \end{aligned} \tag{55}$$

Applying Karush-Kuhn-Tucker (KKT) conditions [51] to (55) yields

$$2|w_i| - 2\lambda |w_i| \sum_{j=1}^{|\mathcal{F}|} |f_j|^2 = 0 \tag{56}$$

$$\lambda \left(\sum_{j=1}^{|\mathcal{F}|} |f_j|^2 \sum_{i=1}^{|\mathcal{F}|} |w_i|^2 - \left(2^{R/B} - 1\right) P_N \right) = 0. \tag{57}$$

Since $\lambda > 0$, (57) holds only if

$$\sum_{j=1}^{|\mathcal{F}|} |f_j|^2 \sum_{i=1}^{|\mathcal{F}|} |w_i|^2 - \left(2^{R/B} - 1\right) P_N = 0. \tag{58}$$

Substituting $w_i = c f_i^*$ in (58) and solving it for c, we have

$$c = \frac{\sqrt{\left(2^{R/B} - 1\right) P_N}}{\sum_{j=1}^{|\mathcal{F}|} |f_j|^2}. \tag{59}$$

We then obtain the optimal transmission power for RUE_i as follows,

$$\begin{aligned} P_{D,i}^{II} = |w_i|^2 &= \left(2^{R/B} - 1\right) P_N \frac{|f_i|^2}{\left(\sum_{j=1}^{|\mathcal{F}|} |f_j|^2 \right)^2} \\ &= \left(2^{R/B} - 1\right) P_N \left(\sum_{j=1}^{|\mathcal{F}|} \frac{|f_j|^2}{|f_i|} \right)^{-2}. \end{aligned} \tag{60}$$

Substituting $|f_i| = \sqrt{g_i}$ in (60) yields the optimal power for CRB mode with MRT beamforming.

Appendix B
Proof of Lemma 2

According to (12), for $EE_{\mathcal{F}}^M > 0$, $RUE_j \in \mathcal{S}$ joins forwarding set only for the case that

$$\begin{aligned} \Delta EE^M &= EE_{\mathcal{F} \cup \{RUE_j\}}^M - EE_{\mathcal{F}}^M \\ &= \frac{RN_D}{E_T^M + E_{S,\mathcal{F} \cup \{RUE_j\}}^M + E_{D,\mathcal{F} \cup \{RUE_j\}}^M} \\ &\quad - \frac{RN_D}{E_T^M + E_{S,\mathcal{F}}^M + E_{D,\mathcal{F}}^M} > 0. \end{aligned} \tag{61}$$

(61) is satisfied for

$$E_{D,\mathcal{F}}^M - E_{D,\mathcal{F} \cup \{RUE_j\}}^M > E_{S,\mathcal{F} \cup \{RUE_j\}}^M - E_{S,\mathcal{F}}^M, \tag{62}$$

where using (5) leads to

$$\Delta E_S^M = \left((|\mathcal{S}| + 1) P_C^{UE} + P_N^{R,M} \right) T_S. \tag{63}$$

From (63), it can be seen that dependency on $|\mathcal{D}|$ is cancelled out. Nevertheless, ΔE_S^M still depends on $|\mathcal{S}|$.

Using $|\mathcal{S}|+1 \leq |\mathcal{D}| \leq N$, upper bound of ΔE_S^M is given by

$$\Delta E_S^M \leq \left((N+1)P_C^{UE} + P_N^{R,M}\right) T_S = \Delta E_S^{M,U} \quad (64)$$

For $\Delta E_D^M > \left((N+1)P_C^{UE} + P_N^{R,M}\right) T_S$ and (64), it follows that $\Delta E_D^M > \Delta E_S^M$ and (61) are satisfied, i.e, $EE^M_{\mathcal{F}\cup\{RUE_j\}} > EE^M_{\mathcal{F}}$.

APPENDIX C

PROOF OF PROPOSITION 1

Using first-order Taylor approximation in (17) leads to (18). The outage probability can be calculated as follows

$$\begin{aligned} p_{out}^M(|\mathcal{F}|) &\approx Prob\left\{\sum_{k=1}^{|\mathcal{F}|} g_{k:|\mathcal{D}|} < \theta_{th}\right\} \\ &= \int_0^{\theta_{th}} p_{\sum\limits_{i=1}^{|\mathcal{F}|} g_{i:|\mathcal{D}|}}(x)dx, \end{aligned} \quad (65)$$

where [47]

$$\begin{aligned} & p_{\sum\limits_{i=1}^{|\mathcal{F}|} g_{i:|\mathcal{D}|}}(x) = \frac{|\mathcal{D}|!}{(|\mathcal{D}|-|\mathcal{F}|)!|\mathcal{F}|!} \\ & \exp\left(-\frac{x}{\overline{g}}\right)\left(\frac{x^{|\mathcal{F}|-1}}{\overline{g}^{|\mathcal{F}|}(|\mathcal{F}|-1)!} + \frac{1}{\overline{g}}\right. \\ & \sum_{l=1}^{|\mathcal{D}|-|\mathcal{F}|} \frac{(-1)^{|\mathcal{F}|+l-1}(|\mathcal{D}|-|\mathcal{F}|)!}{(|\mathcal{D}|-|\mathcal{F}|-l)!l!}\left(\frac{|\mathcal{F}|}{l}\right)^{|\mathcal{F}|-1} \\ & \left.\left(\exp\left(-\frac{lx}{|\mathcal{F}|\overline{g}}\right) - \sum_{m=0}^{|\mathcal{F}|-2}\frac{1}{m!}\left(-\frac{lx}{|\mathcal{F}|\overline{g}}\right)^m\right)\right). \end{aligned} \quad (66)$$

The average energy consumption for the forwarding mode selection ($\overline{E}^M_{S,\mathcal{F}}(.)$) and data transmission ($\overline{E}^M_{D,\mathcal{F}}(.)$) are given by

$$\begin{aligned} & \overline{E}^M_{S,\mathcal{F}}(|\mathcal{F}|) = \Bigg(\left(\left((|\mathcal{D}|+1)P_C^{UE} + P_T^{R,M}\right) N_T\right. \\ & + (|\mathcal{D}|+1)P_C^{UE} + \left(2^{R/B}-1\right) P_N \left(\int_{\theta_{th}}^{\infty} p_h(x)/x dx\right) \\ & \left.\left(1 - \int_0^{\theta_{th}} p_h(x)dx\right)^{-1}\right) + (|\mathcal{F}|-1) \\ & \left((|\mathcal{S}|+1)P_C^{UE} + P_N^{R,M}\right)\Bigg) T_S. \end{aligned} \quad (67)$$

$$\begin{aligned} & \overline{E}^M_{D,\mathcal{F}}(|\mathcal{F}|) = \Bigg(2(1+|\mathcal{F}|)P_C^{UE} + \left(2^{R/B}-1\right) P_N \\ & \Bigg(\left(\left(\int_{\theta_{th}}^{\infty} p_h(x)/x dx\right)\left(1 - \int_0^{\theta_{th}} p_h(x)dx\right)^{-1}\right. \\ & + \left(\int_{\theta_{th}}^{\infty} p_{\sum\limits_{i=1}^{|\mathcal{F}|} g_{i:|\mathcal{D}|}}(x)/x dx\right) \\ & \left.\left(1 - \int_0^{\theta_{th}} p_{\sum\limits_{i=1}^{|\mathcal{F}|} g_{i:|\mathcal{D}|}}(x)dx\right)^{-1}\right)\Bigg) T_D, \end{aligned} \quad (68)$$

where $p_h(x) = \exp(-x/\overline{h})/\overline{h}$. Evaluation of integrals in (65), (67) and (68) lead to (19), (20) and (21), respectively.

APPENDIX D

PROOF OF PROPOSITION 2

By means of Jensen's inequality $\mathbb{E}\{\varphi(X)\} \geq \varphi(\mathbb{E}\{X\})$, where X is a random variable, (24) can be lower bounded as follows

$$\begin{aligned} \mathcal{E}\mathcal{E}_{A1} &\geq \max_{|\mathcal{F}|\in\{1,\ldots,|\mathcal{S}|+1\}} \mathbb{E}\{\left(1 - p_{out}^M(|\mathcal{F}|)\right) EE^M_{\mathcal{F}}(|\mathcal{F}|)\} \\ &= \left(1 - p_{out}^M(|\mathcal{F}|_{A1})\right) \mathbb{E}\{EE^M_{\mathcal{F}}(|\mathcal{F}|_{A1})\}. \end{aligned} \quad (69)$$

Assuming very low outage probability, i.e., $p_{out}^M(|\mathcal{F}|) \approx 0$ due to cooperative diversity gains [41][42] and using Proposition 1, $|\mathcal{F}|_{A1}$ is obtained from

$$\begin{aligned} & \min_{|\mathcal{F}|} \left(\overline{E}^M_{S,\mathcal{F}}(|\mathcal{F}|) + \overline{E}^M_{D,\mathcal{F}}(|\mathcal{F}|)\right) \\ & s.t. \\ & |\mathcal{F}| \leq |\mathcal{S}|+1, |\mathcal{F}| \in \mathbb{N}. \end{aligned} \quad (70)$$

Using integer relaxation in (70), the optimization problem becomes convex

$$\begin{aligned} & \min_{|\mathcal{F}|} \left(\overline{E}^M_{S,\mathcal{F}}(|\mathcal{F}|) + \overline{E}^M_{D,\mathcal{F}}(|\mathcal{F}|)\right) \\ & s.t. \\ & |\mathcal{F}| - |\mathcal{S}| - 1 \leq 0. \end{aligned} \quad (71)$$

The optimization problem in (71) can be solved by applying KKT conditions [51]

$$\begin{aligned} \frac{d}{d|\mathcal{F}|}\left(\overline{E}^M_{S,\mathcal{F}}(|\mathcal{F}|) + \overline{E}^M_{D,\mathcal{F}}(|\mathcal{F}|) + \lambda\left(|\mathcal{F}| - |\mathcal{S}| - 1\right)\right) &= 0, \\ \lambda\left(|\mathcal{F}| - |\mathcal{S}| - 1\right) &= 0, \\ \lambda &\geq 0. \end{aligned} \quad (72)$$

The conditions above are only fulfilled for $\lambda = 0$ and

$$\frac{d}{d|\mathcal{F}|}\left(\overline{E}^M_{S,\mathcal{F}}(|\mathcal{F}|) + \overline{E}^M_{D,\mathcal{F}}(|\mathcal{F}|)\right) = 0. \quad (73)$$

$\overline{E}_{D,\mathcal{F}}^{M}(|\mathcal{F}|)$ can be approximated as follows

$$\overline{E}_{D,\mathcal{F}}^{M}(|\mathcal{F}|) \approx \Bigg(2\left(1+|\mathcal{F}|\right)P_{C}^{UE} + \left(2^{R/B}-1\right)P_{N} \\ \left(\mathbb{E}\{g_{1:|\mathcal{D}|}^{-1}\} + \mathbb{E}\left\{\left(\sum_{i=1}^{|\mathcal{F}|} g_i\right)^{-1}\right\}\right)\Bigg)T_D \approx \Bigg(2\left(1+|\mathcal{F}|\right) \\ P_{C}^{UE} + \left(2^{R/B}-1\right)P_{N}\left(\mathbb{E}\{g_{1:|\mathcal{D}|}^{-1}\} + (|\mathcal{F}|\overline{g})^{-1}\right)\Bigg)T_D. \tag{74}$$

Evaluation of (73) for $1 \leq |\mathcal{F}|_{A1} \leq |\mathcal{S}|+1$ leads to (26).

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