A SWIPT-based Device-to-Device Cooperative Network

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***Abstract*—This paper proposes a simultaneous wireless information and power transfer (SWIPT)-based cooperative device-to-device (D2D) network, where the D2D pairs are distributed in a circular area. Such networks are particularly helpful in public safety scenarios, where battery constraints signify the need for a resource efficient communication protocol. The node distribution in the circular area is modeled through a homogeneous Poisson point process (PPP), where a central node is responsible for intra-region signaling. Expressions for the ergodic rates of single-hop and dual-hop scenarios are derived, assuming a Rayleigh fading channel with path loss. A transmission flow mechanism encompassing energy harvesting and decode-and-forward nodes is devised for end-to-end transmission. Performance analysis of the proposed technique reveals the impact of different network parameters on the magnitude of energy harvested and outage capacity.**

***Index Terms*—D2D, multi-hop network, SWIPT, outage capacity, cooperative communication.**

I. Introduction

The explosive growth of wireless devices has led to a significant rise in demands for high data rates in order to sustain services that include live data and video sharing. Viewing the new challenges with regards to resource limitations and rising demands for network capacity, the concept of fifth generation (5G) communication networks has been proposed. Device-to-device (D2D) communication was introduced under third generation partnership project (3GPP) as a futuristic technology for providing proximity services and is now regarded as one of the technologies that would undergo standardization under the umbrella of 5G, providing numerous opportunities for establishing high data rate peer-to-peer (P2P) links. D2D networks communicate by establishing direct links between devices instead of routing transmissions through the cellular base station (BS).

Apart from other applications, the D2D communications can prove to be quite helpful in establishing public safety networks. The loss of infrastructure in disaster scenarios signifies the need for a D2D network based on hand-held user equipments [1]. However, D2D networks based on hand-held devices have battery constraints, which need consideration [2]. Therefore, a large chunk of literature on energy-constrained D2D networks calls for multi-hop communications. The authors in [3] evaluated a multi-hop D2D network with power control scheme to ensure energy and spectral efficiency. The analysis indicates the gains of the proposed scheme in terms of network scalability. In [4], the authors present an analog network coding-based multi-hop D2D network. A comparison of single-hop and multi-hop network reveals enhanced performance of multi-hop design with regards to energy-efficiency. D2D cluster networks could prove to be quite suitable for public safety networks. The authors in [5] analyzed a D2D cluster network in terms of coverage and area spectral efficiency, where the D2D user distribution is modeled through Poisson cluster process. Recently, the concept of simultaneous wireless and information power transfer (SWIPT) has been analyzed extensively, incorporating energy harvesting (EH) into wireless communication network. The authors in [6] discuss a SWIPT system based on multi-antenna relay equipped with a decoder and an energy harvester. The analysis is expanded to power splitting and time switching techniques of SWIPT, providing an insight into the impact of the placement of relay nodes and transmit powers on the system performance. SWIPT technology can open up a number of avenues for D2D network deployment in scenarios with limited battery resources by augmenting network lifetime [7]-[8], which is the subject matter of this paper.

In this paper, we consider a circular region (CR) where the node distribution in the region is modeled through a homogeneous Poisson point process (PPP). A central node (CeN) in a CR is responsible for intra-region signaling and information transmission. A comparison of single-hop D2D link and cooperative dual-hop D2D link is presented. In single-hop, a single-input single-output (SISO) link exists between the source and the destination, whereas in cooperative dual-hop, a distinction between the type of link can be made on the basis of the number of relay nodes. In case of a single relay, a SISO link exists between the relay and destination. On the other hand, the use of multiple relays for transmission leads to a multi-input single-output (MISO) link between relays and the destination. The proposed model can be adopted to D2D networks involving multi-hop transmissions, as well. We derive expressions for the ergodic capacity of the network under Rayleigh fading conditions and path loss. A relay selection problem is formulated, based on several performance metrics such as the stored energy and spatial distribution of the relay nodes, which selects cooperating nodes to provide spatial diversity gain. A transmission flow scheme is also

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devised to realize mode selection for SWIPT by identifying the decode-and-forward (DF) and energy harvesting (EH) nodes. The impact of varying network parameters is quantified in terms of energy harvested and outage capacity.

The rest of the paper is organized as follows. In Section II, the system model of the proposed cooperative D2D network is presented, followed by discussion on transmission flow and energy-harvesting in Section III. Section IV presents these results and the analysis, highlighting the system performance with regards to network parameters, and finally in Section V, we present our conclusions.

II. System Model

In this section, we describe the system architecture of the proposed cooperative D2D network. Consider a CR of radius R_1, which consists of a CeN and randomly distributed nodes a_i, where i depends on the node density, as shown in Fig. 1. The CR can be considered a sub-entity of a larger cluster of D2D nodes distributed in the cell of a conventional cellular network.

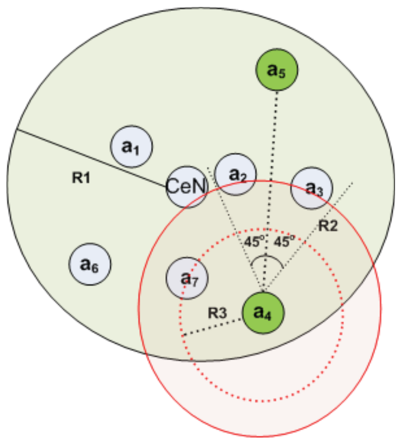

Fig. 1: Example of a circular region with randomly deployed D2D nodes

We assume that the CeN is chosen such that it is always located around at the center of the circular region and possesses the required energy to maintain connectivity with all other nodes [9]. The nodes in the CR are distributed according to an independent homogeneous PPP, ϕ_n, with density λ_n. The nodes in the CR send regular beacon signals to CeN allowing the CeN to maintain the record of stored energy levels and the location of the nodes [10]. We define two modes of operation: 1) single-hop D2D network, and 2) dual-hop D2D network. The link setup mechanism is dynamically controlled by the CeN and depends on the spatial distance between the transmitter and the receiver. Fig. 1 depicts an example of a D2D CR, where the source node labeled a_4 transmits a signal intended for destination a_5. The source node requests the CeN to setup a mode for transmission by sending the information about the intended destination. If the destination node is in one-hop range of the source node, the CeN signals for a direct (or single-hop) D2D connection. In case, the destination is spatially distant from the transmitter, CeN signals for a dual-hop transmission, where a_4 would first send the message to the selected relay(s), (the relay selection procedure is described in Section III), which in turn would forward the message to the destination using the cooperative DF mechanism.

Two regions around a transmitter are defined; the decode-and-forward (DF) region, and the energy harvesting (EH) region, which are bounded by circles of radii R_2 and R_3, respectively, as shown in Fig. 1. The selected relays act in a DF manner, while the idle nodes in the proximity of the transmitter can activate the EH mode. The nodes in the DF region are identified by the set $\mathbb{S}$, $\mathbb{S} = \{a_i | Pr_{Sa_i} \geq \tau\}$, where Pr_{Sa_i} is the received power of the node a_i and τ is the threshold. For example, $\mathbb{S} = \{a_2, a_3, a_7\}$ for the network deployment shown in Fig. 1. Similarly, we define a set of potential relay nodes, $\mathbb{M}$, which comprises of nodes that lie in an angular range $-\frac{\pi}{4} < \theta < \frac{\pi}{4}$ as reference to the source-destination (S-D) vector [11], where $\mathbb{M} \subseteq \mathbb{S}$, e.g., $\mathbb{M} = \{a_2, a_3\}$ from Fig. 1, representing the nodes positioned towards the destination. Although, all the nodes belonging to set $\mathbb{M}$ can act as candidate relays for source-destination (S-D) pair, we would later show that the optimal relay selection also depends on other network parameters, such as the received signal-to-noise ratio (SNR), the magnitude of energy stored and spatial distribution of relay nodes. It is also assumed that the system employs carrier sense multiple access with collision avoidance (CSMA/CA) technique to avoid collisions during a transmission phase.

III. Network Transmission Flow Model and Energy Harvesting

During each transmission, the idle nodes in the transmitter proximity, which are not acting as relays, can activate the EH mode. The energy harvesting region, bounded by radius R_3, is defined as $R_3 = \left(\frac{\Delta}{T}\right)^{1/\beta}$, where $\Delta = \eta P_t$ with $\eta \in (0, 1]$ signifying the EH efficiency, P_t denotes the transmit power of the source, T is the EH threshold required to activate the EH circuit and β is the path loss exponent for the EH link (which might be different or same as the data transmission links) [12]. The EH region may be larger or smaller than the DF region, depending on the EH parameters that define R_3. The probability that a node exists in the EH region, P_{EH} is given by the probability that the distance to the closest transmitting node is not larger than R_3, i.e.,

$$P_{EH} = 1 - \mathbb{P}[(r(x, R_3)) = 0] = 1 - e^{-\pi\lambda_n R_3^2}, \qquad (1)$$

where $r(x, R_3)$ denotes the number of nodes in a ball with radius R_3 centered at x, where x represents the source position.

When the source transmits the data, the power received at the first hop nodes existing in the DF region is given by

$$Pr_{Sa_i} = \frac{P_t \mu_{Sa_i}}{(d_{Sa_i})^{\beta}}, \qquad (2)$$

where μ_{Sa_i} is an independent and identically distributed (i.i.d.) random variable (RV) drawn from an exponential distribution, which corresponds to the squared envelope of the underlying

Rayleigh fading channel, and d_{Sa_i} denotes the Euclidean distance between the source and the relay node. The impact of interference from other clusters is not analyzed in this work and left as a future direction of this work.

For the SISO link between the source and a relay (or destination in case of single-hop link), the probability that the relay is able to successfully decode the message is given by

$$\mathbb{P}\{Pr_{Sa_i} \geq \tau\} = exp\{d_{Sa_i}^{\beta}\tau\}, \quad (3)$$

where a unit transmit power is assumed. Similarly, in case of dual-hop communication, all the selected nodes, after relay selection mechanism, cooperatively transmit the message to the destination. We define a set $\mathbb{M}_t$, where $\mathbb{M}_t \subseteq \mathbb{M}$, denoting the set of nodes, which have successfully decoded the message transmitted by the source. The power received at the destination after diversity combining is then given by

$$P_{r_D} = P_t \sum_{m \in \mathbb{M}_r} \frac{\mu_{a_m D}}{(d_{a_m D})^{\beta}}, \quad (4)$$

where $\mathbb{M}_r \subseteq \mathbb{M}_t$ and $\mathbb{M}_r$ denotes the set of relay nodes selected for transmission to destination. The probability density function (PDF) of the received power at the destination depends on the number of nodes in the set $\mathbb{M}_r$, which is not known apriori. If the cardinality of the set $\mathbb{M}_r$ is unity, i.e., $|\mathbb{M}_r| = 1$, a SISO link exists between the cooperating relay and the destination and the outage expression is similar to (3). In case, $|\mathbb{M}_r| > 1$, a virtual multiple-input single-output (MISO) link exists between the destination and the relay nodes and the PDF of the received power is defined by the hypoexponential distribution given as $f_{P_{r_D}}(y) = \sum_{m \in \mathbb{M}_r} \lambda_{a_m} exp\{-\lambda_{a_m} y\} \prod_{k \neq m} \frac{\lambda_{a_k}}{\lambda_{a_k} - \lambda_{a_m}}$, where $\lambda_{a_m} = \frac{d_{a_m D}^{\beta}}{P_t}$. The success probability of the MISO link is then given as

$$\mathbb{P}\{P_{r_D} \geq \tau\} = \sum_{m \in \mathbb{M}_r} \prod_{k \neq m} \frac{\lambda_{a_k}}{\lambda_{a_k} - \lambda_{a_m}} exp\{\lambda_{a_m}\tau\}. \quad (5)$$

On the other hand, let the initial vector of the energy stored at each node of the CR (before the source has transmitted) is given by $\mathbb{E} = \{E^{st}(a_1), E^{st}(a_2), ...\}$. The proposed SWIPT-based mechanism allows the nodes in the EH region to harvest energy in each transmission cycle. The energy level of EH nodes at the end of each transmission cycle is updated as $E^{st}(a_i) = E^{st}(a_i) + E_{h_{a_i}}$, where $E_{h_{a_i}}$ denotes the energy harvested in that transmission cycle by the node a_i. We define a set $\mathbb{D}$, which represents the nodes in the EH region bounded by radius R_3. The energy harvested by the nodes in EH region in a single transmission cycle is given by

$$E_{h_{a_i}} = \frac{\eta P_t \mu_{Sa_i}}{(d_{Sa_i})^{\beta}} T_{frac}, \quad (6)$$

where $i \in \mathbb{D}$, η is the energy conversion efficiency, and T_{frac} is the fraction of time for energy harvesting.

A. Relay selection problem

The selection criteria of relay nodes depends upon the rate requirements at the destination. A SISO or MISO link is established between relay(s) and the destination, depending upon the number of relay nodes chosen for transmission, represented by the set $\mathbb{M}_r$.

We define $R_{a_j}^{(S)}$ as the ergodic rate between the source and a relay node given by $R_{a_j}^{(S)} = \mathbb{E}(log_2(1 + \gamma_{a_j}^{(S)}))$, where $\gamma_{a_j}^{(S)} = P_{r_{Sa_j}}/\sigma^2$ with σ^2 denoting the variance of noise at the receiver, which is assumed to be unity without loss of generality. The nodes exhibiting maximum source-to-relay rate $R_{a_j}^{(S)}$ and having maximum stored energy $E_{a_m}^{st}$ are selected as relay nodes for transmission to destination. An approximation of the upper bound of ergodic rate can be found by using the Jensen's inequality as

$$R_{a_j}^{(S)} \leq log_2(1 + \mathbb{E}(\gamma_{a_j}^{(S)})), \quad (7)$$

where the expectation is defined as $\mathbb{E}(\gamma_{a_j}^{(S)}) = 1/d_{Sa_j}^{\beta}$. Similarly, R_D is defined as the ergodic rate at the destination. The upper bound of R_D is defined as $R_D \leq log_2(1+\mathbb{E}(\gamma_D))$, where $\mathbb{E}(\gamma_D) = \sum_{j \in \mathbb{M}_r} 1/\lambda_{a_j}$.

The optimal relay selection is discussed in Algorithm 1, where the relay selection factor f_{a_j} depends on the stored energy levels and the ergodic rate provided by the relays in the set $\mathbb{M}_t$. The purpose of introducing the relay selection factor f_{a_j} is to define a metric which incorporates both stored energy and ergodic rate, thereby modeling the relay selection as a collective problem. In the next step, the nodes in the set $\mathbb{M}_t$ are sorted on the basis of descending order of the relay selection factor values and stored in $\mathbb{G}$. The first element of set $\mathbb{G}$ represents the best relay node in terms of energy stored and ergodic rate. The relay set $\mathbb{M}_r \subseteq \mathbb{G}$ is identified as the set of relay nodes chosen for transmission. For example, let the set $\mathbb{M}_t$ consist of three nodes a_1, a_2 and a_3, where the ergodic rate and energy stored at each node is $R_{a_j}^{(S)} = \{3, 4, 2\}$ and $E_{a_j}^{st} = \{2, 3, 5\}$ for nodes a_1, a_2 and a_3, respectively. The relay selection factor is calculated for each node, which is given as $f_{a_j} = \{5, 11, 7\}$. The nodes in the set $\mathbb{M}_t$ are sorted in descending order of f_{a_j}, which leads to set $\mathbb{G} = \{a_2, a_3, a_1\}$. In this example, node a_2 is the best choice to act as a relay, viewing the energy stored and ergodic rate collectively, followed by node a_3 and a_1, respectively.

Algorithm 1 Optimal Relay Selection

1: Calculate $f_{a_j} = ((R_{a_j}^{(S)} E_{a_j}^{st}) - |R_{a_j}^{(S)} - E_{a_j}^{st}|)$, $j \in \mathbb{M}_t$
2: Sort nodes $\mathbb{M}_t$ in descending order of f_{a_j} and store in $\mathbb{G}$
3: Relay set $\mathbb{M}_r \subseteq \mathbb{G}$

For dual-hop communications, once the relay selection is performed, the end-to-end sum rate is given as

$$R_{SD} = \frac{1}{2} min\{\underset{j \in \mathbb{M}_r}{min}\{R_{a_j}^{(S)}\}, R_D\}, \quad (8)$$

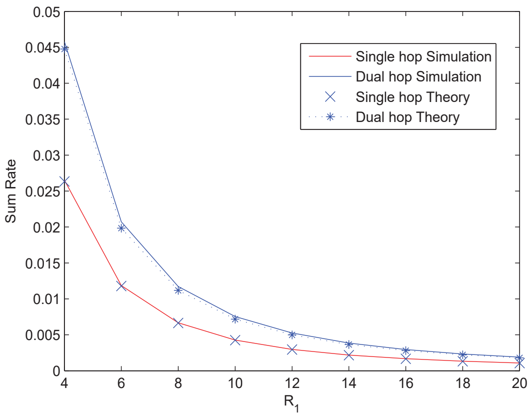

Fig. 2: Sum rate versus circular region radius

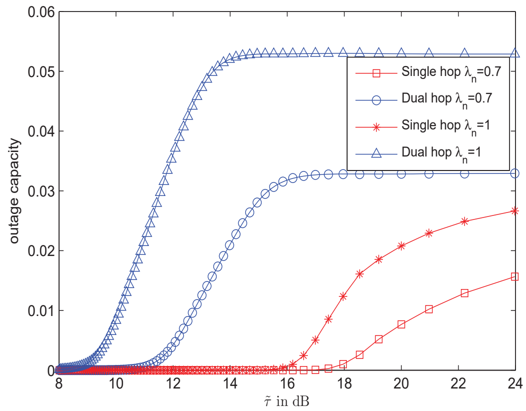

Fig. 3: Outage capacity versus $\tilde{\tau}$ $\beta = 2.7$, $\lambda_n = \{0.7, 1\}$

where the factor of $1/2$ appears due to the half-duplex nature of nodes.

The efficiency of transmissions in terms of energy consumed is analysed by the energy efficiency factor defined as $\kappa = (R_{SD})/P_{total}$, where P_{total} denotes the total power consumed for end-to-end transmission, while the power consumed during initial connection setup and signaling is not considered at this stage. An appropriate transmission mode (one hop or dual-hop) enables efficient utilization of resources and provides performance gains in terms of end-to-end rate.

IV. Results and Analysis

In this section, we present our results and analyze the system performance with respect to different performance metrics. First, we validate our analytical model by comparing it with the simulation results. The nodes in a CR are distributed through homogeneous PPP and we calculate the received power at relay nodes and destination using (2) and (4), respectively. Keeping in view the utility of D2D communication in public safety networks, we consider the S-D pair with maximum Euclidean distance to ascertain the system performance. The outage probability is calculated by comparing the received power with the threshold τ. We also define a normalized threshold $\tilde{\tau} = 10log(1/\tau)$ and call it the SNR margin. Several results are presented with respect to network parameters such as the radius of CR R_1, the CR node density λ_n, and the SNR margin $\tilde{\tau}$. For the sake of representation of results, we choose a maximum of two relay nodes, i.e., $|\mathbb{M}_r \leq 2|$ for dual-hop network topology.

In Fig. 2, the sum rate versus CR radius R_1 is plotted, which depicts a close agreement between the analytical model given in (7) and (8) for single-hop and dual-hop network topologies, respectively, and the simulation results. The node density is given by $\lambda_n = 20/A_n$, where A_n is calculated as $\pi {R_1}^2$ and $\beta = 2$. The sum rate is calculated for each iteration and is averaged out by conducting Monte Carlo trials.

To gauge the system performance, we define a metric identified as outage capacity R_{out}, which is the product of the end-to-end transmission success probability and the sum rate, i.e., $R_{out} = \mathbb{P}\{P_{r_D} \geq \tau\}R_{SD}$. The outage capacity signifies the system performance on the basis of the realizable capacity of the network. Fig. 3 shows the outage capacity when observed at different values of $\tilde{\tau}$ for $\lambda_n = \{0.7, 1\}$, respectively. The graph highlights the enhanced performance of the dual-hop D2D network as compared to the single-hop D2D network. It can be observed that for $\lambda_n = 0.7$ and $\tilde{\tau} = 22$dB, the dual-hop D2D case achieves an outage capacity of 0.033, which provides an outage capacity gain of a magnitude of approximately 2.5 as compared to outage capacity of 0.0125 achieved by the single-hop case. Furthermore, the increase in node density λ_n leads to an increase in the outage capacity for both single-hop and dual-hop cases.

The analysis of energy efficiency and the performance of SWIPT system is presented in Fig. 4 and Fig. 5. Fig. 4 shows the energy efficiency factor κ with respect to node density λ_n. Initially, for lower node density, the one hop D2D network is more energy-efficient, which is signified by the plots for $\beta = 2.7$. However, at node densities greater than $\lambda_n = 0.1$, the dual-hop D2D network performs better in terms of energy efficiency. The results are compared with a higher path loss exponent $\beta = 3.3$, where the dual-hop case allows transmission, which is twice more energy efficient as compared to the single-hop case. Fig. 5 shows the total energy harvested (dB) by the nodes after 10 communication cycles. The energy levels are observed for different values of the energy harvesting efficiency factor η and the path loss exponent β, where the energy harvested is calculated using (8). It can be seen that the harvested energy levels increase with the increase in λ_n. The figure provides an insight into the impact of η on the magnitude of energy harvested for different node densities λ_n. For $\beta = 2, \eta = 0.9$, maximum harvested energy of 29.8 dB is observed for $\lambda_n = 0.7$. A higher path loss exponent and decrease in energy harvesting efficiency factor lead to a decrease in the magnitude of energy harvested. The figure highlights the efficacy of SWIPT in dual-hop D2D networks, which allows the network to harvest

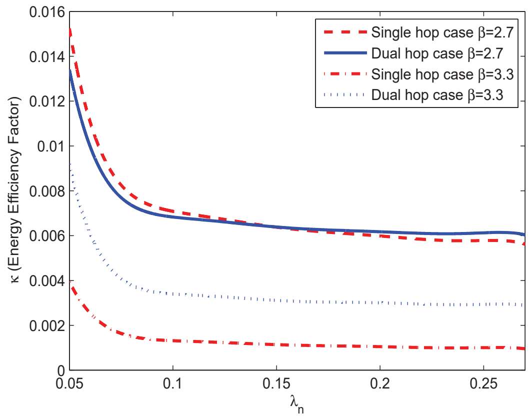

Fig. 4: Energy efficiency factor versus node density

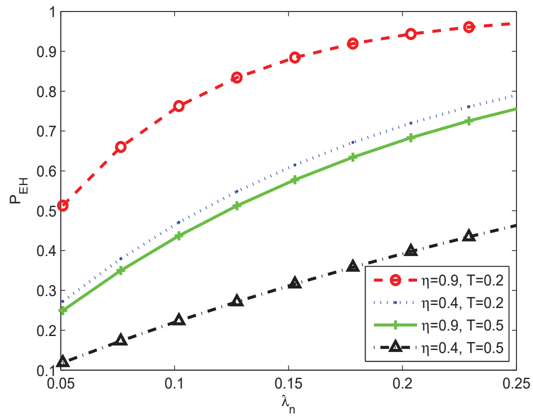

Fig. 6: P_{EH} versus node density

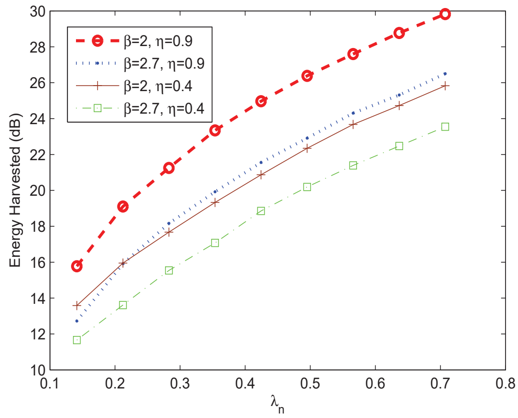

Fig. 5: Average energy harvested in 10 communication cycles versus node density

energy depending upon network parameters, such as β.

Fig. 6 shows the impact of EH threshold T and η on the probability that a node exists in EH region bounded by R_3. The least probability is observed for $\eta = 0.4$ and $T = 0.5$. High value of T signifies that a higher power is required to activate the EH circuit. Similarly, lower $\eta = 0.4$ suggests that only 40% of received power is harvested by the node. It can also be seen that higher node density increases the probability that a node exists in the EH region, which in turn increases the magnitude of energy harvested in a communication cycle.

V. Conclusion

In this paper, we have proposed and analyzed a SWIPT-based cooperative D2D network, where the distribution of D2D pairs in a circular region is modeled through a homogeneous PPP. A transmission flow mechanism is proposed for D2D networks involving multi-hop transmissions. The network model comprises of a central node, which is responsible for intra-region signaling. We present a comparison between single-hop and dual-hop D2D network and derive expressions for ergodic rate. It has been shown that for a larger distance between D2D communication nodes, dual-hop D2D network is more suitable for reliable end-to-end communication. We also quantify outage capacity and energy harvested for single-hop and dual-hop D2D networks and highlight the gains achieved through the use of SWIPT in D2D networks.

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