

# Energy Consumption Performance of Opportunistic Device-to-Device Relaying Under Lognormal Shadowing

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**Abstract**—Efficient transmission protocols are required to minimize the energy consumption of mobile devices for ubiquitous connectivity in the next generation of wireless networks. In this paper, we analyze the energy consumption performance of a two-hop opportunistic device-select relaying (ODSR) scheme, where a device can either transmit data directly to a base station (BS) or relay the data to a nearby device, which forwards the data to the BS. We select a single device opportunistically from a device-device (D2D) network based on the energy required for transmission including the energy consumed in the circuitry of the devices. By considering the log-normal shadowing as the dominant factor between devices and the BS, and Rayleigh fading in D2D links, we derive analytical bounds and scaling laws on average energy consumption. The derived analytical expressions show that the energy consumption of the ODSR decreases logarithmically with an increase in the number of devices, and achieves near-optimal performance only with a few nearby devices. This is an important design criterion to reduce latency and overhead energy consumption in a relay-assisted large scale network. We also demonstrate the performance of the ODSR using simulations in realistic scenarios of a wireless network.

**Index Terms**—5G, device to device (D2D) communications, energy consumption, log-normal shadowing, performance analysis, Rayleigh fading, relaying.

## I. INTRODUCTION

Energy efficiency has become a primary concern for the present and future wireless networks in addition to the conventional performance measures such as throughput, bit-error-rate, and latency [1]–[5]. Like the phenomenal growth in mobile communication, the 5G technology is expected to connect billions more smartphones and devices with much higher data rates [6]. However, devices are equipped with

batteries of limited capacity, which can quickly run down if the energy consumption required for data transmission is not appropriately addressed. Moreover, the wireless fading channel adversely affects the energy consumed by devices for data transmissions. Hence, efficient transmission protocols are desirable to reduce the energy consumption of devices which can prolong the battery life of devices for ubiquitous communications under wireless fading channels.

Relay-assisted communication is a potential technique to deal with the channel fading [7]–[13]. Here, many intermediate nodes can assist data transmission between a single source and destination. Although the complex multi-hop relaying can provide a better performance, a dual-hop relaying selects a single relay opportunistically to harness the diversity among many spatially distributed nodes in a wireless network. This opportunistic relay selection scheme is very popular when attempting to minimize transmission energy and maximize the lifetime of wireless sensor networks [14]–[20]. The authors in [21] analyzed the total energy cost of data transmission using cooperative beamforming with multiple relays to forward the data to a destination node in a wireless network. Since the computational complexity and the overhead for the centralized relay selection is extremely high, distributed relay selection has been proposed using opportunistic carrier sensing [15], [17], [18], [22]–[26]. A popular distributed implementation for single relay selection exploits the timer-based relay selection proportional to the instantaneous channel [7].

Traditionally, opportunistic relaying schemes select a single relay from the whole network, increasing the overhead energy and latency of the network. Recently, device to device (D2D) communication has emerged as a potential technique for wireless networks, and it is considered as one of the key technology for the LTE (Long Term Evolution) based cellular networks [27]–[30]. In contrast to the conventional relaying, relaying in a D2D network is a pragmatic shift where devices can itself act as relays to avoid deployment and maintenance of relaying nodes [31]–[40]. An opportunistic scheduling of the devices is studied in [31] to improve the spectral efficiency of orthogonal frequency division multiple access (OFDMA) networks. An experimental analysis of an out-band D2D relaying scheme is presented in [36] to integrate D2D communications in a cellular network. The authors in [34] derived a geometrical zone for energy efficient D2D relaying. In [37], a network-assisted opportunistic D2D clustering has been analyzed in terms of throughput, energy efficiency, and

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fairness under Rayleigh fading channel models. Considering D2D fading links as Rician distributed, power control methods have been devised to optimize the power consumption and throughput of networks [38]–[40]. A joint optimization of uplink subcarrier assignment and power allocation in D2D underlying cellular networks is investigated to minimize the energy cost of all users [41]. Recently, authors in [42] model an energy consumption for the Wifi direct which enables D2D communications between proximity devices.

In the light of aforementioned and related works, criteria for the relay selection is mostly based on the magnitude of channel gain or the received signal to noise ratio (SNR) at the relays [7]–[13]. Although few works consider energy consumed in data transmission for relay selection, they ignore the energy consumed in the circuitry of the transceiver which may affect the optimality of the solution to achieve the minimum energy consumption. Moreover, the performance of relay-assisted networks under fading channels has been studied for various parameters such as outage probability, throughput, SNR, and bit-error-rate, but the issue of energy consumption has not yet been considered. Even for the conventional performance parameters, most of the works ignore the large scale shadowing effect and focus on the short term fading.

The shadow fading between a device and the base station (BS) is commonly found in various practical scenarios including smart metering, shopping malls, offices, and the university building which imposes significant constraints on communication with a faraway destination [43]. This drawback becomes much more pronounced at high frequencies, such as millimeter-wave communications, where quality of direct transmission is weak [44]. The shadow fading is modeled using the lognormal distribution which is generally considered harder for performance analysis comparing to the short term fading models. In [45], the author analyzed the average SNR performance of opportunistic relaying techniques under large scale channel effects.

In this paper, we analyze the energy consumption performance of an opportunistic device select relaying (ODSR) scheme for uplink data transmissions in a wireless network. In the ODSR, we select a single device opportunistically from the D2D network based on the instantaneous transmission energy including the energy consumed in the circuitry of the devices. Thus, the ODSR exploits selection diversity due to the randomness in the circuit transmission power of devices and fading of the log-normal shadow. The ODSR employs a two-hop transmission model, where the source device can either transmit data directly to the BS or relay the data to a nearby device, which forwards the data to the BS. We derive analytical bounds on the average energy consumption of the ODSR by considering the log-normal shadowing as the dominant factor between devices and the BS and Rayleigh fading in D2D links. We also derive a scaling law on the energy consumption performance of the ODSR to show that that a near-optimal performance can be obtained using only a few devices of the network. This is important to reduce latency and overhead energy consumption of a large scale network. Further, the ODSR is implemented in a distributed way using the opportunistic carrier sensing algorithm with

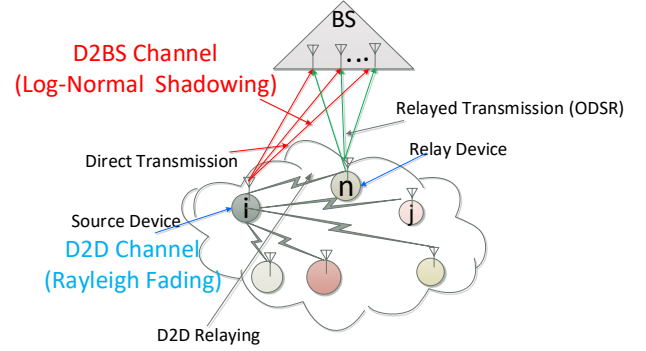


Fig. 1. D2D relaying in the uplink communication of a single cell network. Devices are inside a shopping mall/university building/ offices and the BS is far away separated by walls. The devices have single antenna while the BS has multiple antennas.

a proper adaptation to the single hop protocol developed in [7], [18]. We also demonstrate the energy consumption performance of the ODSR using numerical and simulation analysis with parameters adopted from a realistic wireless network.

The rest of this paper is organized as follows. Section II defines the system model. A distributed protocol for D2D relaying is described in Section III. Performance analysis of the ODSR is presented in Section IV. In Section V, we provide numerical evaluation of the ODSR over various configurations of a wireless network. Section VI concludes the paper.

*Notations:* The following notational convention is assumed throughout the paper. Lower-case normal font symbols denote scalar quantities, while lower-case bold symbols denote column vectors.  $\mathcal{CN}(\cdot)$ ,  $\mathbb{E}\{\cdot\}$ , and  $\exp(\cdot)$  denote the complex Gaussian random variable, the expectation operator, and exponential function, respectively. By  $\log(\cdot)$  we mean the natural logarithm, unless otherwise stated. Important mathematical functions used in the paper are: Q-function  $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-t^2/2} dt$ , exponential integrals  $E_i(x) = -\int_{-x}^\infty \frac{e^{-t}}{t} dt$  and  $E_1(x) = -E_i(-x)$ , error function  $\text{erf}(x) = \frac{2}{\pi} \int_0^x e^{-t^2} dt$  and imaginary error function  $\text{erfi}(x) = -i \text{erf}(ix)$ , where  $i$  is an imaginary number.

## II. SYSTEM MODEL

We consider a single-cell network with a BS (equipped with  $M \geq 1$  antennas) and  $N$  single-antenna devices for uplink data transmissions. The devices are uniformly distributed in the network. We focus on a two-hop transmission model, where a source device can either transmit data directly to the BS or relay the data to a nearby device, which forwards the data to the BS, as depicted in Fig. 1.

In a direct transmission, the received signal vector at the BS from the  $i$ -th device is given as:

$$\mathbf{y}^{\text{BS}} = \sqrt{P} \mathbf{h} x_i + w \quad (1)$$

where  $\mathbf{y}^{\text{BS}} = \{y_1, y_2, \dots, y_M\}^T$  is the  $M \times 1$  received signal vector,  $P$  is the transmit power,  $x_i$  is the transmitted signal with unit power  $\mathbb{E}[|x_i|^2] = 1$ ,  $w \sim \mathcal{CN}(0, N_0)$  is the zero-mean additive white Gaussian noise (AWGN) with variance

$N_0$ , and  $\mathbf{h} = \{h_{1i}, h_{2i}, \dots, h_{Mi}\}^T$  is the  $M \times 1$  channel vector between the  $i$ -th device and  $M$  antennas at the BS. Here  $h_{Mi}$  denotes the channel coefficient between  $i$ -th device and the  $M$ -th antenna of the BS, and has a uniform phase. We model the amplitude power of channel  $|h_{ji}|^2$  for  $j = \{1, 2, \dots, M\}$  as:

$$|h_{ji}|^2 = F_{ji} \cdot GR_i^{-\alpha} \cdot 10^{\frac{S_i}{10}}, \quad i = \{1, 2, \dots, N\} \quad (2)$$

where  $F_{ji}$  models the short-term Rayleigh fading channel between the  $i$ -th device and the  $j$ -th antenna,  $R_i$  is the distance from the  $i$ -th device to the BS,  $\alpha$  is the path loss coefficient, and the term  $G$  is the normalizing factor for the path loss. The term  $S_i \sim \mathcal{N}(0, \sigma^2)$  is normal such that  $10^{\frac{S_i}{10}}$  is log-normally distributed and models shadowing behavior. The parameter  $\sigma$  is known as the dB spread or the shadowing factor.

Since the long term path loss dominates the short term fading, and over longer time scales Rayleigh fading is averaged out, we can represent (2) as normally distributed by taking the logarithm of (2):

$$10 \log_{10} |h_{ji}|^2 \text{ s.t. } X_i \sim \mathcal{N}(10 \log_{10} R_i^{-\alpha} F_i + 10 \log_{10} G, \sigma^2) \quad (3)$$

Indeed, a generalized distribution of  $|h_{ji}|^2$  can be obtained by considering the combined distribution of  $S_i, F_{ji}$ , and  $R_i$ , which may become intractable for performance analysis.

If the direct transmission is not energy-efficient (e.g. due to shadowing effect between devices and the BS), the single-antenna source device sends data to a single-antenna relay device using the D2D communication. The received signal at the  $n$ -th relay device is given as

$$y_n^{(d)} = \sqrt{P} h_i^{(d)} x_i + v \quad (4)$$

where  $h_i^{(d)}$  is the fading channel between the  $i$ -th source device and the selected relay device, and  $v$  is AWGN with power  $N_0$ . Since the quality of signal received at the neighboring relay can be high, a decode-and-forward (DF) protocol can be used at the relay to transmit the data from the source device to the BS. It is noted that all devices use different resource blocks (RB) separated in time and frequency, and thus there is no interference even if a single relay device receives signal from multiple source devices as these are sent at different RBs.

For D2D links, we ignore the shadowing effect, similar to [38], [39] [40]. This assumption is justified since two devices communicate with each other under close proximity as per the 3GPP-LTE standard [46]. We assume that the short-term fading amplitude  $|h_i^{(d)}|$  between the  $i$ -th source device and the relay device is Rayleigh distributed such that

$$|h_i^{(d)}|^2 = r_i^{-\alpha^{(d)}} F_i^{(d)} \quad (5)$$

where  $F_i^{(d)}$  follows the exponential distribution,  $r_i$  is the distance from the  $i$ -th source device to the selected relay device, and  $\alpha^{(d)}$  is the path loss exponent between them. Since devices are close each other in D2D communication, the probability that relay devices receive signal at a very high SNR is high, and thus consume negligible energy compared with the direct transmission.

### III. ODSR RELAYING SCHEME

In this section, we describe the ODSR, which minimizes energy consumption for data transmission and its distributed implementation based on the timer-based protocol of Blestsas et al. [7].

#### A. Criteria of Relaying Device Selection

We consider transmissions of packets with a fixed length of  $L$  bits by the source device to the BS in each transmission slot. We assume that all devices transmit with equal power  $P$ , and denote the circuit power by  $P_i^{\text{ckt}}$  for the  $i$ -th device. Since the power dissipated in the transmitter and receiver circuits is different for different devices, we consider that the circuit power transmission of the devices is uniformly distributed between  $P_{\min}^{\text{ckt}}$  and  $P_{\max}^{\text{ckt}}$ .

Using (1), the energy consumed by the  $i$ -th source device to transmit its data directly to the BS is:

$$\begin{aligned} E_i &= (P + P_i^{\text{ckt}}) \cdot \frac{L}{B \log_2(1 + \gamma_i)} \\ &= \frac{\eta_1}{10 \log_{10}(1 + \gamma_i)} + \frac{\eta_2 P_i^{\text{ckt}}}{10 \log_{10}(1 + \gamma_i)} \end{aligned} \quad (6)$$

where  $B$  is the transmission channel bandwidth,  $\eta_1 = 10 \log_{10}(2)PL/B$ ,  $\eta_2 = \eta_1/P$ , and  $\gamma_i = \frac{\sum_{j=1}^M |h_{ji}|^2 P}{N_0}$  is the received SNR at the BS due to the linear combination of  $M$  signals when the signal is transmitted from the  $i$ -th device.

Using (4), the energy consumed by the D2D communication to relay a data of  $L$  bits is:

$$E_i^{(d)} = \frac{\eta_1^{(d)}}{\log(1 + \gamma_i^{(d)})} + \frac{\eta_2^{(d)} P_i^{\text{ckt}}}{\log(1 + \gamma_i^{(d)})} \quad (7)$$

where  $\eta_1^{(d)} = \log(2)P^{(d)}L/B$ ,  $\eta_2^{(d)} = \eta_1^{(d)}/P^{(d)}$ , and  $\gamma_i^{(d)} = \frac{|h_i^{(d)}|^2 P^{(d)}}{N_0^{(d)}}$  is the SNR at the relay device when the signal is transmitted at a power  $P^{(d)}$  from the  $i$ -th source device.

The relay selection criteria for the ODSR is based on the minimum consumed energy for transmission of packet data to the BS as:

$$n = \underset{1 \leq i \leq N}{\operatorname{argmin}} \{E_i\}. \quad (8)$$

It is noted that ODSR relay selection requires only the channel information from devices to the BS. It should be noted that the component of the relaying energy  $E_i^{(d)}$  is ignored in the relay selection since this may require the channel state information (CSI) between the source to relaying devices. In general, the energy consumption of the D2D relaying (due to the close proximity) is lower than the energy consumed in forwarding the data to the BS (which can be affected by the shadow fading) in the second hop, and thus may not affect the relay selection process. It is good to note that we have included  $E_i^{(d)}$  while deriving bounds on the energy consumption performance of the ODSR.

There is no advantage of considering circuit power transmission for relay selection if it is assumed equal for all devices (i.e.  $P_i^{\text{ckt}} = P^{\text{ckt}}, \forall i$ ). However, in practice, the circuit transmission power for all devices may not be equal due to

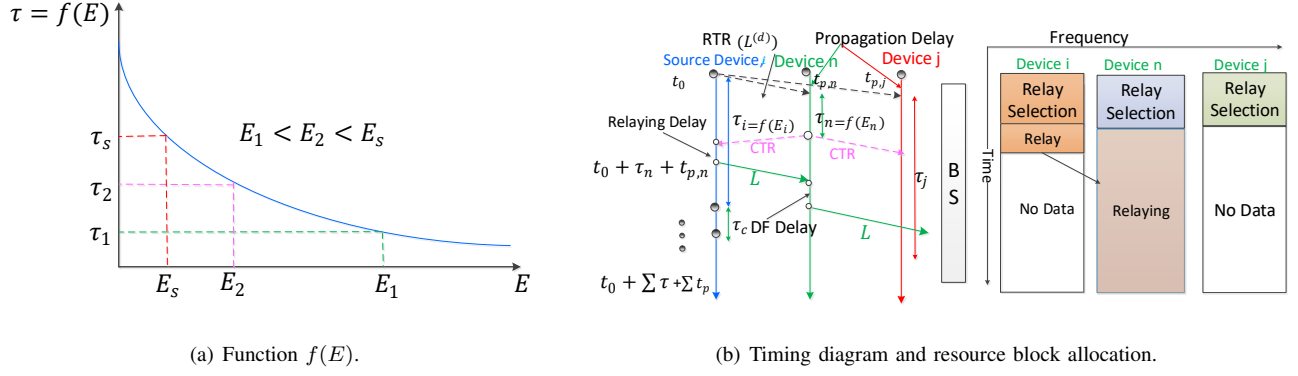


Fig. 2. Schematic diagram of ODSR for three devices with transmission energy  $E_1 < E_2 < E_s$ .

different types and specifications of devices in a network. This will lead to a randomness in the circuit power transmissions and the second term in (6) will become the ratio of random variables. Under this condition, the relay selection will depend on the circuit transmission power of devices, and analyzing the average energy consumption will be challenging due to an additional term of the ratio of random variables.

### B. Distributed Implementation of ODSR

Distributed implementation of the protocol is desired since the centralized relay selection requires the global information of the CSI. Further, the centralized implementation consumes a large energy overhead due to control signaling. In the seminal paper, Blestas et al. [7] describe a timer-based distributed protocol for relay selection (controlled by the BS with RTS (ready-to-send) and CTS (clear-to-send) signals using instantaneous channel information of both hops. This technique has been found to be useful in many relaying based networks [18], [20]. Zhou et al. [20] have used the protocol of [7] for relay selection using power control at each relays for an energy-efficient transmission.

The distributed implementation of the ODSR is based on the back-off principle of the carrier sensing multiple access (CSMA) in the multiple access (MAC) layer supported with the transmission energy from the physical layer. We define an increasing function  $f(E)$  designed judiciously (see Fig. 2a) such that back-off time  $\tau_i = f(E_i)$ ,  $i = 1, \dots, N$  of the devices has distinct energy index  $E_i$ ,  $i = 1, \dots, N$ . Thus, the considered implementation is based on the criteria of consumed energy with proper adaptations for uplink data transmissions in a wireless network using D2D relaying, as described in the following steps (see Fig. 2b):

1) *Request to Relaying (RTR)*: First, the  $i$ -th source device sets its back-off time to  $\tau_i = f(E_i)$  and broadcasts an RTR message (with fields such as user ID) to be received by the devices in close proximity. All the devices are capable of decoding the RTR message with the CSI estimated using the RTR message. The CSI is available if devices are already in the discovery mode compliant with the proximity services of 3GPP-LTE [46]. The RTR transmission costs an energy consumption  $E_{tx}^{RTR}$  to the source device. The energy overhead in decoding the RTR per device is  $E_{rx}^{RTR}$ .

The source device waits for a reply from a potential relay for a duration of  $\tau_i + \tau_c$ , where  $\tau_c$  is an additional delay to compensate for the propagation delays in D2D communication. This delay corresponds to relay selection overhead, as depicted in Fig. 2b. If the device does not receive a reply from any device for relaying in the time limit of  $\tau_i + \tau_c$ , it directly transmits to the BS (step 4), otherwise the data is transmitted through a relay. Note that an increase in the transmission delay is compensated by the use of relay with the best channel which reduces time to transmit the data to the BS.

2) *Distributed Relay Selection*: Upon the receipt of a RTR message from the source, each device sets its back-off time to  $\tau_j = f(E_j)$ ,  $j = 1, \dots, N-1$ . In the opportunistic relaying scheme, the  $n$ -th device selected using the criteria in (8) has the lowest back-off time, and hence occupies the channel first by responding to the source with a clear-to-relay (CTR) message after a waiting period  $\tau_n < \tau_j$ ,  $n \neq j$ . It should be noted that the probability that two users have equal back-off time is zero [7]. Once the selected device transmits the CTR message to the source, all other devices overhear the CTR message (or just a busy tone), and quit the process of relay selection for the given request from the  $i$ -th source device. The overhead energies for a response from the relay device are: transmission of CTR message  $E_{tx}^{CTR}$  and reception of CTR message  $E_{rx}^{CTR}$ .

3) *Source to Relay Transmission*: Upon the successful decoding of the CTR message, the source device sends the data packet to the selected relay device with a transmit energy cost  $E_i^d$  as computed in (7). Using the DF protocol, the selected relay device decodes the data from the source device, encodes it, and transmits to the BS. The DF protocol requires the CSI at the relay device. This can be estimated using the RTR message from the source device after the decision on relay selection. The energy overhead at this stage is: CSI estimation energy  $E^{CSI}$ , transmit energy cost  $E_i^d$ , decoding energy  $E^{DEC}$ , and encoding energy  $E^{ENC}$ .

4) *Data Transmission*: Finally, transmission of data is accomplished by direct transmission from the source or the relay device. The energy consumption in this phase is  $E_i$  as computed in (6). Note that if a single device happens to act as the source for its data and as the relay for other sources, the data transmission can be done simultaneously using full-duplexing mode.

In the following sections, we analyze the performance of the opportunistic relaying by deriving bounds on the average energy consumption by the devices for data transmission.

#### IV. PERFORMANCE BOUNDS OF ODSR

Given the steps of distributed relaying described in the subsection III-B, the total consumed energy by the ODSR is:

$$E^{\text{TOTAL}} = p(E_{\text{ov}}^{\text{RELAY}} + E^{\text{D2D}} + E^{\text{RELAY}}) + (1-p)(E^{\text{DT}} + E_{\text{ov}}^{\text{DT}}) \quad (9)$$

where  $p$  is the probability of the relay-assisted data transmission i.e.,  $p = \Pr(E^{\text{RELAY}} + E^{\text{D2D}} < E^{\text{DT}})$ . We denote  $E^{\text{RELAY}}$  as the energy consumed by the selected relay to transmit the data packet to the BS and  $E^{\text{D2D}}$  as the transmission energy by the source device to the selected relay. Further,  $E_{\text{ov}}^{\text{RELAY}} = E_{\text{tx}}^{\text{RTR}} + (N-1)E_{\text{rx}}^{\text{RTR}} + E_{\text{tx}}^{\text{CTR}} + E_{\text{rx}}^{\text{CTR}} + E^{\text{CSI}} + E^{\text{DEC}} + E^{\text{ENC}}$  is the overhead energy required for relay selection in the case of D2D communication,  $E^{\text{DT}}$  denotes the energy consumed for data transmission directly to the BS when the direct transmission is found to be more energy-efficient than the relay-assisted transmission, and  $E_{\text{ov}}^{\text{DT}} = E_{\text{tx}}^{\text{RTR}} + (N-1)E_{\text{rx}}^{\text{RTR}}$  is overhead energy for the relay selection.

It is noted that the direct transmission (i.e., without relaying protocol) does not incur any overhead energies. However, the overhead energy  $E_{\text{ov}}^{\text{RELAY}}$  of the ODSR is also low (see Table 1, Section V) since the signaling involved is very short and the signaling messages are sent to other local devices with very low power. This is illustrated through simulations in realistic scenarios of a wireless network in Section VI.

##### A. Average Energy Consumption of D2D Transmission: $\bar{E}^{\text{D2D}}$

In this subsection, we analyze the overhead energy of the ODSR due to the D2D transmission. Under the Rayleigh fading for the D2D channel, the SNR  $\gamma^{(d)}$  as given in (7) (we drop the index  $i$ ) is exponential distributed with probability distribution function PDF  $f(\gamma^{(d)}) = \frac{1}{\bar{\gamma}^{(d)}} e^{-\gamma^{(d)}/\bar{\gamma}^{(d)}}$  where  $\bar{\gamma}^{(d)} = \mathbb{E}[\gamma^{(d)}] = \int_0^\infty \gamma^{(d)} f(\gamma^{(d)}) d\gamma^{(d)}$  is the average SNR. Using (7), the average consumed energy for the D2D relaying:

$$\bar{E}^{\text{D2D}} = \left( \eta_1^{(d)} + \eta_2^{(d)} \mathbb{E}[P^{\text{ckt}}] \right) \times \frac{1}{\bar{\gamma}^{(d)}} \int_{\gamma_{\text{th}}^{(d)}}^\infty \frac{1}{\log(1+x)} e^{-x/\bar{\gamma}^{(d)}} dx \quad (10)$$

where  $\gamma_{\text{th}}^{(d)}$  is the threshold SNR (in linear scale) for the D2D communication. Using the series expansion of exponential function in (10), we get an exact expression of the expected energy consumption for the D2D relaying

$$\bar{E}^{\text{D2D}} = \frac{1}{\bar{\gamma}^{(d)}} (\eta_1^{(d)} + 0.5\eta_2^{(d)} (P_{\text{max}}^{\text{ckt}} + P_{\text{min}}^{\text{ckt}})) \times \sum_{k=0}^\infty \frac{(-1)^k}{k!} \frac{1}{(\bar{\gamma}^{(d)})^k} [E_i(\gamma_{\text{max}} + k\gamma_{\text{max}}) - E_i(\gamma_{\text{th}}^{(d)} + k\gamma_{\text{th}}^{(d)})]. \quad (11)$$

Further, we provide simple bounds on (10) in the following Theorem:

**Theorem 1:** If  $P_{\text{min}}^{\text{ckt}}$  and  $P_{\text{max}}^{\text{ckt}}$  are minimum and maximum circuit transmit power of all devices, respectively,  $\gamma_{\text{th}}^{(d)}$  is the threshold SNR, and  $\eta_1^{(d)} = 10 \log(2) P^{(d)} L/B$ ,  $\eta_2^{(d)} = \eta_1^{(d)} / P^{(d)}$ , then the expected energy consumption for D2D under Rayleigh fading channel with average SNR  $\bar{\gamma}^{(d)}$  is bounded as:

$$\begin{aligned} & (\eta_1^{(d)} + 0.5\eta_2^{(d)} (P_{\text{max}}^{\text{ckt}} + P_{\text{min}}^{\text{ckt}})) \\ & \times \left( \frac{1}{\bar{\gamma}^{(d)}} \log_e(1 + \frac{\bar{\gamma}^{(d)}}{\gamma_{\text{th}}^{(d)}}) - \frac{1}{(\bar{\gamma}^{(d)})^2} \log(1 + \frac{\bar{\gamma}^{(d)}}{\gamma_{\text{th}}^{(d)}}) \right) \leq \bar{E}^{\text{D2D}} \\ & \leq (\eta_1^{(d)} + 0.5\eta_2^{(d)} (P_{\text{max}}^{\text{ckt}} + P_{\text{min}}^{\text{ckt}})) \\ & \times \left( \frac{\bar{\gamma}^{(d)}}{\bar{\gamma}^{(d)} + \gamma_{\text{th}}^{(d)}} + \frac{1}{\bar{\gamma}^{(d)} + \gamma_{\text{th}}^{(d)}} \log(1 + \frac{\bar{\gamma}^{(d)}}{\gamma_{\text{th}}^{(d)}}) \right) \end{aligned} \quad (12)$$

**Proof:** Using the expectation of uniform random variable and applying logarithm inequality  $\frac{x}{x+1} \leq \log(1+x) \leq x$  [47], the integral in (10) for expected energy in D2D relaying can be represented in terms of exponential integral:

$$\begin{aligned} & (\eta_1^{(d)} + 0.5\eta_2^{(d)} (P_{\text{max}}^{\text{ckt}} + P_{\text{min}}^{\text{ckt}})) \frac{1}{\bar{\gamma}^{(d)}} E_1(\frac{\gamma_{\text{th}}^{(d)}}{\bar{\gamma}^{(d)}}) \leq \bar{E}^{\text{D2D}} \leq \\ & (\eta_1^{(d)} + 0.5\eta_2^{(d)} (P_{\text{max}}^{\text{ckt}} + P_{\text{min}}^{\text{ckt}})) \left( \exp(-\frac{\gamma_{\text{th}}^{(d)}}{\bar{\gamma}^{(d)}}) + \frac{1}{\bar{\gamma}^{(d)}} E_1(\frac{\gamma_{\text{th}}^{(d)}}{\bar{\gamma}^{(d)}}) \right) \end{aligned} \quad (13)$$

Further, we use the inequality on exponential integral  $0.5 \exp(-x) \log(1+2/x) < E_1(x) < \exp(-x) \log(1+1/x)$  and  $\exp(x) > 1+x$  to get (12) of Theorem 1. ■

From (11) and (12), it can be seen that the expected energy decreases with an increase in the average SNR at the relaying device. Since the relay devices have a higher average SNR due to proximity with the source device in the D2D communication, the energy overhead of the relaying among devices is negligible as compared with the transmission of data to the BS.

##### B. Average Energy Consumption without Relaying: $\bar{E}^{\text{DT}}$

We derive an expression on the expected consumed energy without D2D relaying (i.e., direct transmission). Each device transmits its data to the BS, if  $E^{\text{RELAY}} + E^{\text{D2D}} \geq E^{\text{DT}}$ . Using a simple inequality,  $10 \log_{10}(z) \leq 10 \log_{10}(1+z) \leq 1 + 10 \log_{10}(z)$ ,  $z \neq 0$  in (6), we get bounds on the energy consumption of a device (we drop the index  $i$ ) for the direct transmission as

$$\frac{\eta_1 + \eta_2 P^{\text{ckt}}}{1+X} \leq E^{\text{DT}} \leq \frac{\eta_1 + \eta_2 P^{\text{ckt}}}{X} \quad (14)$$

where  $X = 10 \log_{10}(\gamma)$ . The term  $\sum_{j=1}^M |h_{ji}|^2$  in  $\gamma_i = \frac{\sum_{j=1}^M |h_{ji}|^2 P}{N_0}$  can be approximated as lognormal distributed since  $|h_{ji}|^2$  is lognormal (see (3)) and sum of log-normal random variables can also be approximated as log-normal [48]. Moreover, each antenna gets the same shadowing effect as is typical in wireless channel models [49]. Thus  $\gamma$  is

log-normal distributed with a spreading parameter  $\sigma^2$  in dB,  $X \sim \mathcal{N}(\bar{\gamma}, \sigma^2)$  with

$$\bar{\gamma} = 10 \log_{10} M + 10 \log_{10} F + 10 \log_{10} R^{-\alpha} + 10 \log_{10} G + 10 \log_{10} P/N_0 \quad (15)$$

Considering different specifications of user devices in a network, the devices can have A different circuit power consumption models. Thus, we model the circuit power to be uniformly distributed between  $P_{\min}^{\text{ckt}}$  and  $P_{\max}^{\text{ckt}}$  representing minimum and maximum circuit transmit powers, respectively.

Taking expectation in (14) and noting the independence between the numerator and denominator terms, we get an upper bound on the expected energy consumption with direct transmission as:

$$\begin{aligned} \bar{E}^{\text{DT}} &\leq \mathbb{E}[\eta_1 + \eta_2 P^{\text{ckt}}] \mathbb{E}\left[\frac{1}{X}\right] \\ &= (\eta_1 + \eta_2 \mathbb{E}[P^{\text{ckt}}]) \frac{1}{\sqrt{2\pi}\sigma} \int_{\gamma_{\text{th}}}^{\infty} \frac{1}{x} e^{-\frac{(x-\bar{\gamma})^2}{2\sigma^2}} dx \end{aligned} \quad (16)$$

where  $\gamma_{\text{th}}$  in dB is a SNR threshold. The threshold SNR is selected to achieve a minimum data rate requirement below which communication is possible. The expectation has been taken over SNR  $\gamma$ . A lower bound can be similarly obtained by replacing  $\bar{\gamma}$  with  $\bar{\gamma} + 1$ .

*Theorem 2:* If  $P_{\min}^{\text{ckt}}$  and  $P_{\max}^{\text{ckt}}$  are minimum and maximum circuit transmit power of all devices, respectively,  $\gamma_{\text{th}}$  is the threshold SNR in dB, and  $\eta_1 = 10 \log_{10}(2)PL/B$ ,  $\eta_2 = \eta_1/P$ , then the expected energy with the direct transmission in a log-normal fading channel with average SNR  $\bar{\gamma}$  and variation  $\sigma$  (in dB) is bounded as:

$$\begin{aligned} &\frac{(\eta_1 + 0.5\eta_2(P_{\max}^{\text{ckt}} + P_{\min}^{\text{ckt}}))}{(\bar{\gamma} + 1)} \exp\left(\frac{\sigma^2}{2(\bar{\gamma} + 1)^2}\right) \\ &\times Q\left(\frac{\sigma}{(\bar{\gamma} + 1)} + \frac{(\gamma_{\text{th}} - \bar{\gamma} - 1)}{\sigma}\right) \leq \bar{E}^{\text{DT}} \leq \\ &(\eta_1 + 0.5\eta_2(P_{\max}^{\text{ckt}} + P_{\min}^{\text{ckt}})) [\mathcal{I}_1^{\text{DT}}(\bar{\gamma}, \sigma) + \mathcal{I}_2^{\text{DT}}(\bar{\gamma}, \sigma)] \end{aligned} \quad (17)$$

where

$$\begin{aligned} \mathcal{I}_1^{\text{DT}}(\bar{\gamma}, \sigma) &= \frac{\sigma}{\sqrt{2\pi}(2\sigma^2 + \bar{\gamma}^2)} \left[ 2\sqrt{2}\sigma \log\left(\frac{\bar{\gamma}}{\gamma_{\text{th}}}\right) \right. \\ &\quad \left. \times \log\left(1 + \left(\frac{\bar{\gamma} - \gamma_{\text{th}}}{\sqrt{2}\sigma}\right)^2\right) + \arctan\left(\frac{\bar{\gamma} - \gamma_{\text{th}}}{\sqrt{2}\sigma}\right)^2 \right] \\ \mathcal{I}_2^{\text{DT}}(\sigma) &= \frac{\exp[-\bar{\gamma}^2/2\sigma^2]}{4\sqrt{2\pi}\sigma} [2\pi \text{erfi}\left(\frac{\bar{\gamma}}{\sqrt{2}\sigma}\right) - 2E_1\left(\frac{\bar{\gamma}^2}{2\sigma^2}\right) \\ &\quad + \log\left(\frac{\bar{\gamma}^2}{2\sigma^2}\right) + 4\log\left(\frac{\sqrt{2}\sigma}{\bar{\gamma}}\right) - \log\left(\frac{\sigma^2}{\bar{\gamma}}\right)] \end{aligned} \quad (18)$$

*Proof:* The integral in (16) can be represented as a sum of two integrals:

$$\begin{aligned} \mathcal{I}_{\text{ub}} &= \frac{1}{\sqrt{\pi}} \left[ \int_0^{\frac{\bar{\gamma} - \gamma_{\text{th}}}{\sigma\sqrt{2}}} \frac{1}{\bar{\gamma} - \sqrt{2}t\sigma} e^{-t^2} dt \right. \\ &\quad \left. + \int_0^{\infty} \frac{1}{\bar{\gamma} + \sqrt{2}t\sigma} e^{-t^2} dt \right] \end{aligned} \quad (19)$$

We use the standard mathematical procedure on the second integral in (19) to get an exact solution  $\mathcal{I}_2^{\text{DT}}(\bar{\gamma}, \sigma)$  as given in (18). Using  $\exp[-x^2] \leq \frac{1}{1+x^2}$  and applying the partial fraction method, an upper bound of the first integral is given as  $\mathcal{I}_1^{\text{DT}}(\bar{\gamma}, \sigma)$ . This has been presented in (18). Using these, and the average of uniform random variable, we get the upper

bound (17) of Theorem 2. For the lower bound, we use (14) and  $1 + z \leq e^z$  to get the first integral of (19) as

$$\mathcal{I}_{\text{lb}} = \frac{1}{\sqrt{2\pi}(\bar{\gamma} + 1)} \int_{\frac{(\gamma_{\text{th}} - \bar{\gamma} - 1)}{\sigma}}^{\infty} e^{-\frac{x^2}{2} - \frac{\sigma}{\bar{\gamma} + 1}x} dx \quad (20)$$

Completing the expression in the exponential function in a square form and representing the integral into Gaussian Q-function with a simple substitution, we get the lower bound (17) of Theorem 2. ■

The derived bounds in (17) are presented in terms of simple mathematical functions. It can be seen that a lower average SNR increases the energy consumption for the direct transmission, thus necessitating the use of relaying.

### C. Average Energy Consumption with Relaying: $\bar{E}^{\text{RELAY}}$

Now, we derive an expression for the average energy consumed  $\bar{E}^{\text{RELAY}}$  by the device to the BS in log-normal fading with the selection criteria defined in (8). To simplify the model, we assume that the relaying devices are in the vicinity of the source, so that the path loss of all possible relays are similar [50], but spread enough to experience independent shadowing. We also assume the circuit power is the same for each device i.e.,  $P_{\min}^{\text{ckt}} = P_{\max}^{\text{ckt}} = P^{\text{ckt}}$ . Using the selection criteria in (8) for the log-normal shadowing in (14), we get:

$$E^{\text{RELAY}} \leq \frac{\eta_1 + \eta_2 P^{\text{ckt}}}{X_{(n)}} \quad (21)$$

where  $X_{(n)} = \max(X_1, X_2, X_3, \dots, X_N)$  with  $X_i = 10 \log_{10}(\gamma_i)$ ,  $1 \leq i \leq N$ . It follows from order statistics that the cumulative distribution function (CDF) of  $X_{(n)}$  is given as  $F_{X_{(n)}}(x) = [F_X(x)]^N$ , where  $F_X(x) = [1/2 + 1/2 \text{erf}(\frac{x - \bar{\gamma}}{\sqrt{2}\sigma})]$  is the CDF of normal distribution. The PDF of  $X_{(n)}$  is  $f_{X_{(n)}}(x) = N[F_X(x)]^{N-1} [f_X(x)]$  where  $f_X(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x - \bar{\gamma})^2}{2\sigma^2}}$  is the PDF of normal distribution.

Thus, the average consumed energy  $\bar{E}^{\text{RELAY}} = \mathbb{E}[E^{\text{RELAY}}]$  can be expressed as:

$$\bar{E}^{\text{RELAY}} \leq \mathbb{E}[\eta_1 + \eta_2 P^{\text{ckt}}] \int_{\gamma_{\text{th}}}^{\infty} \frac{N}{x} [F_X(x)]^{N-1} [f_X(x)] dx \quad (22)$$

Using the integration by parts and  $F_X(x) = Q(\frac{\bar{\gamma} - \gamma_{\text{th}}}{\sigma})$ , we can represent (22) as:

$$\begin{aligned} \bar{E}^{\text{RELAY}} &\leq \mathbb{E}[\eta_1 + \eta_2 P^{\text{ckt}}] \times \\ &\left( \mathcal{I}_1^{\text{RELAY}}(N, \sigma) + \mathcal{I}_2^{\text{RELAY}}(N, \sigma) - \frac{1}{\gamma_{\text{th}}} Q^N\left(\frac{\bar{\gamma} - \gamma_{\text{th}}}{\sigma}\right) \right) \end{aligned} \quad (23)$$

where

$$\begin{aligned} \mathcal{I}_1^{\text{RELAY}}(N, \sigma) &= \int_{\frac{\gamma_{\text{th}} - \mu}{\sigma}}^0 \frac{1}{(x\sigma + \bar{\gamma})^2} (1 - Q(x))^N dx \\ \mathcal{I}_2^{\text{RELAY}}(N, \sigma) &= \int_0^{\infty} \frac{1}{(x\sigma + \bar{\gamma})^2} (1 - Q(x))^N dx \end{aligned} \quad (24)$$

*Theorem 3:* If  $P^{\text{ckt}}$  is the circuit transmit power of each device,  $\gamma_{\text{th}}$  is the threshold SNR in dB, and  $\eta_1 = 10 \log_{10}(2)PL/B$ ,  $\eta_2 = \eta_1/P$ , then the average energy consumption with relaying from  $N$  devices in a log-normal

fading channel with average SNR  $\bar{\gamma}$  and variation  $\sigma$  (in dB) is bounded as:

$$\begin{aligned} \bar{E}^{\text{RELAY}} &\leq (\eta_1 + \eta_2 P^{\text{ckt}}) \\ &\times \left( \mathcal{I}_1^{\text{RELAY}}(N, \sigma) + \mathcal{I}_2^{\text{RELAY}}(N, \sigma) \right. \\ &\quad \left. - \frac{1}{\gamma_{\text{th}}} Q^N \left( \frac{\bar{\gamma} - \gamma_{\text{th}}}{\sigma} \right) \right) \end{aligned} \quad (25)$$

where  $\mathcal{I}_1^{\text{RELAY}}(N, \sigma)$  and  $\mathcal{I}_2^{\text{RELAY}}(N, \sigma)$  are given in (26) and (27) (see next page), respectively.

*Proof:* An upper bound on  $I_1^{\text{RELAY}}(N, \sigma)$  in (24) can be obtained using  $Q(t) = 1 - Q(-t)$  with Chernoff bound  $Q(t) \leq \frac{1}{2} \exp[-t^2/2]$ , and  $\exp[-z] < \frac{1}{1+z}$  to express  $I_1^{\text{RELAY}}(N, \sigma)$  as a polynomial function:

$$I_1^{\text{RELAY}}(N, \sigma) \leq \frac{1}{(2)^N} \int_0^{\frac{\bar{\gamma} - \gamma_{\text{th}}}{\sigma}} \frac{1}{(\bar{\gamma} - t\sigma)^2 (1 + \frac{N}{2} t^2)} dt \quad (29)$$

We use the partial fraction to solve the integral in (29) which is given in (26). To analyze  $I_2^{\text{RELAY}}(N, \sigma)$ , we use the binomial expansion of  $(1 - Q(x))^N$  and interchange the summation and the integration to get

$$\begin{aligned} I_2^{\text{RELAY}}(N, \sigma) &= \sum_{k=0}^N \binom{N}{k} (-1)^k \int_0^\infty \frac{[Q(x)]^k}{(x\sigma + \bar{\gamma})^2} dx \\ &= \sum_{r=0}^N \binom{N/2}{2r} \int_0^\infty \frac{[Q(x)]^{2r}}{(x\sigma + \bar{\gamma})^2} dx \\ &\quad - \sum_{r=0}^N \binom{N/2}{2r+1} \int_0^\infty \frac{[Q(x)]^{2r+1}}{(x\sigma + \bar{\gamma})^2} dx \end{aligned} \quad (30)$$

Then, we use Chernoff bounds  $f(\kappa) \exp[-\kappa x^2/2] \leq Q(x) \leq \frac{1}{2} \exp[-x^2/2]$ , where  $f(\kappa) = \frac{\exp((\pi(\kappa-1)+2)^{-1})}{2\kappa} \sqrt{\frac{1}{\pi}(\kappa-1)(\pi(\kappa-1)+2)}$ ,  $\kappa \geq 1$  [51] appropriately in (30) to represent the integral terms in the form  $\int_0^\infty \frac{\exp[-Nx^2]}{(ax+b)^2} dx = \Psi(N, a, b)$ . Using standard mathematical procedures, closed-form expression of  $\Psi(N, a, b)$  is given in (28), and thus we get (27). This concludes the proof of Theorem.

While deriving (27), we have used Chernoff type of bounds of the Q-function in (30). We further simplify the expression  $I_2^{\text{RELAY}}(N, \sigma)$  in (30) by applying an approximation  $Q(x) \approx \exp(q_1 x^2 + q_2 x + q_3)$ , where  $q_1 = -0.4920$ ,  $q_2 = -0.2287$ ,  $q_3 = -1.1893$  [52] to get an approximate expression on  $I_2^{\text{RELAY}}(N, \sigma)$ , as presented in Appendix A.

Thus, using results of Theorem 1, Theorem 2, and Theorem 3 in (9), we can express the energy consumption performance of the ODSR in terms of known mathematical functions. In what follows, we provide a scaling law on the average energy consumption of the relaying to the number of devices in a network for better insight on the network performance.

*Theorem 4:* If  $P^{\text{ckt}}$  is the circuit transmit power of devices and  $\eta_1 = 10 \log_{10}(2) PL/B$ ,  $\eta_2 = \eta_1/P$ , then the average consumed energy with a single relay selection from  $N$  devices

in a log-normal shadow fading channel with average SNR  $\bar{\gamma}$  and variation  $\sigma$  (in dB) is upper bounded as:

$$\begin{aligned} \bar{E}^{\text{RELAY}} &\leq \left( \eta_1 + \eta_2 P^{\text{ckt}} \right) \\ &\times \left( \frac{1}{2^N} \frac{1}{\gamma_{\text{th}}} + \frac{1}{\sigma} \left( \frac{1}{\bar{\gamma} + \sigma \sqrt{c_I \log(N)}} \right. \right. \\ &\quad \left. \left. + \sum_{i=1}^{I-1} \left( \frac{1}{1 + \kappa_2 N^{(1-c_i)}} \right) \left( \frac{1}{\bar{\gamma} + \sigma \sqrt{c_{i-1} \log(N)}} \right) \right) \right) \end{aligned} \quad (31)$$

where  $I$  is a positive integer,  $\kappa_2 = 0.3885$  is a constant, and  $0 \leq c_i \leq 1$ ,  $c_0 = 0$ ,  $i = 1, 2, \dots, I$ . Further, energy consumption scales as

$$\bar{E}^{\text{RELAY}} = \mathcal{O} \left( \frac{\eta_1 + \eta_2 P^{\text{ckt}}}{\bar{\gamma} + \sigma \sqrt{c_I \log(N)}} \right) \quad (32)$$

where  $0 \leq c_I \leq 1$ .

*Proof:* The proof is presented in Appendix B. ■

From the scaling law in (32), it can be seen that energy consumption reduces logarithmic with the number of devices. Hence, near-optimal performance can be achieved with only a few nearby devices selected for D2D relaying. This reduces latency and energy overhead in large scale networks.

## V. SIMULATION AND NUMERICAL ANALYSIS

This section demonstrates the energy consumption performance of the ODSR through numerical analysis and simulations using MATLAB software. We compare the ODSR performance with the optimal and no-relaying (denoted by “direct”) schemes. The optimal criteria is based on the relay selection considering energy consumed in both the hops. We use the energy model presented in [53] to compute the energy consumption by the devices for data transmission. We have considered channel models from ETSI 3rd Generation Partnership Project (3GPP) and 5G channels for our simulations [54], [55].

### A. Direct Transmission versus Relaying

First, we demonstrate the energy consumption performance of relaying by considering various path loss configurations and multi-path fading from 3GPP 5G wireless channel models, as shown Fig. 3. The log-normal spreading factor ranges from 2 dB to 7.8 dB. We consider short term fading using the tapped delay line type A (TDL-A) model with delay spread 100 ns [55]. The channel bandwidth is 720 KHz, and the carrier center frequency is 6 GHz. The background noise for each device and the BS is taken as  $-174$  dBm/Hz with a noise figure of 5 dB. It can be seen from Fig. 3 that the relaying achieves significant improvement compared to the direct transmission for various wireless channels when the shadowing effect is dominant. However, when the shadowing is minimal (i.e.  $\sigma = 2$  dB), the relaying performs very similar to the direct transmission. This motivates us to use relaying based techniques for data transmissions over strong shadow fading channels. The simulation results also show a near-optimal performance of the proposed relaying scheme.



$$\mathcal{I}_1^{\text{RELAY}}(N, \sigma) \leq \frac{\sigma}{(2)^N (2\sigma^2 + N\bar{\gamma}^2)^2} \left[ 2\sigma^2(2\sigma^2 + N\bar{\gamma}^2) \left( \frac{1}{\gamma_{\text{th}}} - \frac{1}{\bar{\gamma}} \right) + 4N\sigma^2\bar{\gamma} \log \left( \frac{\gamma_{\text{th}}}{\bar{\gamma}} \right) + 2N\sigma\mu \log \left( 1 + \frac{N}{2} \left( \frac{\bar{\gamma} - \gamma_{\text{th}}}{\sigma} \right) \right) \right. \\ \left. + \sqrt{2N}(N\bar{\gamma}^2 - 2\sigma^2) \arctan \left( \sqrt{N/2} \left( \frac{\bar{\gamma} - \gamma_{\text{th}}}{\sigma} \right) \right) \right] \quad (26)$$

$$\mathcal{I}_2^{\text{RELAY}}(N, \sigma) \leq \sigma \sum_{r=0}^N \binom{N/2}{2r} \frac{1}{4^r} \Psi(r, \sigma, \bar{\gamma}) - \sum_{r=0}^N \binom{N/2}{2r+1} [f(\kappa)]^{2r+1} \Psi((2r+1)\kappa, \sigma, \bar{\gamma}), \\ \text{where } f(\kappa) = \frac{\exp((\pi(\kappa-1)+2)^{-1})}{2\kappa} \sqrt{\frac{1}{\pi}(\kappa-1)(\pi(\kappa-1)+2)}, \kappa \geq 1, \text{ and function } \Psi(r, \sigma, \bar{\gamma}) : \quad (27)$$

$$\Psi(N, a, b) = \int_0^\infty \frac{\exp[-Nx^2]}{(ax+b)^2} dx = \frac{1}{2a^3b} e^{-\frac{nb^2}{a^2}} \left( 2\pi b^2 \text{Nerfi} \left( \frac{b\sqrt{N}}{a} \right) - 2b^2 \text{NEi} \left( \frac{b^2N}{a^2} \right) + 2a^2 e^{\frac{b^2N}{a^2}} - \right. \\ \left. 2\sqrt{\pi}ab\sqrt{N} e^{\frac{b^2N}{a^2}} - b^2N \log \left( \frac{a^2}{b^2N} \right) + b^2N \log \left( \frac{b^2N}{a^2} \right) + 4b^2N \log \left( \frac{a}{b} \right) - 2b^2N \log(N) \right), N > 0, a > 0, b > 0 \quad (28)$$

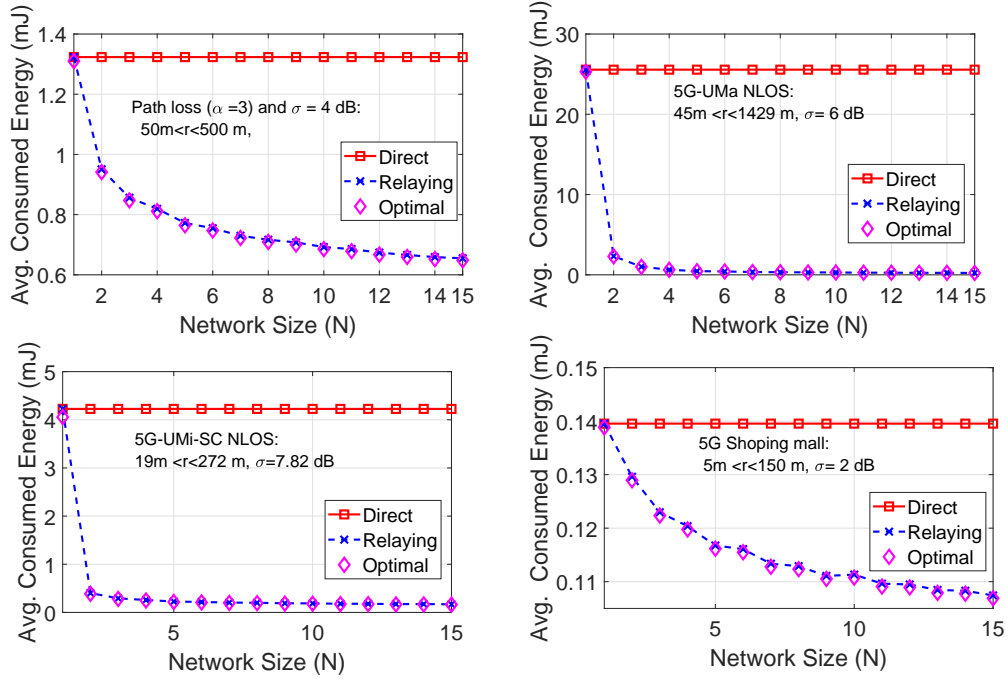


Fig. 3. Energy consumption performance of opportunistic relaying compared to direct transmission over wireless fading channels for various network scenarios. Different acronyms are UMa: Urban macro, UMi: Urban micro, SC: Street Canyon, NLOS: non-line of sight.

### B. ODSR Performance

In order to demonstrate the ODSR performance, we emulate a wireless network using the 3GPP WINNER II wireless fading model and simulation parameters in line with 3GPP recommendations [54]. This simulation environment enables us to include the overhead energy consumed by the control signaling for a fair comparison with the no-relaying and optimal schemes. For each transmission, a data packet length of  $L = 1024$  bytes is considered, and the size of D2D request/reply data is  $L^{(d)} = 10$  bytes.

The channel model considers all three losses: path-loss, short-term fading, and long-term shadowing. The fading chan-

nel between the device and the BS is urban macro log-normal shadowing (spreading factor  $\sigma = 4$  dB) while the channel between devices is modeled as Rayleigh fading generated by the extended pedestrian A model (EPA) with 9 random taps [56]. The devices are assumed to be moving at a speed of 3 km/h. We consider a single-cell network with up to 150 devices distributed uniformly in a radius of 50m to 500 m with a BS in the center. The background noise for each device and the BS is taken as  $-174$  dBm/Hz. We consider 20 dB of interference at the BS due to inter-cell interference coming from base stations of adjacent cells. We assume transmission power 23 dBm, transmission bandwidth



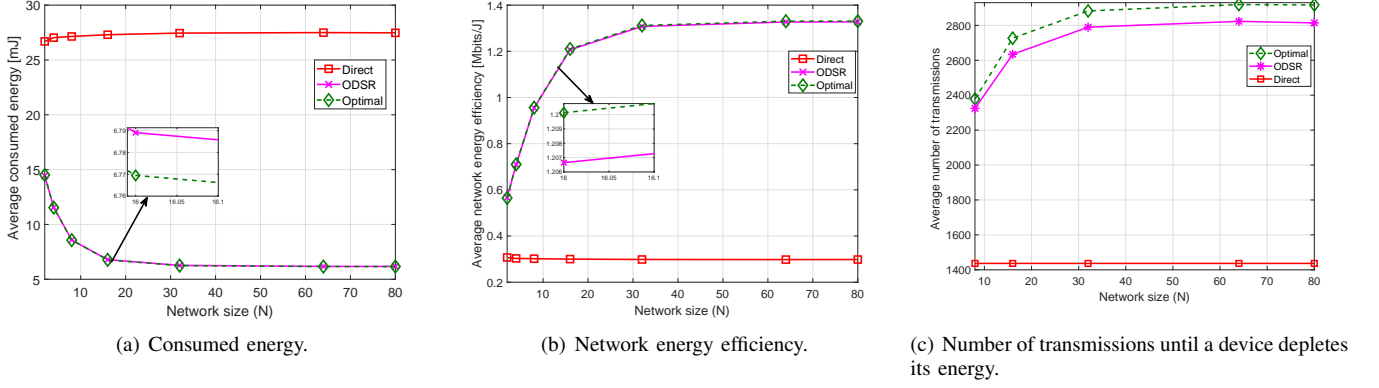


Fig. 4. Performance of ODSR comparing with the optimal and no-relaying schemes under 3GPP WINNER II fading channels.

TABLE I  
AVERAGE ENERGY CONSUMPTION (IN  $\mu\text{J}$ ) OF VARIOUS OVERHEADS  
OBTAINED USING SIMULATION UNDER 3GPP MODEL.

$\bar{E}_{\text{tx}}^{\text{RTR}}$	$\bar{E}_{\text{rx}}^{\text{RTR}}$	$\bar{E}_{\text{tx}}^{\text{CTR}}$	$\bar{E}_{\text{rx}}^{\text{CTR}}$	$\bar{E}_{\text{tx}}^{\text{D2D}}$	$\bar{E}_{\text{rx}}^{\text{D2D}}$
11.60	4.50	3.35	1.30	350.5	135.4

200 KHz, and initial energy 0.72mWh for all devices. We assume that the communication range for the D2D relaying is within 50 m.

In Table I, we present the components of average consumed energy for various overheads. This can be considered negligible by comparing the energy required for data transmission.

In Fig. 4, we analyze the performance of ODSR in terms of average energy consumption, network energy efficiency, and the lifetime of the network. The energy efficiency (bits per Joule) of the network is computed as the ratio of channel capacity of all the nodes to the total power consumption (including the circuit power) of the network. We define the lifetime of the network by the average number of transmissions before the battery of the first device of the network is depleted. The figures show that the relaying provides significant performance improvement comparing to the no-relaying scheme. Further, the ODSR achieves the near-optimal performance with only a few relaying devices i.e., within  $N = 25$ . This happens because the log-normal shadowing of the second hop provides sufficient diversity to achieve the near-optimal performance with a few relaying devices. However, there is a loss in the average number of transmissions by the ODSR compared to the optimal, as shown in Fig. 4c. This is due to the fact that an incremental decrease in the consumed energy results in a higher cumulative gain in the average number of transmissions.

### C. Scaling Law

Finally, we verify the analytical bounds and the scaling law derived in this paper by considering a transmission model without overhead energies, as depicted in Fig. 5. We consider a network of 10 to  $10^5$  devices situated uniformly at 300 m from the BS, situated in the center. For each transmission, a packet length of  $L = 2$  MB is considered for a faster simulation in a large network. We consider channel between devices to the BS

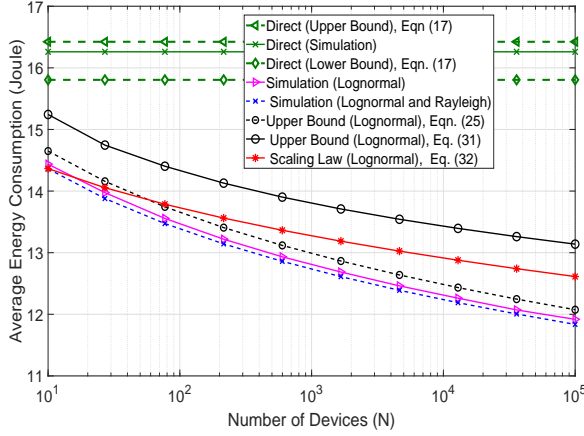
to be log-normal distributed with a spreading factor of 4 dB and a path loss exponent  $\alpha = 4$ . The channel between devices is assumed to be Rayleigh fading with a path loss exponent  $\alpha = 3$ . The transmit power for each device is set to 23 dBm. For scaling law verification, we consider  $M = 4$ ,  $c_M = 0.99$ ,  $\delta_M = \ln(N)$ ,  $\delta_1 = \delta_M/4$ ,  $\delta_2 = \delta_M/2$  and  $\delta_3 = 3\delta_M/4$  based on Theorem 4.

It can be seen from Fig. 5a that the short-term fading has a negligible impact on the energy consumption compared to the long-term shadowing effect. Moreover, the figure verifies the analytical bounds and the scaling law on the average consumed energy. It can also be seen that the energy consumption reduces logarithmically with the number of devices. We have also validated bounds of average energy consumption for the direct transmission (Theorem 2) and relayed transmission (as given in Theorem 3 and Theorem 4) with simulation results.

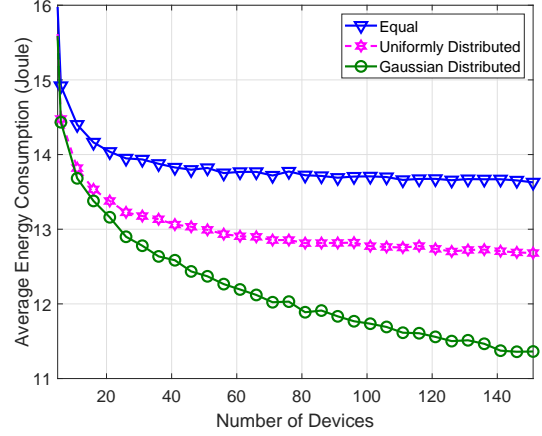
To verify the effect of randomness of the circuit power transmissions on the relay selection, we assume two probability distribution functions: uniform distribution between  $0.5P^{\text{ckt}}$  and  $1.5P^{\text{ckt}}$  and Gaussian distribution  $N \sim (P^{\text{ckt}}, 0.03P^{\text{ckt}})$ . Fig. 5b shows that the relay selection depends on the distribution of circuit transmission power of devices, and that the impact of average energy consumption is more pronounced when the randomness in the circuit transmission power is high.

## VI. CONCLUSION

We analyzed the energy consumption performance of a D2D based opportunistic relaying scheme for uplink data transmissions in a wireless network. We derived closed-form expressions and analytical bounds of the considered ODSR scheme under log-normal shadowing. The analytical expressions show that the ODSR achieves significant performance gain when the devices are in heavy shadowing area with respect to the BS while the devices enjoy strong channel for inter-user D2D communication with negligible energy overhead. Further, the derived scaling law on the consumed energy shows that a near-optimal performance can be achieved in log-normal shadowing with a few devices. This reduces the latency and overhead energy consumed by the devices in the selection of relays. By consider several realistic cellular environments, we show that the ODSR achieves a near-optimal performance using only few



(a) Verification of scaling law and bounds.



(b) Effect of distribution of circuit transmission power.

Fig. 5. Validation of derived analytical bounds and effect of circuit transmission power on the relaying performance.

devices in the network. This can be useful to reduce latency and overhead energy consumption in a large scale network. As such, the ODSR achieves an approximately 300% decrease in energy consumption using only 16 relaying devices compared to direct transmissions. This significant reduction in energy consumption will increase the life time of the network for ubiquitous communications under wireless fading channels.

#### APPENDIX A

##### PROPOSITION 1: APPROXIMATION OF $I_2^{\text{RELAY}}(N, \sigma)$

An approximation on  $I_2^{\text{RELAY}}(N, \sigma)$  is given as:

$$I_2^{\text{RELAY}}(N, \sigma) \approx \sigma \sum_{k=0}^N \binom{N}{k} (-1)^k \left( \frac{A(k) \gamma_{\max}}{\bar{\gamma}^2 + \bar{\gamma} \sigma \gamma_{\max}} + \frac{B(k)}{\bar{\gamma}} \log\left(1 + \frac{\sigma \gamma_{\max}}{\bar{\gamma}}\right) + C(k) \log\left|1 + \frac{\gamma_{\max}}{\alpha(k)}\right| + D(k) \log\left|1 + \frac{\gamma_{\max}}{\beta(k)}\right| \right) \quad (33)$$

where

$$\begin{aligned} A(k) &= \frac{\sigma^2}{(\bar{\gamma} - \alpha(k)\sigma)(\bar{\gamma} - \beta(k)\sigma)}, B(k) = \frac{\sigma^2(\alpha(k)\sigma + \beta(k)\sigma - 2\bar{\gamma})}{(\bar{\gamma} - \alpha(k)\sigma)^2(\bar{\gamma} - \beta(k)\sigma)^2} \\ C(k) &= \frac{1}{(\alpha(k) - \beta(k))(\alpha(k)\sigma - \bar{\gamma})^2}, D(k) = \frac{1}{(\alpha(k) - \beta(k))(\beta(k)\sigma - \bar{\gamma})^2} \\ \{\alpha(k), \beta(k)\} &= (-kq_2 \pm \sqrt{k^2q_2^2 - 4kq_1q_2 - 4kq_1})/2kq_1 \\ q_1 &= -0.4920, q_2 = -0.2287, q_3 = -1.1893 \end{aligned} \quad (34)$$

*Proof:* To derive an approximate expression on  $I_2^{\text{RELAY}}(N, \sigma)$ , we use an approximation on  $Q(x) \approx \exp[-(q_1x^2 + q_2x + q_3)]$  and  $e^{-z} \leq \frac{1}{1+z}, \forall z \leq 0$  in (30) to represent the integral

$$I_2^{\text{RELAY}}(N, \sigma) \approx \int_0^{\gamma_{\max}} \frac{dx}{(x\sigma + \bar{\gamma})^2(1 + k(q_1x^2 + q_2x + q_3))} \quad (35)$$

where  $\gamma_{\max} < \infty$  is chosen to avoid the divergence of the integral. The integration in (35) is derived in exact form as presented in (34). This completes the proof of Proposition 1. ■

#### APPENDIX B

##### THEOREM 4: SCALING LAW ON ENERGY CONSUMPTION

We use  $Q(0) = 1/2$  to get an upper bound on the integral  $\mathcal{I}_1^{\text{RELAY}}(N, \sigma)$  in (24):

$$\mathcal{I}_1^{\text{RELAY}}(N, \sigma) \leq \frac{1}{2^N} \left( \frac{1}{\gamma_{\text{th}}} - \frac{1}{\bar{\gamma}} \right) \quad (36)$$

where the equality is achieved when  $\gamma_{\text{th}} = \bar{\gamma}$ . The integral  $\mathcal{I}_2^{\text{RELAY}}(N, \sigma)$  in (24) can be decomposed:

$$\begin{aligned} \mathcal{I}_2^{\text{RELAY}}(N, \sigma) &= \int_0^{\delta_1} \frac{1}{(x\sigma + \bar{\gamma})^2} (1 - Q(x))^N dx \\ &+ \int_{\delta_1}^{\delta_2} \frac{1}{(x\sigma + \bar{\gamma})^2} (1 - Q(x))^N dx \\ &+ \dots + \int_{\delta_M}^{\infty} \frac{1}{(x\sigma + \bar{\gamma})^2} (1 - Q(x))^N dx \end{aligned} \quad (37)$$

where  $\delta_i > \delta_{i-1} > 0, i = 1, 2, \dots, I$ , where  $I > 0$  is a positive integer. Since  $Q(\delta_i) < Q(\delta_{i-1})$ , we use the minimum of  $Q$ -function in each interval of integration to get an upper bound

$$\begin{aligned} \mathcal{I}_2^{\text{RELAY}}(N, \sigma) &\leq (1 - Q(\delta_1))^N \frac{1}{\sigma} \left( \frac{1}{\bar{\gamma}} - \frac{1}{\sigma\delta_1 + \bar{\gamma}} \right) \\ &+ (1 - Q(\delta_2))^N \frac{1}{\sigma} \left( \frac{1}{\sigma\delta_1 + \bar{\gamma}} - \frac{1}{\sigma\delta_2 + \bar{\gamma}} \right) \\ &+ \dots + \frac{1}{\sigma} \left( \frac{1}{\sigma\delta_I + \bar{\gamma}} \right) \end{aligned} \quad (38)$$

We use  $\delta_i = \sqrt{c_i \log(N)}$  where  $0 \leq c_i \leq 1$ , inequality  $(1-x)^N \leq \frac{1}{1+Nx}$ , and a lower bound on  $Q$ -function  $Q(x) \geq \kappa_2 e^{-x^2}$ , where  $\kappa_2 = 0.3885$  to bound  $(1 - Q(\delta_i))^N$ :

$$(1 - Q(\delta_i))^N \leq \frac{1}{1 + \kappa_2 N^{1-c_i}} \quad (39)$$

Using (39) in (38), we get

$$\mathcal{I}_2^{\text{RELAY}}(N, \sigma) \leq \frac{1}{\sigma} \left[ \frac{1}{\bar{\gamma} + \sigma \sqrt{c_I \log(N)}} + \sum_{i=1}^{I-1} \left( \frac{1}{1 + \kappa N^{(1-c_i)}} \right) \left( \frac{1}{\bar{\gamma} + \sigma \sqrt{c_{i-1} \log(N)}} - \frac{1}{\bar{\gamma} + \sigma \sqrt{c_i \log(N)}} \right) \right] \quad (40)$$

where  $c_0 = 0$ . Using (36), (40) in (23), and neglecting negative terms, we get (31). When  $N \rightarrow \infty$ , the term involving  $1/N$  becomes negligible, and we get the scaling law for the energy consumption of Theorem 4.

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