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# Simple modeling of energy consumption for D2D relay mechanism

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**Abstract**—Reducing energy consumption is a key requirement for Massive Machine-Type Communication (mMTC) devices operating on battery power. Device-to-Device (D2D) communication is a promising technology that can be used in 5G networks for this purpose. In this paper, we identify the interest of using a D2D relay mechanism compared with a direct link with an unfavorable link budget. We first look for an optimal Relay-MTC device configuration that minimizes the energy consumption. We then compare the energy consumption in direct and relaying mode expressing it in terms of the distance between the base station and the MTC device and between the base station and the relay. We show that when the MTC device is close to the base station, D2D relay mechanism can reduce the energy consumed by the MTC device at the expense of an increase in the global energy consumption (i.e. the energy consumed by the MTC device plus the energy consumed by the relay). On the other hand, when the MTC device is far from the base station, D2D relay mechanism allows reducing both the energy consumption by the MTC device and the global energy consumption.

**Index Terms**—Energy consumption, Device-to-Device, MTC

## I. INTRODUCTION

In the coming years, the number of connected devices will grow exponentially [1], many of these devices being Machine-Type Communication (MTC) devices. MTC applications can be grouped into two main categories [2]: critical MTC and massive MTC. Critical MTC applications are characterized by very low latency, very high reliability and availability. On the other hand, massive MTC (mMTC) applications are characterized by a large number of devices, low mobility, small and infrequent data transmission, long battery life, low device cost, and low complexity.

Cellular networks will play an important role in the deployment of MTC applications due to their characteristics, e.g. scalability, reliability, large coverage, security, dedicated spectrum, and simplicity of management [3]. However, using cellular networks for mMTC applications would lead to network congestion and increased cost of deep indoor coverage. Device-to-Device (D2D) is a promising technology that aims to connect two or more devices directly without going through a direct link between the MTC device (MTD) and the Base Station (BS). D2D relaying can reduce the energy consumption, extend the network coverage and have a more efficient use of radio resources [4].

An MTD operating on battery power requires low-energy consumption, since the battery replacement in this device is

a difficult task or even an impossible task in some cases. To answer to this low-energy consumption need, in [5] [6] the authors propose to group terminals in clusters in which direct communication is possible. A particular terminal acts as a cluster head which has the function of a local coordinator and data forwarding. The other cluster members send their data to the cluster head. Certainly, clustering approach is an interesting method to reduce the energy consumption in MTDs. However, the authors analyze the formation of clusters and the selection of cluster-heads considering that all devices have similar characteristics. In this paper, we focus on using relaying mechanisms, considering that a device could be a relay or a cluster-head only if it has better characteristics than an ordinary MTD (e.g. better battery life) since relays may experience major burden in energy consumption. Thus, we consider that a User Equipment (UE) acts as a relay helping in the connection of MTDs with the base station. Also, MTD-UE links are established through a D2D communication as in [7] [8] [9].

We first define an energy consumption model. There are many proposed techniques in the literature for modeling the energy consumption [6] [10] [11]. In [6] a detailed energy consumption model for clustering is presented. In [10] they propose a realistic model for multi-hop networks and power consumption model for wireless sensor devices in [11]. In addition, 3rd Generation Partnership Project (3GPP) specifications suggest an energy consumption evaluation methodology in [12]. The model used in this work is inspired by the models proposed in [6] and [12], but focus only on the transmission phase.

One of our main objectives is to identify criteria for establishing the interest of using D2D relay mechanisms, looking for the optimal configuration minimizing the energy consumption. In [13], the authors have defined the energy consumption in WiFi-D2D and LTE-D2D as a function of the packet size and the number of devices in clustering MTDs. In [14], the authors discuss conditions under which a D2D communication is preferable to a communication via the BS in dynamic Time-Division Duplex (TDD) systems. In our study we compare the energy consumption in direct and relaying mode expressing it as a function of the distances between the BS and the MTD and between the BS and the relay.

The paper is organized as follows. In section II, we present

the scenario and system model. In Section III, we look for the minimum energy consumption in relaying mode. In Section IV, we compare the energy consumption in direct and relaying mode. In Section V, we present simulation results and compare them with derived analytical expressions from sections III and IV. Finally, we conclude in Section VI.

## II. SCENARIO AND SYSTEM MODEL

### A. Scenario and hypotheses

We consider a coverage scenario where both relays and MTDs are in-coverage. In this case, an MTD could connect to the network in two ways: directly to the BS or using a relay. In order to build a simplified model the following assumptions are made:

- Cellular infrastructure supports the discovery and synchronization phases (Network assisted approach). Thus, all devices are synchronized with the BS. We analyze only the energy consumption in data transmission phase.
- MTDs receive the data directly from the BS, i.e. downlink without using a relay.
- Relays are devices that could help MTDs to connect to the network, for which they receive and retransmit the packets coming from MTDs. Our analysis is focused on uplink since MTC applications mainly generate traffic in uplink.
- Relays are connected to the network using cellular links and MTDs are connected to the relays using D2D links. D2D links and cellular links are orthogonal, there is no interference between these systems.
- The communication channel is well known by devices. That means a perfect dynamic adaptation of the modulation and coding scheme.
- Devices transmit at their maximum allowed transmission power, there is no power control.

### B. Channel Model

In order to simplify our analysis, we model the communication channel only considering path loss. According to the Okumura-Hata model, the received power  $P_{rx}$  can be derived as

$$P_{rx} = P_{tx} \frac{K}{d^\gamma}, \quad (1)$$

where  $P_{tx}$  is the transmission power,  $K$  is the constant path loss factor,  $d$  is the distance between the transmitter and the receiver, and  $\gamma$  is the path loss exponent.

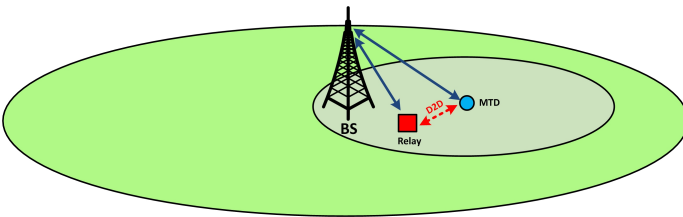


Fig. 1. Coverage scenario.

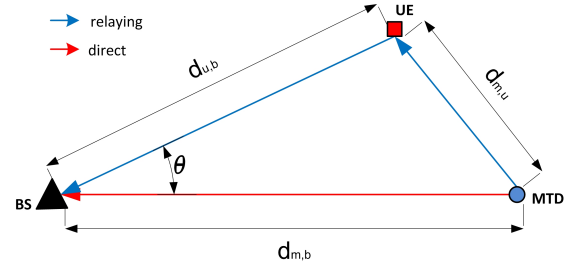


Fig. 2. Transmission scheme in direct and relaying mode.

### C. Link Model

We consider a low load situation. Hence the interference is negligible. Also, we consider only additive white Gaussian Noise (AWGN). From Shannon's capacity equation, the data rate  $R$  is derived as

$$R = W \log_2(1 + \eta), \quad (2)$$

where  $W$  is the transmission bandwidth, and  $\eta$  is the Signal-to-Interference-and-Noise-Ratio (SINR) which can be expressed as  $\eta = P_{rx}/N_0W$ , where  $N_0$  is the noise power spectral density, and  $P_{rx}$  is derived in (1). Note that

$$R \approx W \eta \log_2(e), \text{ when } \eta \approx 0, \quad (3)$$

$$R \approx W \log_2(\eta), \text{ when } \eta \gg 1. \quad (4)$$

Hereafter we consider  $\eta \gg 1$ , then the channel capacity can be rewritten as

$$R_{i,j} = W_i \log_2 \left( \frac{K P_i}{N_0 W_i d_{i,j}^\gamma} \right), \quad (5)$$

where  $W_i$  and  $P_i$  are respectively the bandwidth and the transmission power of the transmitter  $i$ ,  $d_{i,j}$  is the distance between the transmitter  $i$  and the receiver  $j$ . In order to simplify the mathematical analysis, we consider the same path loss parameters ( $K$  and  $\gamma$ ) in all links. However, cellular communications and D2D communications have different path loss parameters in a realistic scenario.

### D. Energy Consumption Model

We study two transmission modes: when an MTD uses a direct transmission to the BS (direct mode) and when it uses a relaying mechanism (relaying mode) as shown in Fig. 2. A device can operate in one of the following states: Tx, Rx, Idle, or Sleep. However, we analyze only the energy consumption when the device is in Tx state or Rx state, since in this research work we use a simplified energy consumption model considering only the transmission phase.

a) *Energy consumption in direct mode:* The MTD energy consumption in direct mode can be defined as

$$E_{m,dir} = P_{m,T} t_{m,T} + P_{m,R} t_{m,R}, \quad (6)$$

where  $P_{m,T}$  and  $P_{m,R}$  are the MTD power consumption in Tx state and Rx state respectively, and  $t_{m,T}$  is the transmission time. After transmitting its data, the MTD remains in Rx

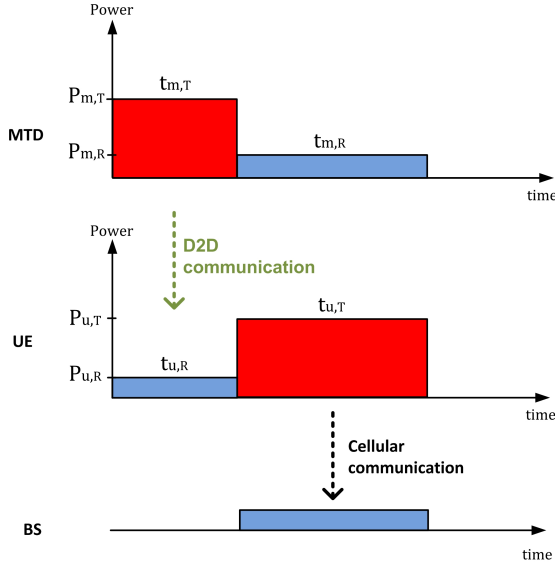


Fig. 3. Relaying process.

state a time  $t_{m,R} = t_{m,T}$  waiting for some other instruction or an acknowledgement (ACK) from the BS. We have  $t_{m,T} = L/R_{m,b}$ , where  $L$  is the packet size, and  $R_{m,b}$  is the MTD transmission rate in the  $MTD \rightarrow BS$  link.  $R_{m,b}$  can be derived from (5) as

$$R_{m,b} = W_m \log_2 \left( \frac{K P_m}{N_0 W_m d_{m,b}^\gamma} \right), \quad (7)$$

where  $W_m$  is the MTD bandwidth,  $P_m$  is the MTD transmission power, and  $d_{m,b}$  is the distance between the MTD and the BS. Then, we obtain an expression for the MTD energy consumption in direct mode:

$$E_{m,dir} = \frac{(P_{m,T} + P_{m,R})L}{R_{m,b}}. \quad (8)$$

b) *Energy consumption in relaying mode:* The total energy consumption in relaying mode ( $E_{T,rel}$ ) can be calculated as the sum of the energy consumed by each device that participates in a relaying process:

$$E_{T,rel} = E_{m,rel} + E_{u,rel}, \quad (9)$$

where  $E_{m,rel}$  and  $E_{u,rel}$  are the energy consumption by the MTD and UE respectively. In a relaying process, the MTD first transmits its data to the UE while the UE remains in Rx state receiving and demodulating. Then, the UE retransmits the data arriving from the MTD to the BS while the MTD stays listening (Rx state) as shown in Fig. 3. In this figure we can see that  $t_{m,T} = t_{u,R}$  and  $t_{m,R} = t_{u,T}$ .

The MTD energy consumption in relaying mode can be derived as

$$E_{m,rel} = P_{m,T}t_{m,T} + P_{m,R}t_{m,R}, \quad (10)$$

where  $P_{m,T}$  and  $P_{m,R}$  are the MTD power consumption in Tx state and Rx state respectively,  $t_{m,T}$  and  $t_{m,R}$  are the duration

of Tx state and Rx state respectively. We have  $t_{m,T} = L/R_{m,u}$  and  $t_{m,R} = t_{u,T} = L/R_{u,b}$ , then

$$E_{m,rel} = \frac{P_{m,T}L}{R_{m,u}} + \frac{P_{m,R}L}{R_{u,b}}. \quad (11)$$

On the other hand, the UE energy consumption in relaying mode can be derived as

$$E_{u,rel} = P_{u,T}t_{u,T} + P_{u,R}t_{u,R}, \quad (12)$$

where  $P_{u,T}$  and  $P_{u,R}$  are the UE power consumption in Tx state and Rx state respectively,  $t_{u,T}$  and  $t_{u,R}$  are the duration of Tx state and Rx state respectively. We have  $t_{u,T} = L/R_{u,b}$  and  $t_{u,R} = t_{m,T} = L/R_{m,u}$ , then

$$E_{u,rel} = \frac{P_{u,T}L}{R_{u,b}} + \frac{P_{u,R}L}{R_{m,u}}. \quad (13)$$

Finally, we obtain the global energy consumption in relaying mode substituting (11) and (13) in (9):

$$E_{T,rel} = \frac{(P_{u,T} + P_{m,R})L}{R_{u,b}} + \frac{(P_{m,T} + P_{u,R})L}{R_{m,u}}, \quad (14)$$

where

$$R_{u,b} = W_u \log_2 \left( \frac{K P_u}{N_0 W_u d_{u,b}^\gamma} \right), \quad (15)$$

$$R_{m,u} = W_m \log_2 \left( \frac{K P_m}{N_0 W_m d_{m,u}^\gamma} \right). \quad (16)$$

### III. MINIMUM-ENERGY CONSUMPTION IN RELAYING MODE

In this part of the study, we look for the UE location minimizing the global energy consumption in relaying mode. Without loss of generality, we consider a BS at the origin of coordinates (0,0), an MTD at a fixed position  $d_{m,b}$  on the x-axis, and a UE located anywhere with polar coordinates  $\theta \in [0, 2\pi)$  and  $d_{u,b} \in (0, R_{cell}]$  (see Fig. 2).

First, we normalize the distance UE-BS:

$$d_{u,b} = x d_{m,b}. \quad (17)$$

Then, the distance MTD-UE can be calculated as

$$d_{m,u} = d_{m,b} \sqrt{x^2 + 1 - 2x \cos(\theta)}. \quad (18)$$

In order to simplify our analysis, let:

$$A_1 = \frac{(P_{u,T} + P_{m,R})L}{\gamma W_u}, \quad B_1 = \frac{1}{\gamma} \log_2 \left( \frac{K P_u}{N_0 W_u} \right) \quad (19)$$

$$A_2 = \frac{(P_{m,T} + P_{u,R})L}{\gamma W_m}, \quad B_2 = \frac{1}{\gamma} \log_2 \left( \frac{K P_m}{N_0 W_m} \right) \quad (20)$$

Finally, the global energy consumption in relaying mode (14) becomes

$$E_{T,rel} = \frac{A_1}{B_1 - \log_2(d_{u,b})} + \frac{A_2}{B_2 - \log_2(d_{m,u})}. \quad (21)$$

$E_{T,rel}$  has two variables,  $\theta$  and  $x$ . Then, to minimize the energy consumption, we calculate the partial derivatives with respect to  $\theta$  and  $x$  and set it equal to zero searching for a minimum.



a) *Partial derivative with respect to  $\theta$ :*

$$\frac{\partial E_{T,rel}}{\partial \theta} = \frac{A_2 x d_{m,b}^2 \sin(\theta)}{\ln(2) d_{m,u}^2 (B_2 - \log_2(d_{m,u}))^2}. \quad (22)$$

Searching for the critical points, we set  $\frac{\partial E_{T,rel}}{\partial \theta} = 0$ , then we have  $\theta = \{0, \pi\}$ . Analyzing these values,  $E_{T,rel}$  is a minimum when  $\theta = 0$  and is a maximum when  $\theta = \pi$ . Thus, the global energy consumption is minimal when BS, UE, and MTD are aligned. Also, the UE cannot be further away than the MTD ( $x < 1$ ) since we search to minimize the global energy consumption. From (18), we can derive  $d_{m,u}$  for  $\theta = 0$ :

$$d_{m,u} = (1-x)d_{m,b}. \quad (23)$$

Using (17) and (23) in (21) we have

$$E_{T,rel} = \frac{A_1}{B_1 - \log_2(xd_{m,b})} + \frac{A_2}{B_2 - \log_2((1-x)d_{m,b})}. \quad (24)$$

b) *Searching for the global minimum:* In order to simplify our analysis, we consider  $A_2 = A_1$  and  $B_2 = B_1$ . In other words, both the MTD and the UE transmit at the same power ( $P_m = P_u$ ), use the same bandwidth ( $W_m = W_u$ ) and consume the same power when they are in the same state ( $P_{m,T} = P_{u,T}$  and  $P_{m,R} = P_{u,R}$ ). Then, substituting in (24) we have

$$E_{T,rel} = \frac{A_1}{B_1 - \log_2(xd_{m,b})} + \frac{A_1}{B_1 - \log_2((1-x)d_{m,b})}. \quad (25)$$

Using the first partial derivative criteria, we can acquire the critical points solving  $\frac{\partial E_{T,rel}}{\partial x} = 0$ . Thus we have

$$(1-x)(B_1 - \log_2((1-x)d_{m,b}))^2 - x(B_1 - \log_2(xd_{m,b}))^2 = 0, \quad (26)$$

we can find a critical point at  $x = 0.5$ . To determine if this point is a local minimum or a local maximum, we have to calculate the second partial derivative with respect to  $x$  and evaluate it at  $x = 0.5$ :

$$\left. \frac{\partial^2 E_{T,rel}}{\partial x^2} \right|_{x=0.5} = \frac{8A_1(\log_2(e^2 d_{m,b}) - B_1 - 1)}{\ln(2)(B_1 + 1 - \log_2(d_{m,b}))^3}. \quad (27)$$

Using the second derivative criteria, if expression (27) is negative then  $E_{T,rel}$  is concave around  $x = 0.5$  (i.e. a local maximum). On the contrary, if expression (27) is positive then  $E_{T,rel}$  is convex around  $x = 0.5$  (i.e. a local minimum). We know that  $A_1 > 0$  and when  $\eta \gg 1$ , so it can be deduced that  $B_1 > \log_2(d_{m,b})$ . Therefore, in (27),  $E_{T,rel}|_{x=0.5}$  is a local minimum when

$$\log_2(e^2 d_{m,b}) - B_1 - 1 > 0, \quad (28)$$

$$d_{m,b} > 2^{B_1+1}/e^2. \quad (29)$$

From (19),  $B_1 = \frac{1}{\gamma} \log_2 \left( \frac{KP_u}{N_0 W_u} \right)$  then we have

$$d_{m,b} > \frac{2}{e^2} \left( \frac{KP_u}{N_0 W_u} \right)^{1/\gamma}. \quad (30)$$

In conclusion,  $E_{T,rel}|_{x=0.5}$  is a local minimum when condition (30) is satisfied, otherwise it is a local maximum.

Condition (30) only ensure a local minimum at  $x = 0.5$  depending on the distance  $d_{m,b}$ . However, we search for the point where  $E_{T,rel}$  is the global minimum, for which we compare all possible local minima and determine which one is the global minimum.  $E_{T,rel}$  may have three local minima at  $x = 0$ ,  $x = 0.5$  and  $x = 1$ , but by symmetry  $E_{T,rel}|_{x=0} = E_{T,rel}|_{x=1}$ . Therefore, we search for the global minimum comparing  $E_{T,rel}|_{x=0.5}$  and  $E_{T,rel}|_{x=1}$ .

Using expression (25) at  $x = 0.5$  we have

$$E_{T,rel}|_{x=0.5} = \frac{2A_1}{B_1 + 1 - \log_2(d_{m,b})}. \quad (31)$$

$E_{T,rel}|_{x=1}$  is obtained also using expression (25). Physically,  $x = 1$  means that MTD and UE are in the same location. In other words, the receiving power must be equal to the transmission power in the MTD-UE link. Therefore,  $\lim_{x \rightarrow 1} (B_1 - \log_2((1-x)d_{m,b})) = \frac{1}{\gamma} \log_2 \left( \frac{P_m}{N_0 W_m} \right)$ , in (25):

$$E_{T,rel}|_{x=1} = \frac{A_1}{B_1 - \log_2(d_{m,b})} + \frac{A_1}{C}, \quad (32)$$

where

$$C = \frac{1}{\gamma} \log_2 \left( \frac{P_m}{N_0 W_m} \right). \quad (33)$$

$E_{T,rel}|_{x=0.5}$  is the global minimum when:

$$E_{T,rel}|_{x=0.5} < E_{T,rel}|_{x=1}. \quad (34)$$

Substituting (31) and (32) in (34), we have

$$\frac{2A_1}{B_1 + 1 - \log_2(d_{m,b})} < \frac{A_1}{B_1 - \log_2(d_{m,b})} + \frac{A_1}{C}. \quad (35)$$

Expression (35) can be rewritten as

$$Q(\log_2(d_{m,b})) > 0, \quad (36)$$

where

$$Q(y) = y^2 + (C - 2B_1 - 1)y + B_1^2 + B_1 - CB_1 + C. \quad (37)$$

We estimate the discriminant of  $Q(y)$

$$\Delta = C^2 - 6C + 1. \quad (38)$$

If  $\Delta < 0$ , then condition (36) is always satisfied for any value of  $d_{m,b}$ . If  $\Delta > 0$ , then it is satisfied for

$$d_{m,b} < 2^{\frac{2B_1+1-C-\sqrt{\Delta}}{2}} \text{ or } d_{m,b} > 2^{\frac{2B_1+1-C+\sqrt{\Delta}}{2}}. \quad (39)$$

From (19),  $B_1 = \frac{1}{\gamma} \log_2 \left( \frac{KP_u}{N_0 W_u} \right)$  then

$$d_{m,b} < \sqrt{2} \left( \frac{KP_u}{N_0 W_u} \right)^{\frac{1}{\gamma}} 2^{\frac{-C-\sqrt{\Delta}}{2}} \quad (40)$$

or

$$d_{m,b} > \sqrt{2} \left( \frac{KP_u}{N_0 W_u} \right)^{\frac{1}{\gamma}} 2^{\frac{-C+\sqrt{\Delta}}{2}}. \quad (41)$$

In conclusion, if  $\Delta < 0$ , then the global minimum is always  $E_{T,rel}|_{x=0.5}$  for any value of  $d_{m,b}$ . If  $\Delta > 0$ , then  $E_{T,rel}|_{x=0.5}$  is the global minimum only if condition (40) or (41) is satisfied. Otherwise, the global minimum is  $E_{T,rel}|_{x=1}$ . Note that,  $\Delta > 0$  if  $C < 3 - 2\sqrt{2}$  or  $C > 3 + 2\sqrt{2}$ .

#### IV. COMPARISON OF ENERGY CONSUMPTION IN DIRECT MODE AND RELAYING MODE

In this section, we compare the minimum energy consumption in relaying mode and the energy consumption in direct mode. We can rewrite expression (8) as

$$E_{m,dir} = \frac{A_0}{B_0 - \log_2(d_{m,b})}, \quad (42)$$

where  $A_0 = \frac{(P_{m,T} + P_{m,R})L}{\gamma W_m}$  and  $B_0 = \frac{1}{\gamma} \log_2(\frac{KP_m}{N_0 W_m})$ .

$\min(E_{T,rel})$  may be  $E_{T,rel}|_{x=1}$  or  $E_{T,rel}|_{x=0.5}$  depending on  $d_{b,m}$  as we have determined in section III. By doing a simple analysis, we conclude that  $E_{T,rel}|_{x=1}$  is never less than  $E_{m,dir}$ . Therefore, we analyze only the scenario where  $E_{T,rel}|_{x=0.5}$  is the minimum energy consumption in relaying mode, then  $\min(E_{T,rel})$  is less than  $E_{m,dir}$  when:

$$E_{T,rel}|_{x=0.5} < E_{m,dir}, \quad (43)$$

$$\frac{2A_1}{B_1 - \log_2(0.5d_{m,b})} < \frac{A_0}{B_0 - \log_2(d_{m,b})}. \quad (44)$$

Considering  $A_0 = A_1$  and  $B_0 = B_1$  (i.e.  $P_m = P_u$ ,  $W_m = W_u$ ,  $P_{m,T} = P_{u,T}$ , and  $P_{m,R} = P_{u,R}$ ), then

$$\frac{2A_1}{B_1 - \log_2(0.5d_{m,b})} < \frac{A_1}{B_1 - \log_2(d_{m,b})}, \quad (45)$$

$$d_{m,b} > 2^{B_1-1}. \quad (46)$$

From (19),  $B_1 = \frac{1}{\gamma} \log_2\left(\frac{KP_u}{N_0 W_u}\right)$  then we have

$$d_{m,b} > \frac{1}{2} \left( \frac{KP_u}{N_0 W_u} \right)^{1/\gamma}. \quad (47)$$

Therefore, (47) is a condition so that the minimum global energy consumption in relaying mode is less than in direct mode.

#### V. SIMULATION RESULTS

Using the simulation parameters specified in Table I in (30) we deduce that  $E_{T,rel}|_{x=0.5}$  is a local maximum when  $d_{m,b} < 346$  meters and is a local minimum when  $d_{m,b} > 346$  meters. From (38), we have  $\Delta \approx 78$ . Then, from (40) and (41), we have  $\min E_{T,rel} = E_{T,rel}|_{x=0.5}$  if  $d_{m,b} < 1$  meter or  $d_{m,b} > 548$  meters, and  $\min E_{T,rel} = E_{T,rel}|_{x=1}$  if  $1 < d_{m,b} < 548$  meters.

Finally, we compare the above results deduced analytically with a simulation performed using MATLAB. In Fig. 4, we plot the global energy consumption in relaying mode as a function of the distance  $d_{u,b}$  normalized ( $d_{u,b}/d_{m,b}$ ) when the BS, the UE, and the MTD are aligned. We compare the behavior of  $E_{T,rel}$  for  $d_{m,b} = \{200, 400, 600, 800, 1000\}$  meters. As shown in this figure,  $E_{T,rel}$  is minimum at  $x = 0.5$  for  $d_{m,b} = \{600, 800, 1000\}$  meters.

Furthermore, in a scenario where the BS, the UE, and the MTD are aligned, we compare the global energy consumption in direct mode and relaying mode. Simulation results are shown in Fig. 5. Using the simulation parameters in (47), we estimate that the global energy consumption in relaying mode

TABLE I  
SIMULATION PARAMETERS

Parameter	Assumption
Carrier Frequency ( $f_c$ )	900 MHz
MTD transmission power ( $P_m$ )	23 dBm
UE transmission power ( $P_u$ )	23 dBm
Packet Size ( $L$ )	200 bytes
UE power consumption in Tx state ( $P_{u,T}$ )	545 mW
UE power consumption in Rx state ( $P_{u,R}$ )	90 mW
MTD power consumption in Tx state ( $P_{m,T}$ )	545 mW
MTD power consumption in Rx state ( $P_{m,R}$ )	90 mW
MTD Bandwidth ( $W_m$ )	1.4 MHz
UE Bandwidth ( $W_u$ )	1.4 MHz
Noise Power Spectrum Density ( $N_0$ )	-174 dBm/Hz
Cell radius ( $R_{cell}$ )	1000 meters
Path loss exponent ( $\gamma$ )	3.67
Constant path loss factor <sup>1</sup> ( $K$ )	0.0070

<sup>1</sup>Transmitter-Receiver distance in meters.

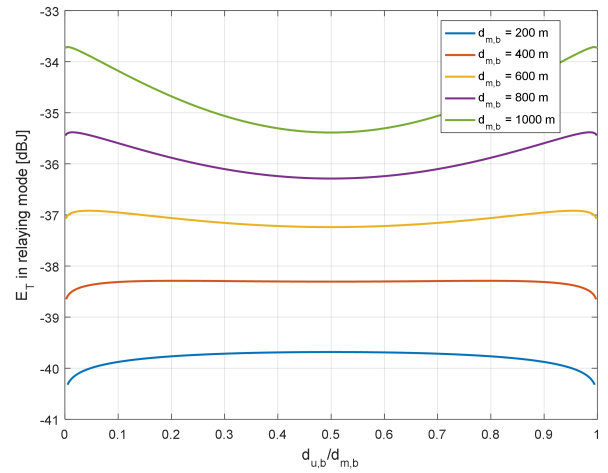


Fig. 4.  $E_{T,rel}$  as a function of the distance  $d_{u,b}$  normalized, considering BS, UE and MTD aligned.

can be less than in direct mode when  $d_{m,b} > 640$  meters. This condition deduced analytically can be verified by simulation.

So far, our work has been focused on searching a point in the cell where the global energy consumption in relaying mode is the lowest possible. However, in a realistic scenario, it is difficult or even impossible to find a UE located just at that point since UEs are distributed randomly in the cell. Therefore, we calculate the global energy consumption by sub-regions. We determine in which sub-regions the energy consumption is the lowest with a probability  $\mathcal{P}$  of finding one or more UEs in these sub-regions. We use MATLAB to calculate the global energy consumption  $E_{T,rel}$  in the whole cell, according to expression (14) and considering the simulation parameters given in Table I. To calculate  $E_{T,rel}$  depending on the relay location  $(x_u, y_u)$ , we follow these steps:

- 1) Subdivide the plane into sub-regions (small squares)
- 2) For each sub-region, we calculate the  $E_{T,rel}$  considering a relay in the center of this sub-region.

Fig. 6 shows the global energy consumption when  $d_{m,b} =$

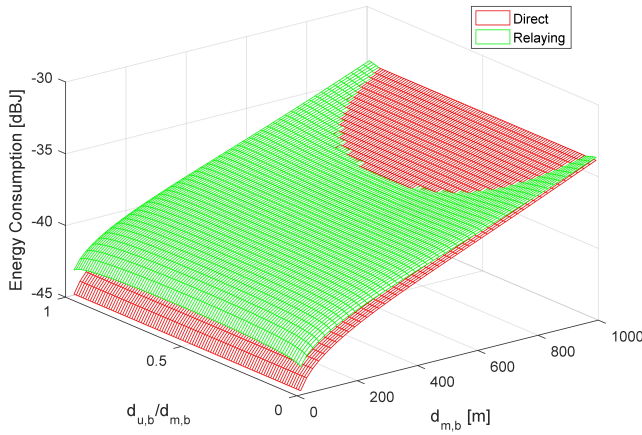


Fig. 5. Energy consumption in direct versus relaying mode as a function of the normalized distance  $d_{u,b}/d_{m,b}$  and  $d_{m,b}$ , considering that the BS, the UE, and the MTD are aligned.

800 meters. We also calculate the energy consumption in direct mode ( $\approx -35.74$  dBJ) which is represented by a white oval in this figure. The sub-region where the global energy consumption is the lowest is located at the midpoint between the BS and the MTD as shown in the figure. Furthermore, as we have determined when  $d_{m,b} > 640$  meters, the energy consumption in relaying mode may be less than in direct mode in some sub-regions.

In Fig. 6, the energy consumption in relaying mode would be less than in direct mode if there were at least one relay within the area enclosed by the white oval. We remark using simulations for different  $d_{m,b}$  values that this area tends to increase when  $d_{m,b}$  increases, so the probability of finding a relay within this area will also increase as a function of  $d_{m,b}$ . Using a nearby UE as a relay, from an MTD point of view implies the reduction of the MTD energy consumption. However, from a global point of view (MTD and relay), the global energy consumption could be reduced only if a relay is selected appropriately. An optimal selection of relay depends on the location of the MTD and the location of the relay.

## VI. CONCLUSION AND FUTURE WORKS

In this paper, we have analyzed the behavior of energy consumption in relaying mode depending on the distance between the transmitter, the relay, and the base station. Furthermore, we have shown the interest of a D2D relay mechanism compared with a direct link with an unfavorable link budget (MTD far from the base station).

An important future work is to extend the energy consumption model considering the power control and the synchronization phase (discovery process). We also plan to consider a cost function weighting the global energy consumption model.

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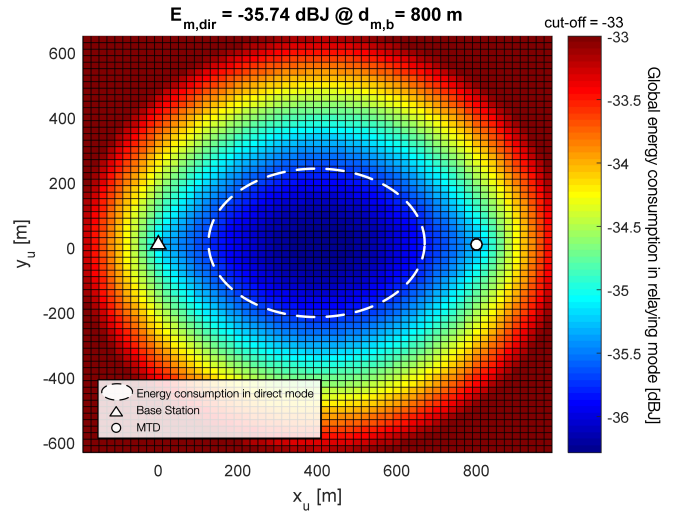


Fig. 6. Global energy consumption depending on the UE location, for  $d_{m,b} = 800$  meters.

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