D2D Mobile Relaying for Efficient Throughput-Reliability Delivering in 5G

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Abstract: **Ensuring high reliability is one of the major goals of 5G systems. This work investigates the problem of cooperative relaying and the optimal number of devices to be directly connected to the base station, in order to meet best uplink performance in terms of throughput and reliability. We first propose a D2D-relaying system where devices cooperate forming groups of cellular devices serving as relays to other groups of D2D transmitters. Second we adopt a Markov chain framework, where the states are defined as the numbers of D2D-relays present in the network. Based on that, we derive the average network throughput and reliability. Next, we show that there exists an optimal device distribution, that maximizes the overall reliability and throughput. This number is strongly related to the switching probabilities of the devices and the network parameters such as the orthogonality factor, the cooperation level of D2D-transmitter, the network density and the cluster's radius. Simulation results illustrate the optimal switching probabilities and the average number of D2D-relays that maximize the overall throughput and reliability.**

keywords: **5G, Reliability, D2D-relaying, markov chain, cooperation, outage probability**

I. INTRODUCTION

To cope with the traffic increase, D2D-relaying communication has been proposed as a new way to enhance network performance by offloading the traffic to D2D-relays with better channel quality. D2D communication allows devices to communicate directly between each other rather than going through a base station (BS) or access point (AP) [1]. The concept of using D2D communication for relaying information has been introduced to improve network performance by offloading traffic to other devices in the network, thus mitigating wireless fading by reducing path loss and exploiting spatial diversity, as well as reducing interference, which is an efficient way to improve the capacity, the cell coverage, enhance the throughput, the quality of service (QoS) as well as the reliability of transmissions [2],[3]. This is due to the fact that D2D communications benefit from a shorter link distance and fewer hops, which is beneficial from a reliability perspective [4].

Reliability is defined as the success of delivering a packet to the receiver. It guarantees that messages are successfully delivered within low outage probability (i.e. they are not erroneous or lost or arrived late) [5],[6]. The main factors affecting reliability stem from: (i) collisions with other users due to uncoordinated channel access; (ii) coexistence with other systems in the same frequency channels; (iii) interference from users in adjacent channels; (iv) Doppler shifts from moving devices, difficulty of synchronization, outdated CSI; (v) congested cells as well as (vi) time-varying channel effects or delayed packet reception [7].

To improve communication reliability, several techniques have been studied, including modulation techniques, redundancy (different carriers and transmission points), diversity (in frequency and space), multi-connectivity, caching [5],[6], retransmission mechanisms (for error correction) [7] and packet duplication [8],[9]. Among these, ensuring a high reliability can also be achieved by leveraging D2D communication between devices. In [10]-[13], authors discussed the benefits of D2D communication in offloading the network, improving reliability, and enhancing capacity. In [14] the authors propose to combine M2M with D2D to benefit from low transmit power and then to enable efficient resource sharing. Moreover, in [15], D2D communications between IoT devices has been studied focusing on providing connectivity to the maximum number of IoT devices. To improve reliability of high-rate millimeter-wave (mmWave) data connections, D2D-enabled collaborative caching at the wireless edge was shown to constitute a promising solution for augmenting system-level performance and improving data acquisition reliability [16]. In addition to that, tactile internet has also relied on cooperation to reduce the total energy consumption, enhance the reliability as well as the intelligence of Tactile Internet by enabling mobile edge devices to share their communication, computation, and caching (3C) resources via device-to-device (D2D) connections [17].

In this paper, we develop an analytical model to investigate the performance of a network composed of two groups of devices; cellular devices and D2D devices. The group of devices that decide to switch to D2D mode, will relay via cellular devices of the other group to transmit their data in the uplink. A Markov chain is developed to, first, predict average number of cellular devices depending on the devices' probabilities of switching and, second, to analyze the average throughput and outage probability of the network. We characterize the optimal switching probabilities and the average number of D2D-relays that maximize the overall throughput and reliability.

In general, the application of a Markov approximation framework is suitable for solving combinatorial optimization problems. The works in [18], [19], [20], [21] have relied on Markov chains to solve optimization problems in D2D communication and analyse the performance by casting the states as power communication mode, number of packets and energy level.

The main contributions of this work are summarized as follows:

- We present a D2D-relaying model that allows devices to switch from the competitive mode to the cooperative mode.
- A Markov chain framework has been developed to find the steady state and predict the expressions of the network performance metrics namely outage probability and throughput.
- We conclude the optimal switching probabilities as well as the average number of D2D-relays that lead to a maximum overall throughput and reliability.
- We provide analysis of results on different parameter settings and simulation results prove that there exit optimal number of devices that maximizes the overall throughput and reliability.

The structure of the paper is organized as follows: System model is defined in Section II. Problem formulation is discussed in Section III. Markov chain is analyzed in Section IV. Expressions for performance metrics are derived in Section V. Numerical investigation and analysis are presented in Section VI. Finally, concluding remarks and future work are presented in Section VII.

II. NETWORK MODEL

Consider an infinite space with infinitely many devices whose distribution follows homogeneous Poisson point process (PPP) with density of μ (the average number of devices per unit area). In our model, we focus on a circular area with a radius R_{BS} representing the coverage of a BS located at the center and serving a finite and fixed number of devices in an uplink cellular communication. The number of devices within any given area A is given by:

$$Pr[N(A) = n] = \frac{(\mu A)^n}{n!} e^{-\mu A}, \quad (1)$$

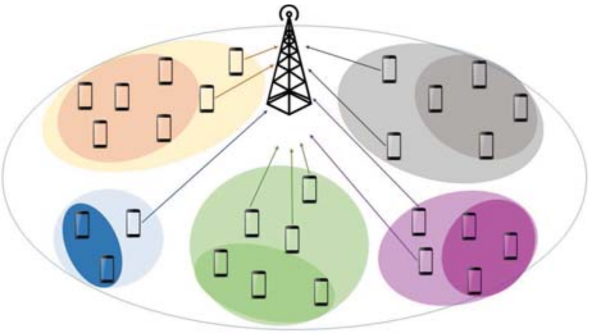

Fig. 1. Clusters Organization in an Uplink Cellular Communication

Note that, the average number of devices in a given area is equal to the density of the devices multiplied by the size of that area.

All the devices are communicating with a base station through fading channels. Of course, during cellular communication, each device is affected by cellular interference of all the other devices, especially those in its vicinity. This leads principally to reducing the performance of the wireless communication system; reducing its throughput as well as affecting its reliability. Without forgetting that network congestion and fading channels are also other potential factors for performance deterioration. In order to mitigate such effects, we propose for devices to switch from the competition mode (cellular communication) to the cooperation mode (D2D communication). The underlying idea is that instead of all devices communicate with the base station, some of them act as D2D-relays while others switch to communicate through D2D link. This cooperation is beneficial from many sides: Apart from the network congestion that decreases, it also leads to less interference for both cellular and D2D devices, the outage probability decreases, the throughput is enhanced and the reliability is improved.

To elaborate further, as Fig. 1 shows, the devices are first efficiently organized based on the spatial proximity and mutual interests [22] in such a way to guarantee a reliable service. Then, each cluster contains cellular devices in cooperation with D2D devices. The cluster is then divided into 2 groups, each with random number of devices, as shown in fig 2, where a group represents cellular devices that will serve as D2D-relays and the other group represents D2D-transmitters.

III. PROBLEM FORMULATION

We consider a base station serving many clusters. Each cluster with a radius R_{cl} contains m devices, with m is equal to the density of the devices multiplied by the size of the area of the cluster (i.e. $m = \mu A_{cl} = \mu\pi R_{cl}^2$). n devices D_i with i $\in$ N={1,2,...,n} remain in the cellular communication and serve as D2D-relays to $(m - n)$ D2D-transmitters. A device has the right to quit the cellular side and to go back to it whenever it wants, it is a random and reversible process. At the beginning of each frame, each device decides, simultaneously, whether to communicate through cellular or D2D link. Overall, each device makes a decision to leave its current group and join another group if in the new group, the network occurs higher transmission rate and higher reliability than the one incurred when it is in its current group.

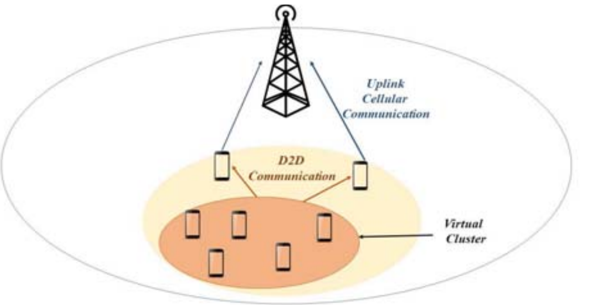

Fig. 2. Uplink D2D cooperation representing two groups of devices: D2D-relays (cellular devices) and D2D-transmitters

We consider a communication reliable if and only if its SINR is larger than a given threshold γ_{th}. In other words, if the transmission rate doesn't exceed the capacity of the channel.

The reliability depends, then, on many parameters: let P_i be the transmit power of device i, and let σ^2 denotes the variance of the thermal additive white Gaussian noise, h_i is the gain experienced by device i over the fading channel and let's take d_i as the distance that separates the device i from its serving base station and α as the path-loss exponent. Assuming that the inter-clusters interference are neglected, and the multiple access technology utilized is OMA (Orthogonal Multiple Access) based on SC-FDMA for uplink, the instantaneous SINR of device i transmitted to the BS is given by:

$$SINR_i = \frac{P_i|h_i|^2 d_i^{-\alpha}}{\sigma^2 + \sum_{j\in N\setminus\{i\}} \beta_{i,j} P_j |h_j|^2 d_j^{-\alpha}} \tag{2}$$

where $\beta_{i,j}$ denotes the orthogonality factor between the transmitter and the interfering signals. Theoretically, if there is a perfect synchronization of time and frequency, there will be no interference and the sub-channels will be considered orthogonal. However, in real networks, there can always be a fraction of interference that we noted β. Note that in what follows we consider the orthogonality factor symmetrical for all signals.

Let's define the throughput of a transmission as the rate of successful information bits that are delivered to the destination over a communication channel, it is directly affected by the outage probability, thus principally by the device's transmission power, interference, the transmission distance, the channel gain as well as the number of devices in the network as it is seen in equations 3 and 7.

$$\Theta(\gamma) = \frac{M}{L} R(1 - P_{out}(\gamma)), \tag{3}$$

M is the data payload length (i.e. number of information bits). L denotes the total number of bits in a frame with L = M+H data bits, H is the header's length. R is the fixed transmission rate. P_{out} denotes the probability of outage; it represents the probability that the SINR is less than a given SINR threshold (γ_{th}), i.e.

$$P_{out}^i = Pr(SINR_i \leq \gamma_{th}) \tag{4}$$

Then, the outage probability of device i P_{out}^i is calculated as follows:

$$\begin{aligned} P_{out}^i =& Pr\left(\frac{P_i|h_i|^2 d_i^{-\alpha}}{\sigma_N^2 + \beta\sum_{j\in N\setminus\{i\}} P_j|h_j|^2 d_j^{-\alpha}} \leq \gamma_{th}\right) \\ &= Pr\left(|h_i|^2 \leq \frac{\gamma_{th}\sigma_N^2}{P_i d_i^{-\alpha}} + \frac{\gamma_{th}\beta}{P_i d_i^{-\alpha}} \sum_{j\in N\setminus\{i\}} P_j|h_j|^2 d_j^{-\alpha}\right) \\ &= \int_0^{+\infty} f_{|h_{n-1}|^2}(x_{n-1}) \int_0^{+\infty} f_{|h_{n-2}|^2}(x_{n-2})... \\ &\int_0^{+\infty} f_{|h_1|^2}(x_1) \int_0^{A} f_{|h_i|^2}(x_i)\, \mathrm{d}x_i \mathrm{d}x_1 ... \mathrm{d}x_{n-1}, \end{aligned} \tag{5}$$

with $A = \frac{\gamma_{th}\sigma_N^2}{P_i d_i^{-\alpha}} + \frac{\gamma_{th}\beta}{P_i d_i^{-\alpha}} \sum_{j\in N\setminus\{i\}} P_j|h_j|^2 d_j^{-\alpha}$. All channels are assumed to undergo Rayleigh fading, then the channel power gain $|h|^2$ is an exponential random variable with PDF:

$$f_{|h|^2}(x, \lambda) = \lambda e^{-\lambda x}, \tag{6}$$

where $\frac{1}{\lambda} \geq 0$ is the mean and scale parameter of the distribution, often taken equal to 1. Therefore, the outage probability can be expressed as follows:

$$P_{out}^i = 1 - \frac{\left(\Pi_{j\in N\setminus\{i\}}\lambda_j\right) e^{-\frac{\gamma_{th}\sigma_N^2\lambda_i}{P_i d_i^{-\alpha}}}}{\Pi_{j\in N\setminus\{i\}}\left(\lambda_j + \frac{\beta\gamma_{th}P_j d_j^{-\alpha}}{P_i d_i^{-\alpha}}\lambda_i\right)} \tag{7}$$

IV. MARKOV ANALYSIS

To find the solution of stable group formation and analyze the network performance, we formulate a discrete-time Markov chain. The state of the Markov chain can be expressed as the set of devices in the cellular group. The transition from one state to another depends on the probabilities of devices to switch from a group to another.

We use the Markov chain analysis to obtain the optimal switching probabilities that lead to a maximum overall throughput and reliability. At the beginning of each frame some devices switch from cellular to D2D, whereas others from D2D to cellular while others remain in their states as Fig.3 shows.

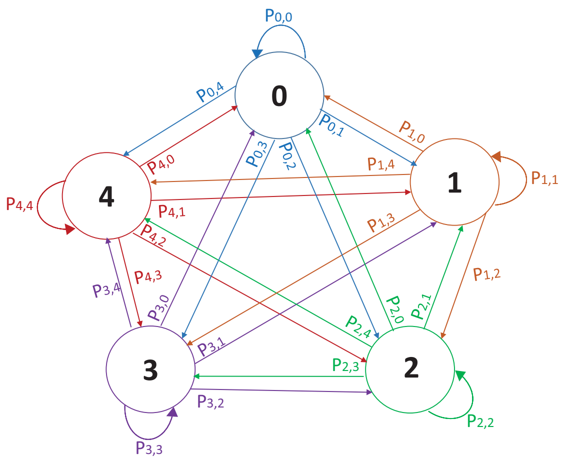

Fig. 3. Markov chain for the four-device case. The state of the system is the number of devices communicating through the cellular link, it can increase or decrease by an arbitrary amount less than or equal m-n (m=4 in this case).

A. Switching probabilities

The probability of a device to switch from cellular to D2D communication follows a Bernoulli process with parameter $q_{c,d}$ (i.e. at the beginning of each frame, there is a probability $q_{c,d}$ that a device switches from cellular to D2D). Similarly we consider that a device switches from D2D to cellular communication with probability $q_{d,c}$. The switching processes of different devices in each frame are assumed to be independent.

Recall that we consider as a state of the system the stochastic process representing the number of devices that communicate through the cellular link. The state decreases by the number of devices that decide to switch from cellular to D2D and increases if it is the opposite.

Our process is similar to birth-death but the state in our case could decrease or increase with one or more, where a birth is equivalent to the arrival of new devices to the cellular side while a death is their departure.

Assume that at the beginning of each frame, there are n devices in cellular communication, m devices in the network, then $m - n$ devices in D2D communication. Each device decides independently and simultaneously whether to stay in that state or to switch to the other one. Let $Q_{c,d}(i,n)$ be the probability that i out of n devices switch from cellular to D2D communication.

$$Q_{c,d}(i,n) = \binom{n}{i} q_{c,d}^{i}(1 - q_{c,d})^{n-i} \tag{8}$$

We denote by $Q_{d,c}(i,n)$ the probability that i devices switch from D2D to cellular communication knowing that there are n devices in the cellular side.

$$Q_{d,c}(i,n) = \binom{m-n}{i} q_{d,c}^{i}(1 - q_{d,c})^{m-n-i} \tag{9}$$

Let $Q_{c,d}(i,0)$= 0 and $Q_{d,c}(i,m)$= 0

For any choice of values $q_{c,d}$ and $q_{d,c}$ ∈ [0,1[we obtain transition probabilities that define the Markov chain and that lead to either increasing or decreasing the number of devices in both groups.

B. Transition Probability:

Let $P_{n,n+i}$ be the transition probability of the system that gives the probability of switching from a state to another at each frame. Based on the probability that a player switches from a group to another, the transition probability from state n to state n+i can be found in the following system of equations:

$$P_{n,n+i} = \begin{cases} \sum\limits_{k=0}^{n} Q_{c,d}(k,n) Q_{d,c}(i+k,n), & 0 \leq i \leq m-n \\ \sum\limits_{k=0}^{n+i} Q_{c,d}(-i+k,n) Q_{d,c}(k,n), & -n \leq i < 0 \\ 0 & i > m-n \end{cases}$$

C. Steady state probability

Let's denote by $\pi_n(q)$ the equilibrium probability that the network is in state n. We have $m+1$ discrete states where a state can be increased or decreased arbitrarily. The 0-th and m-th states respectively denotes that the group of D2D-relays is empty and the group is totally full. Given the transition matrix $P(q)$, the stationary probability vector $\Pi(\vec{q})$ can be obtained by solving the following equilibrium state equations:

$$\begin{cases} \Pi(\vec{q}) = \Pi(\vec{q}) \cdot P(q) \\ \sum\limits_{n=0}^{m} \pi_n(q) = 1, \\ \pi_n(q) \geq 0 \end{cases} \tag{10}$$

with: $\Pi(\vec{q}) = [\pi_0(q), \pi_1(q), \pi_2(q), ..., \pi_m(q)]$ for $n = 0, 1, ..., m$, where q is the probability of switching and P(q) is the transition matrix defined as:

$$P(q) = \begin{pmatrix} P_{0,0}(q) & P_{0,1}(q) & .. & P_{0,i}(q) & .. & P_{0,m}(q) \\ P_{1,0}(q) & P_{1,1}(q) & .. & P_{1,i}(q) & .. & P_{1,m}(q) \\ P_{2,0}(q) & P_{2,1}(q) & .. & P_{2,i}(q) & ... & P_{2,m}(q) \\ . & . & .. & . & .. & . \\ . & . & .. & . & .. & . \\ P_{i,0}(q) & P_{i,1}(q) & .. & P_{i,i}(q) & .... & P_{i,m}(q) \\ . & . & .. & . & .. & . \\ . & . & .. & . & .. & . \\ P_{m,0}(q) & P_{m,1}(q) & .. & P_{m,i}(q) & .. & P_{m,m}(q) \end{pmatrix} \tag{11}$$

As a result, the average number of cellular devices is given by:

$$\bar{n} = \sum_{n=0}^{m} n.\pi_n(q) \tag{12}$$

Then, the average number of devices in D2D side is: $m - \bar{n}$

V. RELIABILITY AND THROUGHPUT

To characterize the network performance, we derive closed-form expressions for the overall reliability and throughput using different transition probabilities found in the above Section. Those performance metrics depend on the average number of D2D-relays and D2D-transmitters present in the network.

A. Network's Reliability

The reliability of a system is defined as the probability that a system performs its intended function under specific requirements and stated conditions. For our system, we be consider the reliability as the probability of successful transmission, so it is inversely proportional to the outage probability. The less the outage, the better the reliability.

We consider the network's outage probability $\bar{P}_{out}$ as the mean of cellular and D2D outage probabilities:

$$\bar{P}_{out}(\bar{n}) = \frac{P_{out}^{C}(\bar{n}).\bar{n} + D_p.(m - \bar{n})}{m}, \tag{13}$$

with: $D_p = P_{out}^{D}(\bar{n}) + (1 - P_{out}^{D}(\bar{n})) P_{out}^{C}(\bar{n})$ is the end to end outage probability for D2D transmitters.

P_{out}^{C} is the cellular outage probability, calculated through relaying on stochastic geometry. We consider each cellular device associates with its serving BS randomly distributed within a given average distance d_c from it and given by:

$$P_{out}^{C}(\bar{n}) = 1 - \frac{e^{-\frac{\gamma_{th}\sigma_N^2}{P_i d_c^{-\alpha_c}}}}{(1 + \beta\gamma_{th})^{\bar{n}-1}}, \tag{14}$$

Note that we consider the devices transmitting with the same power in order to simplify the calculus.

Besides, based on the fact that the number of devices has a Poisson distribution but their location follows the uniform distribution over the area, we consider the average distances between different devices in the network.

$$f_{d_c}(r) = \frac{2r}{R_{BS}^2} \tag{15}$$

Concerning D2D communication, the outage probability for each D2D user can be expressed as: $P_{out}^{D}(\bar{n}) =$

$\frac{P_{out}^{d,r}(\bar{n})+(\bar{n}-1)*P_{out}^{d2d}(\bar{n})}{\bar{n}}$, with $P_{out}^{d,r}$ is the outage probability for communicating with the closest relay, while P_{out}^{d2d} happens when communicating with the other D2D-relays.

$$P_{out}^{d,r}(\bar{n}) = 1 - \frac{e^{-\frac{\gamma_{th}\sigma_N^2}{P_i d_{d,r}^{-\alpha_d}}}}{\left(1+\beta\gamma_{th}\frac{d_{d2d}^{-\alpha_d}}{d_{d,r}^{-\alpha_d}}\right)^{m-\bar{n}-1}} \tag{16}$$

$$P_{out}^{d2d}(\bar{n}) = 1 - \frac{e^{-\frac{\gamma_{th}\sigma_N^2}{P_i d_{d2d}^{-\alpha_d}}}}{(1+\beta\gamma_{th})^{m-\bar{n}-1}}, \tag{17}$$

Each D2D-transmitter communicates with the closest relay (less power transmission, less path loss ...) through a distance $d_{d,r}$. It has a Rayleigh distribution and is given by:

$$f_{d_{d,r}}(r) = 2\pi\mu r e^{-\mu\pi r^2}, \quad \text{for} \quad 0 \leq r \leq \infty \tag{18}$$

with parameter: $\sigma = \frac{1}{\mu\pi\sqrt{2}}$. As we are interested in a restricted domain where r does not exceed D; D = $min\{D_{max}, 2R_{cl}\}$; D_{max} is the maximum distance allowable between D2D devices and R_{cl} is the radius of the cluster. So we use a truncated distribution given by:

$$\begin{cases} f_{d_{d,r}}^{T}(r) = \frac{f_{d_{d,r}}(r)}{F(D)} \quad \text{for} \quad 0 \leq r \leq D \\ \\ 0 \quad else; \end{cases} \tag{19}$$

With F(.) denotes the cumulative distribution function (CDF) given by:

$$F(D) = 1 - e^{-\mu\pi D^2} \tag{20}$$

While for D2D interference, each D2D-transmitter associates with each D2D-relay within a given distance d_{d2d} from it. This distance follows the uniform distribution and can be expressed as:

$$f_{d_{d2d}}(r) = \frac{2r}{R_{cl}^2} \tag{21}$$

The average distances of the above cases will be concluded from the following expression:

$$d = E[r] = \int r f(r) \quad dr \tag{22}$$

B. Network's Throughput

As mentioned earlier, devices that switch from cellular to D2D communication relay on devices that stayed connected to the BS, to transmit their data.

Besides, each device that acts as both a cellular user and a relay sends a large packet to the BS combining the two packets (i.e. its packet and D2D devices packets). In other words the relay device will not use the whole throughput assigned from the BS to itself, it, instead, uses a part of it x to itself and let $1-x$ to D2D devices. Based on that, and also on the fact that D2D devices communicate through the outband mode (i.e. there is no interference between cellular and D2D communication), the system throughput is given by:

$$Thp(\bar{n}) = \frac{Thp_c(\bar{n}).\bar{n} + Thp_D(\bar{n}).(m-\bar{n})}{m}, \tag{23}$$

with $Thp_c(\bar{n})$ denotes the throughput each cellular device has in each frame during cellular uplink communication:

$$Thp_c(\bar{n}) = \begin{cases} x\Theta & \bar{n} \neq m \\ \Theta & \bar{n} = m, \end{cases} \tag{24}$$

and $Thp_D(\bar{n})$ is the average throughput each device earns during D2D communication. All D2D-transmitters benefit equally from the fraction of throughput given from D2D-relays, and each device takes a fraction of throughput from its closest device and from the all other D2D-relays present in the cellular group.

$$Thp_D(\bar{n}) = \begin{cases} \frac{(1-x)\Theta\left((1-P_{out}^{d,r})+(\bar{n}-1)(1-P_{out}^{d2d})\right)}{m-\bar{n}} & \bar{n} \neq m, \\ 0 \quad \bar{n} = m \end{cases} \tag{25}$$

C. Solution of the optimization problem

The throughput and reliability issues are therefore given by the following optimization problems:

$$\max_q Thp(\bar{n}) s.t. \begin{cases} \Pi(q) = \Pi(q).P(q) \\ \\ \sum_{n=0}^{m} \pi_n(q) = 1, \\ \\ \pi_n(q) \geq 0 \end{cases} \tag{26}$$

$$\min_q \bar{P}_{out}(\bar{n}) s.t. \begin{cases} \Pi(q) = \Pi(q).P(q) \\ \\ \sum_{n=0}^{m} \pi_n(q) = 1, \\ \\ \pi_n(q) \geq 0 \end{cases} \tag{27}$$

To explain more, a solution to this problem can be obtained by computing recursively the steady state probabilities, that leads to conclude $\bar{n}$ (i.e. average number of cellular devices). Then, an explicit expression for $Thp(\bar{n})$ and $\bar{P}_{out}(\bar{n})$, as a function of $\bar{n}$ and q^o (i.e. optimal switching probabilities), could be obtained. For each $q \in [0, 1[$, we obtain a certain throughput and outage probability. The maximum value of all those throughput values and the minimum value of all those outage probabilities lead up to q^o (i.e. the optimum switching probability) and to the optimum number of cellular devices that satisfy a maximum throughput and reliability, as it will be seen in the sequel.

VI. NUMERICAL INVESTIGATION & ANALYSIS

In this section we obtain the optimal switching probabilities that solve the optimization problem. We find $q_{d,c}^o$ and $q_{c,d}^o$ that maximize the network's average throughput and reliability. The average number of D2D-relays that maximizes the network's performance could be concluded from equation 12. The following figures are plotted for P_i= 0.1W, $P_{d2d} = 0.05$W, R = 1Mbit/s, L = M = 1024bits, γ_{th} = 2, α_c = 3, α_d = 2 and $\sigma_N^2 = -116$ dBm, R_{BS} = 2.10^3 m, $D_{max} = R_{cl} = 500m$, and $x = 0.2$.

Fig. 4 shows the impact of the switching probabilities on the average number of cellular devices present in the cluster. We observe that the average number of cellular devices increases as q_{cd} decreases while q_{dc} increases. The less the probability of switching from cellular to D2D or the higher probability of switching from D2D to cellular, the devices tend to join the

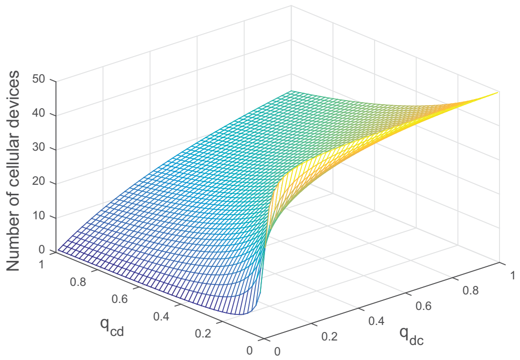

Fig. 4. Average Number of Cellular Devices function of the Switching Probabilities (q)

cellular group and vice versa. If the probability of devices to switch from cellular to D2D group increases, then the transition probability from a state n to a state n+i with $i \geq 0$ gets higher too which explains the increase in the average number of cellular devices. While if it is the probability of switching from cellular to D2D that increases, the transition probability from a state n to a state n+i with $i \leq 0$ gets higher, so the number of D2D devices increases, which explains the decrease in the average number of cellular devices.

A. Maximum Throughput

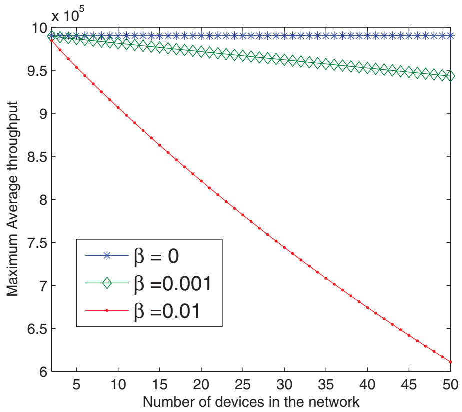

Fig. 5. Maximum throughput obtained from different values of q, function of the number of devices in the network and of the orthogonality factor β

Fig. 5 reports the impact of the network's density μ, the radius of the cluster (i.e. $m = \mu\pi R_{cl}^2$) and the orthogonality factor on the network's maximum average throughput. β is a random parameter that depends on the network, we take some possible values of it in this work in order to study its impact on the network's performance and on the optimal switching probabilities. Here, the maximum throughput $Thp_{max}(\bar{n})$ decreases with the increase of the number of devices in the network, which includes either the rise of μ or R_{cl} and with the increase of β.

The fall in $Thp_{max}(\bar{n})$ with the increase of m is due to the network congestion that leads to bad channels conditions, reduced quality of service and high outage probability, on the other hand, the increase of β causes high interference that affects directly the network's capacity.

The throughput and the capacity of the network are then reduced if the network is more crowded, the radius of the cluster is higher and if β increases too.

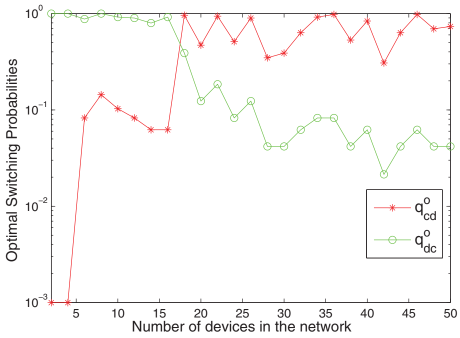

Fig. 6. Optimum Switching Probabilities q^o that lead up to a **maximum throughput**, with respect to the number of devices in the network

We explore the impact of q_{cd}^o and q_{dc}^o and m on the average throughput in Fig.6. q_{cd}^o and q_{dc}^o are the optimum probabilities of switching from cellular to D2D and from D2D to cellular, respectively, that lead to a maximum throughput. We notice that in the case of few number of devices, the maximum throughput is reached for a low q_{cd}^o and a high q_{dc}^o. While for a high number of devices (i.e., the network is more crowded) the maximum throughput is attained for a small value of q_{dc}^o and a high q_{cd}^o.

For few m, $Thp_{max}(\bar{n})$ is attained with the increase of q_{dc}^o and the decrease of q_{cd}^o, so the increase of cellular devices. This is because there is no need for D2D devices in this case, interference are low, the network is not crowded and the quality of service is good, so it is not beneficial for a device to share its throughput. While for high m, devices accept to give a fraction of their throughput in order to get rid of interference as much as possible and to have a less crowded network, hence the increase of q_{cd}^o and the decrease of q_{dc}^o, thus the rise in the number of D2D devices.

B. Reliable Communication

In this subsection we study the effects of the network's density, the radius of the cluster as well as the orthogonality factor on the outage probability, so on the reliability.

Fig.7 outlines the effect of q_{cd}^o, q_{dc}^o and m on the reliability. We notice that the minimum outage probability is attained when q_{cd}^o is high and q_{dc}^o is low. The maximum reliability is then reached by increasing the number of D2D devices in comparison with cellular devices. This is because having a high number of D2D-devices leads to minimizing interference and using less transmission power which decreases the outage probability and increases the overall reliability.

In Fig. 8 we plot the minimum outage probability function of m and β. We notice that the less the orthogonality factor (i.e. the less interference), the less the outage probability, thus the high the overall reliability. Also, the outage probability increases with the increase of m, that is to say, with the increase of μ and R_{cl}. This is due to the fact that a good orthogonality (i.e., small β) decreases interference, which leads to high reliability. Moreover, having many devices in the network decreases the

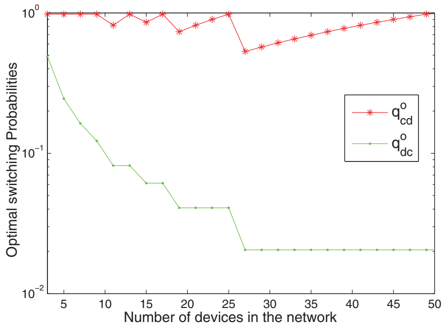

Fig. 7. Optimum Switching Probabilities q^o that lead up to a **minimum outage probability**, function of the number of devices in the network

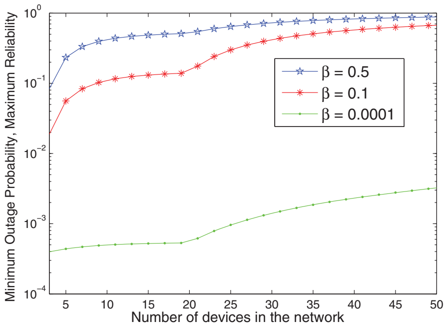

Fig. 8. Minimum outage probability (i.e., maximum reliability) obtained from different values of q, function of the number of devices in the network and of the orthogonality factor β

capacity and the quality of service which minimizes the overall reliability.

Roughly speaking, a device prefers to switch from a group to another if the overall throughput and reliability will be better in comparison to those if it stays in that group. Generally, network congestion, interference, orthogonality factor, power transmission, device's battery are the main elements that affect the optimal switching probabilities, so the number of devices in each group, in order to maximize the network's throughput and reliability.

VII. CONCLUSION

In this paper, we present a Markov chain framework for D2D cooperative relaying. We consider the number of D2D relays present in the network as state of the Markov chain. Next, we determine the long term average number of D2D-relays in the network as function of the devices' switching probabilities, under a probabilistic D2D cooperation assumption. Our goal is to analyze the uplink D2D cooperative transmissions and to find the optimal switching probabilities, and the optimal number of D2D-relays that lead to a maximum overall reliability and throughput. The results show that there exist optimal switching probabilities and an average number of D2D-relays that maximize the average throughput and reliability of the network. These results are strongly related to the orthogonality factor, degree of cooperation, network density and coverage range.

However, enhancing reliability comes at the price of increasing latency. For future work, we will deal with ensuring simultaneously a high reliability and low latency, required by URLLC Communications.

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