Content- and Context-Aware Opportunistic Cellular Communications in Device-Centric Wireless Networks

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***Abstract*—Device-centric wireless networks, including Device-to-Device communications and Multi-hop Cellular Networks, are expected to be a relevant component of future 5G wireless networks. Traditionally, opportunistic networking has been proposed for disconnected networks that cannot always reliably ensure real-time end-to-end connections. However, previous studies have demonstrated that opportunistic schemes can also be utilized in connected networks to improve their efficiency by intelligently exploiting context- and content-awareness. In this context, this paper proposes and evaluates a mechanism to select the adequate configuration of opportunistic cellular communications in single-hop and multi-hop cellular networks. To this aim, the mechanism probabilistically identifies for each communications mode the adequate times for cellular transmissions to take place in order to reduce the cellular channel occupancy and improve its capacity. The obtained results show that the proposed scheme reduces the channel occupancy of cellular transmissions for delay-tolerant information by up to 70% compared to conventional single-hop cellular communications.**

***Keywords*—5G; device-centric wireless networks; multi-hop cellular networks; opportunistic; D2D**

I. Introduction

Device-centric wireless networks will be part of the 5G network ecosystem, and transform mobile devices into producers and consumers (prosumers) of both data and wireless connectivity. In device-centric wireless networks, mobile devices provide wireless connectivity for other users and enable direct Device-to-Device communications (D2D) and Multi-hop Cellular Networks (MCNs). D2D communications have been proposed to facilitate proximity services, offload cellular data traffic from the infrastructure, and improve the system's capacity and spectral efficiency [1]. MCNs integrate D2D and cellular communications, and allow mobile devices to connect to the cellular infrastructure through intermediate nodes. MCNs have shown to provide significant benefits in terms of quality of service (QoS), energy consumption and capacity [2]. MCNs exploit the increasing capabilities of mobile devices (including communication, computing, processing, storage, sensing, and connectivity) that are underutilized nowadays. An example is the 4GFi project presented by Vodafone at the Mobile World Congress 2016. 4GFi proposes that 4G devices act as hotspots for 2G/3G devices with reduced bandwidth and throughput connectivity to the cellular infrastructure. In 4GFi, the D2D connection between 2G/3G devices and 4G devices is performed using WiFi technologies.

Device-centric wireless communications usually establish links as soon as nodes are within coverage. This could be inefficient if the communications link quality is not adequate, and retransmissions and low data rate transmission modes are necessary. Traditionally, opportunistic networking has been proposed for disconnected networks that cannot always reliably ensure real-time end-to-end connections. However, recent studies have shown that opportunistic mechanisms can also improve the efficiency of device-centric wireless communications by relaxing the need to establish real-time end-to-end connections [3]-[5]. Opportunistic schemes capitalize on the 'store, carry and forward' paradigm to establish communication links under favorable communication conditions and not just as soon as two nodes enter their corresponding communication range. The utilization of opportunistic networking should focus on services that tolerate certain delay in the delivery of information. It is important noting that according to Cisco's forecasts delay tolerant services (e.g. file sharing, mobile video streaming, email, etc.) could represent up to three-quarters of the increasing mobile data traffic by 2020 [6].

Previous results have demonstrated that the integration of opportunistic communications into MCNs can improve the capacity and energy consumption compared to conventional single-hop cellular communications [5]. For example, [5] shows that the use of opportunistic networking in MCN can reduce the total energy consumption by 90% and increase the cellular capacity by more than 70% for delay tolerant services. Given these promising findings, this study proposes and evaluates a mechanism to select the adequate configuration of opportunistic cellular communications in single-hop and multi-hop cellular networks. To this aim, the proposed mechanism probabilistically identifies for each communications mode the adequate times for cellular transmissions to take place in order to reduce the cellular channel occupancy and hence increase the cellular capacity. The proposed scheme has been designed for delay tolerant services and considering unknown trajectories of mobile devices and relays at the time of making the selection between communication modes.

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The rest of this paper is organized as follows. Section 2 introduces the scenario and objectives of the paper, describes the opportunistic communications modes, and introduces the proposed mechanism to select the adequate configuration of opportunistic cellular communications. Section 3 describes the evaluation environment and shows the performance results. Finally, Section 4 concludes the paper.

II. OPPORTUNISTIC COMMUNICATIONS

A. Scenario and Objectives

This study considers a scenario where a mobile user (U) needs to upload information to the base station (BS). The study does not focus on any particular traffic service but considers that a message of size F needs to be transmitted before a deadline T. The study considers that the user U can use different opportunistic communication modes to upload the message to the BS:

- The first mode integrates opportunistic and (single-hop) cellular communications. In this context, U stores the information and conducts the cellular transmissions to the BS when favorable link quality conditions are experienced. This mode is referred to as 'opportunistic cellular'.

- The second mode considers a MCN link with 2 or 3 hops. The intermediate nodes in the MCN link are mobile nodes, and there is always a final cellular link to the BS. The second mode integrates opportunistic communications into the cellular link of the MCN connection (and not into the D2D links) following the principles defined for the first communications mode. Opportunistic communications are not considered for the D2D links, and the D2D communication range is limited to increase the robustness of D2D links. The second mode is referred to as '2-hop opportunistic MCN' or '3-hop opportunistic MCN' depending on the MCN configuration.

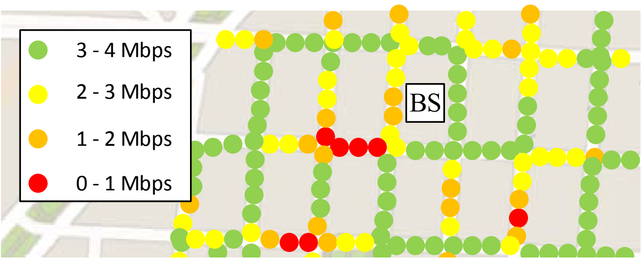

Fig. 1. Example of connectivity map illustrating the uplink cellular throughput.

The objective of this paper is to propose a process for selecting the most adequate opportunistic communication mode. The process here proposed has been designed with the objective to minimize the cellular transmission time required to upload the message of size F to the BS. By reducing the cellular channel occupancy, opportunistic communications could help increase the cellular capacity without augmenting the number of cellular radio resources. The study considers that the trajectory of mobile devices in the scenario is unknown at the time of making the selection. A process is therefore necessary to probabilistically estimate the cellular channel occupancy benefit that each opportunistic communication mode could provide considering all possible trajectories of devices. To this aim, the study proposes to exploit context- and content-awareness to create a process that identifies the time instants at which opportunistic cellular communications should take place to exploit favorable link quality conditions, increase the transmission throughput and reduce the cellular channel occupancy. For this purpose, the study assumes that mobile devices have a connectivity map providing statistical information about average uplink cellular throughput per location[1] (example in Fig. 1).

B. Opportunistic Cellular Communications

The 'opportunistic cellular' mode integrates opportunistic and (single-hop) cellular communications. In this case, user U does not need to start the cellular transmission to the BS as soon as it has information to transmit. Instead, U can store the information and start the cellular transmission to the BS when favorable link quality conditions are experienced. Under favorable link quality conditions, retransmissions are reduced and U can utilize transmission modes with high data rates. This reduces the time cellular radio resources are needed to transmit a file of a given size compared to the case in which low data rates are used. Reducing the cellular channel occupancy increases the capacity. To achieve this objective, the integration of opportunistic and cellular communications requires a process to decide the time instants at which cellular transmissions should take place. In this study, the mechanism is designed with the objective to minimize the time cellular radio resources are utilized. The proposed mechanism uses the following optimization framework (P1) and objective function to identify the time instants (within the defined deadline) at which U should transmit information to the BS in order to minimize the cellular channel occupancy:

$$(\text{P1}) \quad o.f{:}\ \min N_U = \min \sum_{t \in T} a_t \tag{1}$$

$$s.t{:}\ \sum_{t \in T} a_t \cdot thr_U(t) \geq F \tag{1.1}$$

$$a_t \in \{0, 1\} \tag{1.2}$$

N_U represents the total cellular transmission time from U to the BS. The time available to complete the cellular transmission from U to the BS (T) has been discretized into time instants (e.g. t=1s) in the optimization framework. The binary variable a_t indicates for time instant t whether a cellular transmission from U to the BS is carried out (a_t=1) or not (a_t=0). The objective function is defined subject to the requirement that the message of size F is completely transmitted before the deadline T (1.1). In equation (1.1), $thr_U(t)$ represents the uplink cellular throughput experienced by U at time instant t. This throughput is obtained from the connectivity map (Fig. 1), and depends on the estimated position of user U.

This study considers that the trajectory of mobile devices is unknown. As a result, it is not possible to know the exact location of U at a particular time instant t. On the other hand, this study takes into account all possible trajectories or paths

[1] The connectivity map could be provided by the cellular infrastructure or be derived by the devices from historical and statistical data.

of user U from its initial location. An example is illustrated in Fig. 2. The length of each path is limited by the deadline T and the speed at which user U moves; this study considers a constant pedestrian speed. Six paths are possible in the example in Fig. 2: $P_U=\{p_1, p_2, p_3, p_4, p_5, p_6\}$. However, P_U can be reduced if we consider the movement direction of U. We assume it is possible to infer such direction from the sensors available at mobile phones. The optimization framework (P1) is executed for each possible path in P_U, which results in a set of values $N_U^{p_i}$ ($\forall$ $p_i \in P_U$). $N_U^{p_i}$ represents the cellular transmission time required to upload the message to the BS over each path p_i. The probability that U follows a particular path $p_i \in P_U$ can be estimated as the product of turning probabilities at each intersection I (Pr(I)) of path p_i:

$$\Pr(p_i) = \prod_{I \in p_i} \Pr(I) \tag{2}$$

It is then possible to calculate the expected cellular transmission time from U to the BS ($\overline{N_U}$) using the weighted average of the set $N_U^{p_i}$ ($\forall p_i \in P_U$):

$$\overline{N_U} = \frac{\sum_{p_i \in P_U} N_U^{p_i} \cdot \Pr(p_i)}{\sum_{p_i \in P_U} \Pr(p_i)} \tag{3}$$

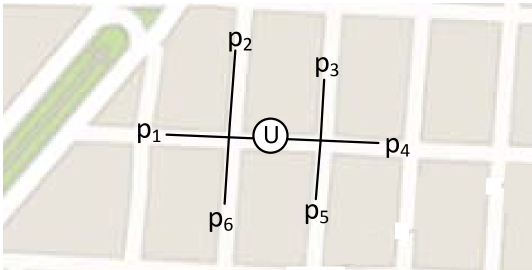

Fig. 2. Example of possible paths from the initial location of U.

C. 2-hop Opportunistic MCN

Under this mode, user U uses an intermediate mobile relay (R_1^i) to forward the information to the BS. In this study, opportunistic communication is considered for the cellular link between R_1^i and the BS, but not for the D2D link between U and R_1^i. This study considers that U can only select mobile relays that are within a radio range r_{D2D} and under line-of-sight (LOS) conditions. This is done so to ensure stable and efficient D2D links. R_1^i is a mobile relay i of the set of mobile relays R_1 that fulfill such conditions (i.e. $R_1^i \in R_1$). r_{D2D} is selected so that D2D transmission of the message of size F from U to R_1^i is completed before t_{D2D} seconds elapse; further details on the definition of t_{D2D} are provided in Section III. This study assumes that the cellular transmission from R_1^i to the BS starts once the complete file is transmitted from U to R_1^i. In this case, R_1^i has T-t_{D2D} seconds to complete the cellular transmission to the BS. For simplicity, we establish t_{D2D} as the time consumed in the D2D communication from U to any mobile relay in R_1. The time instants at which R_1^i should transmit information to the BS in order to minimize the cellular channel occupancy can then be derived using an optimization framework and objective function similar to (P1):

$$(\text{P2}) \quad o.f{:}\ \min N_{R_1^i} = \min \sum_{t \in [t_{D2D}, T]} a_t \tag{4}$$

$$s.t{:} \sum_{t \in [t_{D2D}, T]} a_t \cdot thr_{R_1^i}(t) \geq F \tag{4.1}$$

$$a_t \in \{0, 1\} \tag{4.2}$$

where the main difference with (P1) lies in the fact that the time instants (t) are limited to $t \in [t_{D2D}, \text{T}]$.

The same process defined for U to estimate $\overline{N_U}$ (eq. (3)) is now followed to estimate $\overline{N_{R_1^i}}$ (expected cellular transmission time from R_1^i to the BS) for all mobile relays in R_1. The mobile relay R_1^i to be used should be the one that minimizes the expected cellular transmission time. In this context, the expected cellular transmission time for 2-hop opportunistic MCN communications is estimated as:

$$\overline{N_{R_1}} = \min_{R_1^i \in R_1} \left\{ \overline{N_{R_1^i}} \right\} \tag{5}$$

D. 3-hop Opportunistic MCN

The '3-hop opportunistic MCN' mode includes two D2D links and an opportunistic cellular link. To establish a 3-hop opportunistic MCN connection, U selects first a mobile relay $R_1^i \in R_1$. R_1^i should then select another mobile relay R_2^i to establish the second D2D link. The opportunistic cellular link is established between R_2^i and the BS. R_2^i must be within the radio range r_{D2D} of R_1^i and under LOS conditions. In addition, R_2^i should be at a distance of U higher than r_{D2D}. Fig. 3 illustrate an example of the possible locations of R_2^i for a given position of U. In Fig. 3, L represents the area where R_2^i can be found, and l a specific location in L. The distance between transmitting and receiving nodes is lower than r_{D2D} for both D2D links. t_{D2D} seconds are then consumed in each D2D transmission. The time available to complete the cellular transmission from R_2^i to the BS is equal to T-2t_{D2D}.

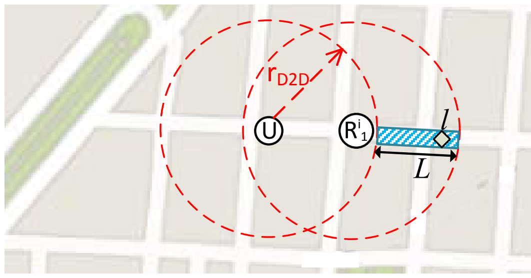

Fig. 3. Example scenario for 3-hop opportunistic MCN.

This study considers that U is not aware of the presence of relay nodes beyond r_{D2D}, and therefore cannot identify R_2^i. As a result, the process to derive the total cellular transmission time from R_2^i to the BS is conducted considering all possible locations of R_2^i. As illustrated in Fig. 3, the possible locations of R_2^i are limited to the area *L*. An optimization process (P3) similar to (P1) or (P2) is then carried out for all locations $l \in L$ where R_2^i could be located. In this case, (P3) is executed considering that the time instants (*t*) for the cellular transmission to the BS are limited to $t \in [2t_{D2D}, T]$.

A similar process defined for U to estimate $\overline{N_U}$ (eq. (3)) is now followed to estimate $\overline{N_{R_2^i,l}}$ that represents the expected cellular transmission time from a R_2^i (initially located at *l*) to the BS. R_2^i could be located at any location within *L*. The expected value of the cellular transmission time from R_2^i to the BS can then be estimated as:

$$\overline{N_{R_2^i}} = \frac{\sum_{l \in L} \overline{N_{R_2^i,l}}}{L} \cdot \frac{1}{\Pr\left(R_2^i \; in \; L\right)} \quad (6)$$

where $\Pr(R_2^i \; in \; L)$ represents the probability to find at least a R_2^i in *L*. For a uniform distribution of nodes within the cell, $\Pr(R_2^i \; in \; L)$ can be estimated as $\Pr(R_2^i \; in \; L)=1-\exp(-\lambda \cdot L)$, where λ is the spatial density of mobile devices in the cell [5].

$\overline{N_{R_2^i}}$ has been computed considering that U establishes the first D2D link with a relay R_1^i ($R_1^i \in R_1$). The D2D link could be established with any $R_1^i \in R_1$. $\overline{N_{R_2^i}}$ should hence be computed for all possible R_1^i in R_1, and U would select the mobile relay R_1^i that minimizes the expected cellular transmission time of the 3-hop opportunistic MCN link:

$$\overline{N_{R2}} = \min_{R_1^i \in R_1} \left\{ \overline{N_{R_2^i}} \right\} \quad (7)$$

It should be noted that R_1^i is in charge of selecting R_2^i. This study considers that R_1^i performs a random selection of R_2^i among the mobile relays that fulfill the defined criteria, i.e. the mobile relays should be within a radio range r_{D2D} and under line-of-sight (LOS) conditions to R_1^i.

E. Selection of the Opportunistic Communication Mode

The previous sections have presented the method proposed to probabilistically estimate the cellular channel occupancy obtained when integrating opportunistic communications in conventional single-hop or multi-hop cellular networks. This section defines the criteria for the selection of the opportunistic communication mode. Establishing MCN connections is not extent of risks (e.g. finding a relay or potentially varying D2D link quality). As a result, the proposed criteria considers that the '2-hop opportunistic MCN' and '3-hop opportunistic MCN' modes should only be utilized if they reduce the expected cellular transmission time (or channel occupancy) compared to 'opportunistic cellular'. In particular, the '2-hop opportunistic MCN' communication mode is selected if $(1-\alpha) \geq \overline{N_{R_1}} / \overline{N_U}$, where α represents the reduction factor in the expected cellular transmission time when using '2-hop opportunistic MCN'. Similarly, the '3-hop opportunistic MCN' communication mode is selected if $(1-\beta) \geq \overline{N_{R_2}} / \overline{N_U}$, where β represents the reduction factor in the expected cellular transmission time when using '3-hop opportunistic MCN'. The reduction factor could be different for both modes since MCN can face more challenges as the number of hops increase. In this case, a higher reduction factor could be reasonably demanded to the '3-hop opportunistic MCN' mode compared to the '2-hop opportunistic MCN' one. When both modes fulfill their corresponding criteria, the one minimizing the expected cellular transmission time will be selected.

The nodes participating in a possible opportunistic MCN link are selected once the decision on the most adequate mode is made. Once the communication mode is selected, this study assumes that the nodes that transmit the information to the BS through a cellular link (U, R_1^i or R_2^i depending on the opportunistic communication mode) know their own trajectory, and can then identify the time instants at which cellular transmissions should take place in order to minimize the cellular channel occupancy. For example, if the '2-hop opportunistic MCN' mode is selected, U selects the mobile relay $R_1^i \in R_1$ and completes the D2D transmission. At this stage, it is assumed that R_1^i knows its own trajectory, and can then identify the adequate time instants that minimize the cellular channel occupancy.

III. Performance Analysis

A. Evaluation environment

This work used Matlab to simulate a scenario of 6x6 blocks following a Manhattan structure. The main simulation parameters are summarized in Table I. The BS is located at the centre of the scenario and mobile nodes are initially distributed across the streets following a homogeneous uniform distribution. Mobile nodes move at a speed of 1 m/s. At each intersection corner, mobile nodes have equal turning probabilities for left, right and forward directions (the study assumes that nodes do not move backward at intersection corners). The simulation guidelines reported in [7] for the test case "dense urban information society" have been taken into account to determine the density of nodes in the scenario (λ). In particular, λ has been set equal to $0.25 \cdot \lambda_{duis}$[2], with λ_{duis}=8.500 users/km^2 being the spatial density of pedestrians reported in [7] for this test case. The user U is randomly selected among the mobile nodes within the cell. The study considers that U needs to upload a message of size *F*=30 Mb before a deadline *T*= 60 s. Several experiments are conducted (minimum 10.000) to guarantee the statistical accuracy of the results.

In the scenario, cellular transmissions are performed using 6 resource blocks (RBs) of LTE at 2GHz. The propagation losses (PL) for cellular transmissions are modeled using the 3D urban macro-cellular (3D-UMa) channel model for LTE

[2] The conducted evaluation showed similar results for $\lambda > 0.25 \cdot \lambda_{duis}$.

reported in 3GPP TR36.873. The model includes log-normal shadow fading with standard deviation σ_{SF} =4 dB and σ_{SF} =6 dB under LOS and NLOS conditions, respectively. The LOS probabilities are given by the expressions reported in 3GPP TR36.873. The Signal to Noise Ratio (SNR) for the uplink cellular communications is calculated using the parameters reported in Table I as: SNR = *Ptx_UE* – PL – *eNB_rxNF* – *Th_N* – BW. The LTE uplink throughput is then estimated using the SNR-BER curves reported in [8] for different CQIs (we consider a target BER of 0.1), and the tables reported in 3GPP TS36.213 that map the CQI values to the associated transport block size for a number of RBs. This study considers that D2D transmissions utilize IEEE 802.11g (3GPP considers both IEEE 802.11 and LTE technologies for D2D). r_{D2D} is set to 80m using the models reported in [9] for D2D communications. [9] demonstrated that distances up to 80m allow for D2D communications to be performed under LOS conditions using highest data rate transmission mode (i.e. 54 Mbps). In this case, the time required to complete the D2D transmission (t_{D2D}) is equal to 2 seconds.

TABLE I. SIMULATION PARAMETERS

Parameter	*Description*	*Value*
B_width	Buildings' width	89 m
B_heigh	Buildings' height	15 m
S_width	Streets' width	11 m
BW	System bandwidth	10 MHz
Ptx_UE	Transmission power of mobile nodes	23 dBm
eNB_rxNF	Base station receiver noise figure	5 dB
Th_N	Thermal noise	-174 dBm/Hz

B. *Performance results*

Fig. 4 compares the quality experienced during the cellular transmissions to the BS for different communication modes. The cellular quality is represented using the CQI parameter that varies between 1 and 15. Higher CQI values indicate the use of higher order modulation and coding schemes, and consequently higher cellular throughput levels. Fig. 4 depicts the performance that would be obtained with our proposal to dynamically select the opportunistic communication mode that minimizes the cellular channel occupancy ('Proposal'). This performance is compared against that obtained when always using the 'opportunistic cellular', '2-hop opp. MCN' or '3-hop opp. MCN' modes (i.e. there is no dynamic selection). Fig. 4 also shows the quality associated to conventional single-hop cellular communications that do not integrate opportunistic schemes ('cellular')[3].

The results in Fig. 4 show that the integration of opportunistic and cellular communications increases the experienced CQI compared to conventional single-hop cellular communications; this trend is observed for all evaluated opportunistic communication modes. For example, 50% of the cellular transmissions carried out under the '2-hop opportunistic MCN' mode experienced CQI values higher than 12. When using conventional single-hop cellular communications, this percentage drops to only 13%. The performance depicted for 'Proposal' was obtained with $\alpha = \beta =$ 0.1. The results show that dynamically selecting the opportunistic communication mode using our proposed process results in the highest CQI values, and therefore the highest throughput levels that can reduce the cellular channel occupancy.

Table II shows the percentage of time that each opportunistic communication mode was selected when implementing our proposal for their dynamic selection (Section II.E). The table also shows how many of these selections were correct. A selection is considered to be correct if the selected opportunistic communication mode is the one that minimizes the cellular transmission time and hence the cellular channel occupancy. Table II shows that the proposed scheme results in high percentages of correct mode selections. The highest percentage of correct mode selections for 'opportunistic cellular' is obtained with the lowest values of α. When α increases, the 2-hop and 3-hop opportunistic MCN modes need to achieve higher reduction levels of the expected cellular transmission time to be selected. This results in a conservative operation that generally increases the selection of the 'opportunistic cellular' mode while it was not in reality the mode that minimized the cellular transmission time.

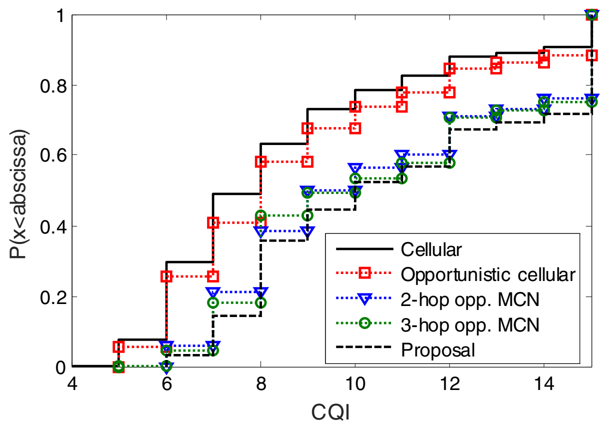

Fig. 4. CDF of the CQI experienced by the cellular transmissions to the BS.

TABLE II. OPERATION AND PERFORMANCE OF THE SCHEME PROPOSED FOR THE DYNAMIC SELECTION OF OPPORTUNISTIC COMMUNICATION MODES

	% of connections			*Correct selection [%]*		
Mode	*α=0.1*	*α=0.2*	*α=0.3*	*α=0.1*	*α=0.2*	*α=0.3*
'Opportunistic cellular'	43.8	53.0	70.2	76.3	65.9	50.2
'2-hop opportunistic MCN'	28.4	22.3	12.0	90.2	90.4	87.0
'3-hop opportunistic MCN'	27.8	24.7	17.8	85.8	85.8	86.1

Fig. 5 highlights the cellular channel occupancy benefits that can be obtained from the integration of opportunistic and cellular communications. In particular, the figure represents the CDF (cumulative distribution function) of the reduction in the cellular transmission time achieved by the proposed scheme that dynamically selects opportunistic communication modes ('Proposal' in Fig. 4) compared to when using

[3] In this case, user U starts the cellular transmission to the BS as soon as the session starts and the information is ready to be sent.

conventional single-hop cellular communications. Fig. 5 shows that 50% of the cellular transmissions carried out using the proposed scheme reduce the cellular channel occupancy by more than 25%. Fig. 5 also shows that the proposed scheme does not reduce the cellular transmission time for 30% of the cellular transmissions. This actually happens when user U is close to the BS. In this case, conventional single-hop cellular communications already experience high CQI values. On the other hand, the proposed scheme significantly reduces the cellular channel occupancy compared to conventional single-hop cellular communications when the distance between user U and the BS augments. Reduction levels up to 70% can be achieved when U is at the cell edge.

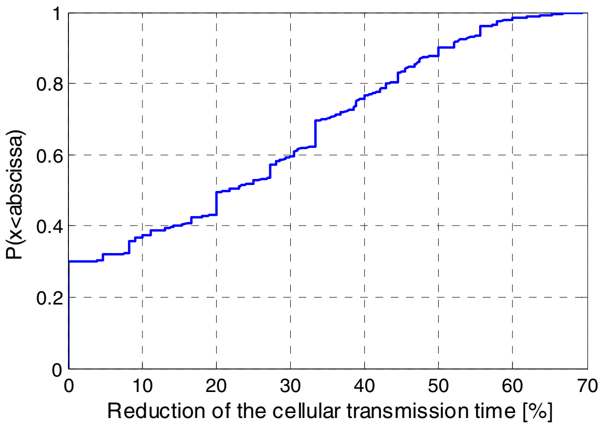

Fig. 5. CDF of the reduction in the cellular transmission time achieved by the proposed scheme that dynamically selects opportunistic communication modes compared to when using conventional single-hop cellular communications.

IV. CONCLUSIONS

This paper has proposed and evaluated a mechanism to select the configuration of opportunistic cellular communications that minimizes the cellular channel occupancy, and therefore increases the cellular capacity. The proposed scheme considers the integration of opportunistic schemes in both single-hop and multi-hop cellular networks. To realize the selection, the proposed mechanism probabilistically identifies for each communication mode the adequate time instants at which cellular transmissions should take place in order to reduce the cellular channel occupancy. The proposed scheme has been designed for delay tolerant services and considering unknown trajectories of mobile devices and relays at the time of making the selection between communication modes. The obtained results demonstrate that the integration of opportunistic and cellular communications can significantly reduce the cellular channel occupancy, in particular when the integration is done in the framework of multi-hop cellular networks. In this case, the cellular channel occupancy can be reduced by as much as 70% for users at the cell edge.

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