Opportunistic Cellular Communications for Uplink Capacity Enhancement

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***Abstract*- Device-centric wireless networks, including Device-to-Device communications and Multi-hop Cellular Networks, are expected to perform a pivotal role in the design of future 5G wireless networks. In addition, opportunistic schemes have shown to have the potential to enhance the efficiency of device-centric wireless networks by intelligently exploiting context- and content-awareness. In this context, this paper contributes towards the development of practical opportunistic mechanisms that allow achieving the expected benefits of device-centric wireless networks. In particular, the paper studies the use of opportunistic cellular communications to identify adequate time instants (and locations) for cellular transmissions to take place in device-centric wireless networks under uncertain trajectories of mobile nodes. The obtained results show that the proposed opportunistic schemes allow reducing the time the cellular channel is occupied for the transmission of delay-tolerant information by up to 70% compared to traditional single-hop cellular communications.**

I. INTRODUCTION

Device-centric wireless networks are expected to represent a fundamental part of the 5G network ecosystem. Device-centric wireless networks transform mobile devices into producers and consumers (prosumers) of both data and wireless connectivity, and empower mobile devices to take a more active role in the network management and operation. 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). MCNs integrate D2D and cellular communications, and allow mobile devices to connect to the cellular infrastructure through intermediate mobile devices. MCNs have shown to provide significant benefits in terms of quality of service (QoS), energy consumption and capacity. The expectations arisen by device-centric wireless networks have been fuelled by the increasing capabilities of mobile devices that are underutilized nowadays [1]. An example of the increasing interest on device-centric wireless networks is the recently released project 4GFi of Vodafone. 4GFi enables 4G devices to act as hotspots for 2G/3G devices. The D2D connection between 2G/3G devices and 4G devices is performed using WiFi technologies.

Currently, device-centric wireless communications (both D2D and MCNs) tend to establish links as soon as nodes are within coverage. However, this can be highly inefficient (because of the need to use retransmissions and low data rate transmission modes) if the communication conditions are not good, and unnecessarily increase the channel occupancy and hence reduce the system capacity. Recent studies have shown that opportunistic technologies can help increasing the efficiency of device-centric wireless communications by relaxing the need to establish real-time end-to-end connections and seeking good communication conditions [2]-[3]. 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 get in contact with each other. This operation can only be considered appropriate for services that can tolerate certain delay in the delivery of information (e.g. file sharing, mobile video streaming). According to Cisco forecasts this traffic will generate more than three-quarters of the mobile data traffic by 2020.

In this context, this work builds from previous results of the authors that demonstrate the capacity and energy consumption benefits of the integration of opportunistic networking schemes into device-centric MCNs compared to traditional single-hop cellular communications [2]. In particular, the study presented in [2] shows that the use of opportunistic networking in MCN networks could help reduce by 90% the energy consumption and increase the cellular capacity by more than 70% for delay tolerant services. Based on the promising findings of the dimensioning study presented in [2], the aim of this work is to contribute towards the design of the necessary mechanisms to achieve such gains.

II. SCENARIO AND OBJECTIVES

This study considers a scenario where a mobile user (U) needs to upload to the base station (BS) certain message, of size F, within a given time window (T). The study considers that U can use different communication modes to upload the message to the BS. The first mode considers that U can exploit its opportunistic networking capabilities in the communication with the BS. In particular, the user U can carry out the cellular transmissions to the BS when favorable communication conditions are found (this will be referred to as 'opportunistic cellular'). The second communication mode considers that U can use a MCN communication mode composed of 2 hops: a D2D link from U to the selected mobile relay, and a cellular link from the mobile relay to the BS. In this communication mode, we consider opportunistic communications in the cellular link between the mobile relay and the BS. Opportunistic communications are not performed in the D2D links, but the D2D communication range is limited to ensure stable and efficient transmissions (this mode will be referred to as '2-hop opportunistic MCN'). The study also uses as a reference for comparative purposes the traditional single-hop cellular communication mode (this will be referred to as 'traditional cellular').

For the scenario described above, the objective of this paper is to derive the opportunistic communication mode that minimizes the cellular transmission time required to upload the message to the BS. In fact, this is equivalent to optimize the utilization of the cellular radio resources which will in turn result in an increase of the network's capacity. To this aim, the study proposes to exploit context- and content-awareness to establish high throughput opportunistic cellular connections (and as a consequence to reduce the cellular transmission time). In particular, the study focuses on identifying the adequate time instants (and locations) for cellular transmissions to take place based on the experienced cellular throughput and service constraints. For this purpose, the study considers that the cellular network provides mobile devices with a connectivity map that illustrates the average uplink cellular throughput. However, it is considered that the trajectory of mobile devices in the scenario is unknown. In this context, it is not possible to know with certainty the locations of mobile devices with time. This avoids to plan in advance the time instants (and locations) at which cellular transmissions should take place. The study addresses this issue using the probability of turning at intersection corners that allows identifying the probability that a mobile device follows a particular path. In this context, the decision about the opportunistic communication mode to use will be based on the expected value of the cellular transmission time required to upload the message to the BS.

III. PROBLEM FORMULATION

This study seeks identifying the opportunistic communication mode (i.e. 'opportunistic cellular' and '2-hop opportunistic MCN') that allows reducing the time the cellular channel is occupied to upload a delay-tolerant message of size F to the BS. This section describes the processes we propose to calculate the expected value of the cellular transmission time by means of exploiting context- and content-awareness.

A. Opportunistic cellular

In 'opportunistic cellular', U directly communicates with the BS. However, unlike 'traditional cellular', U seeks to establish high throughput cellular transmissions with the BS that allow reducing the cellular transmission time required to upload the information to the BS. The following optimization framework (P1) is defined to identify the time instants (within the available time window) at which U should perform the cellular transmissions to the BS in order to minimize the time required to complete the transmission of the information.

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

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

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

In the objective function (1), N_U represents the total transmission time of the cellular communication from U to the BS. The time available to complete the cellular transmission from U to BS (T) has been discretized into time instants (e.g. t=1s) in the optimization framework. In this context, the binary variable a_t is defined to decide at every time instant whether the cellular transmission from U to 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. The uplink cellular throughput is obtained from a connectivity map.

It should be noted that identifying the time instants at which to carry out the cellular transmissions (i.e. a_t=1) could be equivalent to identify the locations within the cell at which the cellular transmissions should take place. This is the case if it is considered that the location of mobile devices with time is known (or the trajectory). As it has been stated in Section II, this study considers that the trajectory of mobile devices is unknown. In this context, it is not possible to know the location of U at a particular time instant and therefore its uplink cellular throughput with the BS using the connectivity map. On the other hand, this study takes into account all possible trajectories or paths of U from its initial location. This results in a set of possible paths ($P_U=\{p_1, \dots p_i, \dots\}$). It should be noted that the paths' length is limited by the deadline T the speed at which U moves (this study considers that the walking speed is constant). Given the uncertainty in the trajectory of U, the optimization framework (P1) is carried out for each possible path in P_U. This results in a set of values $\{N^{pi}_U \mid \forall\ p_i \in P_U\}$ that represent the cellular transmission time required to upload the message to the BS over each of the possible paths included in P_U. It should be noted that the probability that U follows a particular path $p_i \in P_U$ is given by the probabilities at the intersection corners (I) that define such path ($I \in p_i$), and can be calculated as follows:

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

Pr(I) can be considered as context-information derived from historical and statistical dada.

In this context, it is possible to calculate the expected time of the cellular transmission from U to the BS ($\overline{N_U}$) using the weighted average of the set $\{N^{pi}_U \mid \forall\ p_i \in P_U\}$, as follows:

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

B. 2-hop opportunistic MCN

In '2-hop opportunistic MCN', the user U uses an intermediate mobile relay ($\mathrm{R_i}$) to forward the information to the BS. In the D2D link between U and $\mathrm{R_i}$ we do not consider opportunistic communications. However, U can only select mobile relays that are within a radio range r_{D2D} and under line-of-sight (LOS) conditions. Actually, $\mathrm{R_i}$ is a mobile relay i of the set of mobile relays R that fulfill such conditions (i.e. $\mathrm{R_i} \in \mathrm{R}$). The selection of r_{D2D} guarantees that the transmission of the message of size F in the D2D link from U to any $\mathrm{R_i} \in \mathrm{R}$ is completed in t_{D2D} seconds. The selected mobile relay (e.g. $\mathrm{R_i}$) has the time window $[t_{D2D}, T]$ to complete the cellular transmission with BS. The time instants at which $\mathrm{R_i}$ should carry out the cellular transmissions that minimize the total cellular transmission time are derived using (4), that is an optimization framework similar to that presented in (P1). In this case, the optimization framework to derive the total cellular transmission time from $\mathrm{R_i}$ to BS (i.e. N_{Ri}) needs to consider that the time instants (t) are limited to $t \in [t_{D2D}, T]$, and the uplink cellular throughput experienced by R_i (thr_{Ri}) The resulting optimization framework will be referred to as (P2).

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

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

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

The uncertainty in the trajectory that mobile devices follow also affects R_i. To address this issue, N_{Ri} needs to be computed for all possible paths that R_i could follow. In this case, P_{Ri} represents the set of possible paths that start at the location of R_i once the D2D transmission from U to R_i is completed. It should be noted that the paths' length of R_i is limited by the available time window [t_{D2D}, T]. In this context, $N_{R_i}^{p_i}$ would represent the total cellular transmission time that R_i would require to upload the message to the BS over the path $p_i \in P_{Ri}$ computed using (P2). Following a similar process to that reported in equation (3), that takes into account the set of possible paths of R_i (i.e. P_{Ri}) and the probability that R_i follows each path ({Pr(p_i) | ∀ $p_i \in P_{Ri}$}, see equation (2)), it can be calculated the expected time of the cellular transmission from R_i to BS ($\overline{N_{R_i}}$).

The process described above to derive the expected time of the cellular transmission to BS is carried for all mobile relays in R. This results in a set of values {$\overline{N_{R_i}}$ | ∀ $R_i \in$ R}. In this context, the mobile relay to be used in the '2-hop opportunistic MCN' communication will be that one that minimizes the expected time of the cellular transmission. The expected cellular transmission time of the 2-hop opportunistic MCN communication can then be computed as:

$$\overline{N_R} = \min_{R_i \in R}\left\{\overline{N_{R_i}}\right\} \tag{5}$$

IV. SELECTION OF THE OPPORTUNISTIC COMMUNICATION MODE

Section III identified the expected cellular transmission times of the cellular connections for the 'opportunistic cellular' and '2-hop opportunistic MCN' communication modes. This section focuses on defining the criteria for the selection of the opportunistic communication mode. In this process it has been taken into consideration that the implementation of (opportunistic) MCN communications is not exempt of technical and management challenges. In this context, this paper establishes that the '2-hop opportunistic MCN' is only selected if it reduces the expected cellular transmission time compared to 'opportunistic cellular'. In particular, the '2-hop opportunistic MCN' communication mode is selected if $(1-\alpha) \geq \overline{N_R}/\overline{N_U}$. Therefore, α represents the reduction factor in the expected cellular transmission time for the selection of '2-hop opportunistic MCN'.

It is important to notice that the decision about the opportunistic communication mode to use in the communication between U and the BS is conducted using the expected times of the cellular transmission. Once this decision is made, the communication is established. For example, in the case of '2-hop opportunistic MCN', the user U selects the mobile relay $R_i \in$ R and completes the D2D transmission. At this stage, it is assumed that the mobile node that communicates with the BS (R_i in case of '2-hop opportunistic MCN', or U in case of 'opportunistic cellular') knows its own trajectory. Therefore, it can identify the time instants (and locations) at which to carry out the cellular transmissions that minimize the cellular transmission time following the optimization frameworks (P1 or P2) defined in Section III. The time instants at which the cellular transmissions are conducted that minimize the cellular transmission time are given by the binary variable a_t.

V. PERFORMANCE ANALYSIS

A. Evaluation environment

This work has been evaluated in Matlab considering a 6x6 blocks' Manhattan-like scenario. The BS is located at the centre of the scenario and mobile nodes are initially distributed across the cell's streets following a homogeneous uniform distribution. Mobile nodes move with a speed of 1 m/s and at each intersection corner, mobile nodes have similar turning probabilities for moving left, right and forward. The simulation guidelines reported in [4] 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 $\lambda=0.25\lambda_{duis}$, with λ_{duis}=8.500 users/km2 being the spatial density of walking users reported in [4] 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 adequate statistical accuracy.

In the scenario, cellular transmissions are performed using LTE at 2GHz with 6 resource blocks (RBs) allocated. The propagation losses (PL) for cellular transmissions are modeled using the 3D urban macro-cellular (3D-UMa) channel model for LTE 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: $SNR = Ptx\_UE - PL - NFrx_{BS} - Th\_N - BW$; Ptx_UE is the mobile nodes' transmission power (23dBm), $NFrx_{BS}$ is the noise figure at the BS (5dB), Th_N is the thermal noise (-174 dBm/Hz), and BW is the system bandwidth (10MHz). The LTE uplink throughput is then estimated using the SNR-BER curves reported in [5] 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. On the other hand, D2D communications are performed using IEEE 802.11g (3GPP considers both IEEE 802.11 and LTE technologies to perform D2D communications). Using the models derived in [6] for D2D communications, r_{D2D} is set to 80 m. Based on [6], communication distances up to 80 meters ensure that D2D communications are performed using the most efficient transmission mode (i.e. 54 Mbps) under LOS conditions. In this case, the time required to complete the D2D transmission (t_{D2D}) is set to 2 seconds.

B. Performance results

The results reported in Fig. 1 show the quality associated to the cellular transmissions that have been carried out to the BS. The quality of the cellular transmissions 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 the consequent higher cellular throughput levels. Fig. 1 shows the performance that would be achieved if it is always used the same communication mode ('opportunistic cellular' and '2-hop opp. MCN' in Fig. 1). Fig. 1 also shows the quality associated to the cellular transmissions when operating the 'traditional cellular' communication mode. The reported results show that the cellular transmissions carried out using any of the considered opportunistic communication modes are associated to higher CQI values than those carried out using the 'traditional cellular' mode. For example, 50% of the cellular transmissions carried out using the '2-hop opportunistic MCN' communication mode are associated to CQI values higher than 10. The percentage of cellular transmissions that are associated to CQI values higher than 10 reduces to 20% when using the 'traditional cellular' mode.

Fig. 1 also shows the CQI associated to the cellular transmissions when using the considered opportunistic communication modes presented in Section III and the scheme presented in Section IV to select the opportunistic communication mode ('Proposal' in Fig. 1, where α is set to 0.1). As shown in Fig. 1, when the scheme proposed to select the opportunistic communication mode is used, the conducted cellular transmissions are associated to higher CQI values, and hence higher cellular throughput levels, than when it is not used. This is the case because the proposed scheme allows identifying for each situation the opportunistic communication mode that minimizes the expected cellular transmission time. It should be noted that the 'opportunistic cellular' and '2-hop opportunistic MCN' modes are selected 46.9% and 53.1% of the times, respectively.

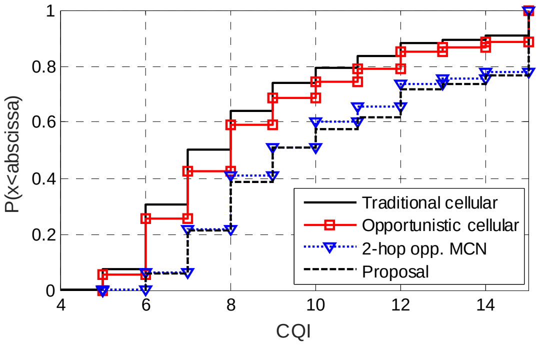

Fig. 1. CDF of the CQI associated to the conducted cellular transmissions.

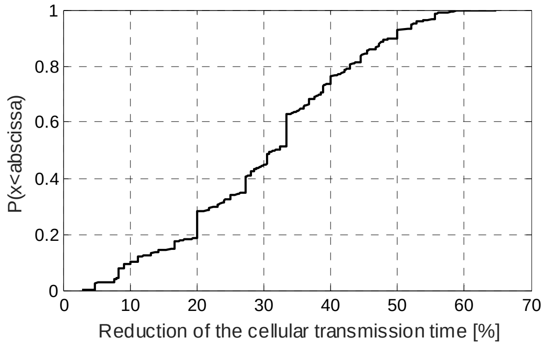

Fig. 2. CDF of the reduction of the time consumed to complete the cellular transmission when using opportunistic communication modes compared to traditional single-hop communications.

Finally, Fig. 2 highlights the benefits resulting from the use of high throughput cellular transmissions (Fig. 1) in the opportunistic communication modes compared to 'traditional cellular'. In particular, Fig. 2 shows the CDF of the reduction of the time to complete the cellular transmission when using the proposed mode selection scheme compared to the time consumed by traditional single-hop cellular communications. It is important noting that the results reported in Fig. 2 are for the 70% of the opportunistic connections that outperform the 'traditional cellular' communication. For the remaining 30% of the connections both communication modes achieve the same performance; this is the case for when U is close to the BS. As the distance from the user U to the BS increases, the reported results show that the 50% of the cellular transmissions carried out using the selected opportunistic communication mode allows reducing the occupancy of the cellular channel by more than 30%. It is worth noting that the the selected opportunistic modes achieve higher reduction levels in the channel occupancy compared to the traditional single-hop cellular communication when U is located further away from the BS. In particular, reduction levels up to 70% can be achieved when U is at the cell edge.

VI. CONCLUSIONS

This work has studied the utilization of opportunistic communication modes to reduce the cellular channel occupancy, and as a consequence to increase the system's capacity. The considered scenario imposes certain limitations, namely the one that the trajectories of mobile devices are unknown. The study addresses this issue exploiting context- and content-awareness to probabilistically indentify the mobile nodes' possible paths and the adequate times (and locations) where the cellular transmission should take place in order to minimize the occupancy of the cellular channel. In addition, the paper has proposed a simple yet effective scheme to select the appropriate opportunistic communication mode based on their expected performance. When the opportunistic communication modes are correctly selected, the obtained results have shown that the utilization of cellular channel can be reduced by up to 70% for delay tolerant services compared to traditional single-hop cellular communications.

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REFERENCES

[1] F. Boccardi, R.W. Heath, A. Lozano, T.L. Marzetta and P. Popovski, "Five disruptive technology directions for 5G", *IEEE Commununications Magazine, vol. 52, no. 2, pp. 74–80*, Feb. 2014.

[2] B. Coll-Perales, J. Gozalvez and V. Friderikos, "Context-aware opportunistic networking in multi-hop cellular networks", *Ad Hoc Networks, vol. 37, part 2, pp. 418–434*, Feb. 2016.

[3] Y. Li, C. Song, D. Jin and S. Chen, "A Dynamic Graph Optimization Framework for Multihop Device-to-Device Communications Underlaying Cellular Networks", *IEEE Wireless Communications, vol. 21, no. 5, pp. 52-61*, Oct. 2014.

[4] METIS Deliverable D.6.1. "Simulation guidelines". Oct. 2013.

[5] J. Blumenstein, et al., "Simulating the long term evolution uplink physical layer", *Proc. IEEE ELMAR*, Sept. 2011, Zadar (Croatia).

[6] B. Coll-Perales, et al., "Empirical Performance Models for P2P and Two Hops Multi-hop Cellular Networks with Mobile Relays", *Proc. ACM PM2HW2N*, Nov. 2013, Barcelona (Spain).