Opportunistic D2D-Aided Uplink Communications in 5G and Beyond Networks

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Abstract. 5G and Beyond 5G networks are calling for advanced networking schemes that can efficiently contribute to deal with the foreseen increase of the mobile data traffic, which inherently brings along an increase of the energy consumed by mobile nodes to support it. The non-real-time nature of an important share of that traffic makes it possible to use opportunistic networking mechanisms in cellular networks that can exploit the traffic's delay-tolerance to find efficient transmission conditions. In this context, this paper proposes an scheduling and mode selection scheme that integrates opportunistic Device-to-Device (D2D) networking mechanisms in cellular networks to reduce the energy consumption for non-real-time traffic. The proposed scheme utilizes a probabilistic model that exploits context information available in cellular networks to obtain an a-priori estimate of the energy cost for transmitting the different fragments of a content using any of the following modes: single-hop traditional, opportunistic cellular and opportunistic D2D-aided cellular. Based on these estimates, the proposed scheme selects the communication mode for each fragment, and schedules the time instant at which the transmission should take place. Our performance evaluation shows that the proposed scheme results in up to 90% energy consumption reduction, compared to traditional single-hop cellular communications, and performs closely to an optimal scheme which assumes full knowledge of network conditions and nodes' trajectories.

Keywords: 5G · D2D · Energy efficiency · Opportunistic networking

1 Introduction

5G and Beyond 5G networks will be challenged, in terms of both spectrum use and energy consumption, by the increasing mobile data traffic demand. The integration of Device-to-Device (D2D) communications in the design of cellular networks [1] has been proposed as a powerful means to cope with this unprecedented traffic demand, and is expected to play a key role in 5G networks and beyond [2]. 5G and beyond 5G networks will require advanced networking mechanisms to adapt data transfers to the variable spatial-temporal characteristics

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of the traffic demands [2,3]. This includes opportunistic networking mechanisms that empower mobile devices to become more active members of the network with the ability, for instance, to autonomously establish communication links under favorable conditions. Traditionally, opportunistic networking has focused on self-organized/ad-hoc mobile networks that lack end-to-end connections [3]. In these scenarios, the devices are allowed to temporarily store the information, and eventually forward it to another device, which is more likely to be within the communication range of the destination, when a connection opportunity arises. In cellular networks, the end-to-end connectivity is not an issue thanks to the increasing densification of the infrastructure. Hence, devices will have a direct cellular connection to the infrastructure almost everywhere. In this context, opportunistic networking can be used for dynamically selecting, at each point in time, the best communication mode among the available ones. In particular, this work considers the following communication modes: (i) *Single-Hop (SH) traditional:* direct cellular transmission between the UE (user equipment) and the BS; (ii) *opportunistic cellular:* direct but *deferred* transmission between the UE and the BS which seeks to take advantage of better channel quality in the near future; (iii) *opportunistic D2D-aided cellular:* eventual D2D transmission from the source node to an intermediate UE (or relay), which forwards the data to the BS. The decision on the communication mode to use can be based on latency, reliability or throughput metrics, to name a few. This paper focuses on selecting the communication mode that minimizes the energy consumption while guaranteeing the traffic QoS.

The integration of D2D-aided communications and opportunistic networking concepts can be exploited with the aim to increase the energy efficiency of non-real-time data transmissions. Indeed, according to recent estimates [4], non-real-time services (e.g. social networking, cloud services, data metering, mobile video, etc.) will represent an important share of the forthcoming mobile data traffic. And, for this type of services, the amount of data in the uplink direction is expected to increase considerably. The potential benefits of opportunistic D2D-aided uplink mechanisms are especially relevant in the context of this type of services.

The idea of integrating D2D communications in the architecture of a cellular network dates back to the work of Lin and Hsu [5], where a Multi-hop Cellular Network (MCN) architecture was proposed. In the last decade, researchers have been working on the integration of D2D in wideband multicarrier-based cellular networks (i.e., 4G, 5G, and beyond). The initial studies focused on local (proximity) services (see, e.g., [6]) whereas, subsequently, the research on D2D data offloading techniques (e.g. [7]) has widened the scope of integrating D2D and opportunistic networking concepts. Indeed, the combination of D2D and opportunistic networking can induce a significant performance improvement in obtaining/uploading contents from/to some remote server. In some recent theoretical and experimental studies, we have shown that considerable benefits can be obtained, in terms of energy consumption and cellular spectral efficiency, from the integration of D2D and opportunistic networking in cellular networks in the uplink ([3,8,9]) and in the downlink ([10–12]). However, these studies target a different problem than the one studied in this work, namely data offloading, or have focused on deriving and identifying optimum locations at which the D2D and cellular transmissions should take place to minimize the energy consumption.

Giving these previous promising findings, this work proposes and evaluates a mechanism that integrates opportunistic D2D-aided transmissions in cellular networks. In particular, this work develops a novel probabilistic model, and apply it to decide, at a source mobile node, through which communication mode (i.e. SH traditional, opportunistic cellular or opportunistic D2D-aided cellular) data should be transferred to the BS in order to minimize the transmission energy consumption. Using context information available in cellular networks (e.g. spatial density and distribution of nodes within the cell, nominal channel gains between each pair of locations in the physical area of interest, etc.), which we assume to be periodically broadcast by the BS, the devised model estimates the energy cost for each of the communication modes along the time available to complete the data transfer. The proposed mode selection scheme also considers that the data can be fragmented into chunks or fragments that can be uploaded at separate time instants within the available time. For each of these fragments, the proposed scheme selects a communication mode, and schedules the time instant at which the transmission should take place in order to minimize the overall energy consumption. Finally, the proposed scheme executes the selected communication modes at the scheduled time instants considering the real network conditions (e.g. location of potential relays).

The obtained results show that the proposed scheme, that integrates opportunistic D2D networking in cellular network, results in up to 90% energy consumption reduction compared to traditional SH cellular communications, and performs closely to an ideal optimal scheme (used for upper-bound benchmarking) that assumes full knowledge of the network state and all nodes' trajectories to select the most efficient communication mode.

2 Opportunistic D2D-Aided Scheduling and Transmission

Without loss of generality, we focus on a mobile node having to transmit to the BS a content of size D_c bits. The application QoS sets a time limit $T_{\max}$ to upload the content. Time is organized in Control Intervals (CI) of duration T_{CI}. The duration of a control interval is considered to be smaller than the time limit, i.e. $T_{\text{CI}} << T_{\max}$. For instance, $T_{\max}$ can be in the order of tens of seconds, or even several minutes, whereas T_{CI} is in the order of 1 s. We consider that the content size is larger than some maximum data that can be transmitted by a user in a CI. Therefore, the content to be transmitted is divided into fragments or chunks. Within each control interval CI, each transmitter can be allocated an amount of radio resources so that it can transmit D_{CI} bits ($D_{\text{CI}} < D_c$). In this context, the content to be uploaded is divided into $N_c = \lceil D_c/D_{\text{CI}} \rceil$ fragments. Each source node s has $N_{\text{CI}} = T_{\max}/T_{\text{CI}}$ control intervals to complete the transmission of the N_c fragments. In the considered scenario $N_c \leq N_{\text{CI}}$ and each node can transmit at most one fragment in a control interval.

Considering the scenario setup described above, this work proposes a scheme that seeks identifying the subset of N_c control intervals where fragments should be uploaded in order to minimize the overall energy consumption. For these identified control intervals, the proposed scheme also decides what communication mode to use (i.e. SH traditional, opportunistic cellular or opportunistic D2D-aided cellular) for the transmission of the fragment. The proposed scheme is carried out in two phases that are described below: mode selection & scheduling phase, and execution phase.

2.1 Mode Selection and Scheduling Phase

First, the mode selection & scheduling phase is executed at the source node when the content to be uploaded is generated. The source node uses a probabilistic model to estimate the energy cost of performing opportunistic cellular and opportunistic D2D-aided cellular transmissions in each of the available N_{CI} control intervals[1]. Then, and building on these estimates, the mode selection & scheduling phase selects the transmission mode and the control interval at which the source node will transmit each fragment of the content. To calculate the cost estimates, the proposed scheme uses context information that can be made available in the cellular network, and a trajectory prediction of the source node. More specifically, contextual information refers to (i) a map of nominal channel gains between each pair of locations (x, y) in the region, indicated with $g_{\text{D2D}}(x, y)$, where x and y represent the location of the transmitter and receiver of a D2D transmission, respectively, and a map of the nominal channel gains between any location x and the BS, indicated with $g_{\text{cell}}(x, x_b)$, where x_b is the location of the BS[2]; (ii) information about the urban structure of the region (streets, buildings, etc.); (iii) statistical information about the nodes' density and distribution within the cell.

In the following, we indicate with $E_{\text{cell}}(x, x_b)$ the energy cost of transmitting a fragment from a node (be it a source or a relay) located at x, to the BS through a cellular link, and with $E_{\text{D2D}}(x, y)$ the energy cost of transmitting a fragment from a source located at x to a relay located at y. These energy costs are deterministic functions of the respective nominal channel gains $g_{\text{cell}}(x, x_b)$ and $g_{\text{D2D}}(x, y)$, and of the cellular and D2D technologies (see Sect. 3). We represent the (discrete-time) trajectory, of a source node s as $x_s(t_k) = x_s(t_0) + v_s k T_{\text{CI}}$, where $t_k \triangleq kT_{\text{CI}}$, and both the location (x_s) and speed (v_s) vectors belong to $\mathbb{R}^2$. At this stage, we assume that the source node knows its own trajectory, which is not constrained to a specific model. We leave the evaluation considering source nodes' trajectory uncertainty to our future work. Finally, we indicate with

[1] It should be noted that the opportunistic cellular mode includes the SH traditional mode if the transmission between the UE and the BS is not deferred.

[2] The nominal channel gains depend on the geometry of the system, and not on the instantaneous channel conditions that are subject to time varying effects such as shadowing, fast fading and frequency selectivity (these effect are taken into account by adding a suitable link margin, see Sect. 3). We assume that the nominal channel gains maps $g_{\text{cell}}(x, x_b)$ and $g_{\text{D2D}}(x, y)$ are computed offline, or acquired through measurements sent periodically by the devices and suitably processed, over a very large time scale, by the network operator.

$\hat{E}_{\text{cell}}^{(s,k)}$ the expected energy cost associated to the direct cellular transmission of a fragment from source node s to the BS in the k-th control interval, and with $\hat{E}_{\text{D2D-aided}^*}^{(s,k)}$ the expected energy cost for the D2D-aided transmission in the k-th control interval. $\hat{E}_{\text{D2D-aided}^*}^{(s,k)}$ includes the cost of both transmissions, from source to relay and from relay to BS, and considers that the source node selects, among the available potential relays (i.e. neighboring nodes of the source node), the relay that minimizes the energy consumption of the overall opportunistic D2D-aided transmission.

Estimation of the Energy Cost of Opportunistic Single Hop Cellular Transmissions - The expected energy cost for the direct cellular transmission at time instant t_k, i.e. $\hat{E}_{\text{cell}}^{(s,k)}$, is computed in this work considering the location of the source node and nominal channel gain $g_{\text{cell}}(x, x_b)$ at this location. Based on $g_{\text{cell}}(x, x_b)$ and link margin (see Sect. 3), it can be computed the transmit power and hence the energy cost for a cellular transmission from the source node s to the BS at time instant t_k as

$$\hat{E}_{\text{cell}}^{(s,k)} = E_{\text{cell}}\left(x_s\left(t_k\right), x_b\right), \tag{1}$$

where we recall that the right-hand-side is a deterministic function of the channel gain map $g_{\text{cell}}(x, x_b)$.

Estimation of the Energy Cost of Opportunistic D2D-Aided Transmissions - The estimation of the energy cost $\hat{E}_{\text{D2D-aided}^*}^{(s,k)}$ needs to take into account that the future location of the relays is unknown at the time the mode selection & scheduling phase is performed (i.e., at time $t = t_0$). To this end, we have derived a probabilistic model for computing such cost. For space limit reasons, we omit the details of the derivations (which will be included in a future work). Instead, in this Subsection, we provide an outline of the steps we followed, and the main result given by the estimation of the cost associated to a D2D-aided transmission in Eq. (3).

- First, based on the density and distribution of nodes within the cell, the source node's trajectory prediction, and the nominal channel gain maps, it is possible to compute the cumulative distribution function (CDF) of the energy cost (which includes the cost of both D2D and cellular transmissions) assuming there will be a relay *at an unknown location.*
- Then, *conditioned on the number J of relays* that will be available at a given time instant t_k (at unknown and statistically independent locations), it is possible to obtain the CDF of the minimum energy cost that would be incurred by the opportunistic D2D-aided cellular transmission (achieved by using the "best" relay). This is conditioned to the number of relays that will be available.
- Finally, using the information about the density and distribution of the nodes within the cell, it is possible to compute the probability mass function of the

number of relays that will be available. Removing the conditioning on the J available relays from the CDF of the minimum energy cost, it is possible to obtain the CDF of the minimum cost associated to each instant t_k considering a source node s and, ultimately, its expected value. This expected value is used as an estimate of the energy cost for performing a D2D-aided fragment transmission at the k-th control interval, see Eq. (3).

More technical details are provided in the following. We indicate with $\mathcal{C}_s(t_k)$ the nominal D2D coverage region of a source node s at given time instant t_k. This coverage region is defined as a disk of radius R_{D2D} centered at $x_s(t_k)$, deprived of unreachable spaces for D2D transmissions like, for instance, locations inside buildings. $\mathcal{C}_s(t_k)$ is represented as a tessellation of square tiles of equal surface (e.g. $1\,\text{m}^2$). Let $1, ..., Q$ be an arbitrary labeling of the tiles available at $\mathcal{C}_s(t_k)$, and $x_i(t_k), \forall i \in \{1, \ldots, Q\}$, be the center of the tiles at time instant t_k. Following the previous notation, the total energy cost that would be incurred by opportunistic D2D-aided cellular for transmitting a *fragment* from a source node s located (in the k-th control interval) at $x_s(t_k)$, and using a relay r located at the center of tile i of the coverage region in the k-th control interval, i.e., at $x_i(t_k)$, can be computed as

$$E_{\text{D2D-aided}}\left(x_s(t_k), x_i(t_k)\right) = E_{\text{D2D}}\left(x_s(t_k), x_i(t_k)\right) + E_{\text{cell}}\left(x_i(t_k), x_b\right). \quad (2)$$

The quantities $E_{\text{D2D-aided}}\left(x_s(t_k), x_i(t_k)\right)$, computed for each tile $i \in \{1, \ldots, Q\}$, allow to establish a ranking of the locations (i.e., the tiles) in which it would be more preferable to have a relay. For a given position q in the ranking, we indicate with $i(q)$ the labeling index of the tile at position q in the ranking. Conversely, for a given tile i, we indicate with $q(i)$ the position of the tile i in the ranking. All possible values of the energy cost that would be incurred by the opportunistic D2D-aided cellular transmission at t_k can be expressed as $e_1(t_k), \ldots, e_Q(t_k)$, where the numbering order follows the energy cost-based ranking order, i.e., $e_1(t_k) \leq e_1(t_k) \leq \ldots \leq e_Q(t_k)$. We label the streets in the entire cell with the numbers in the set $\Psi \triangleq \{1, \ldots, N_\Psi\}$ and indicate with λ_ψ the (linear) density of nodes present on street $\psi \in \Psi$. For each time instant t_k, we consider the subset $\Psi_k^{(s)} \triangleq \left\{\psi_1^{(s,k)}, \ldots, \psi_{N^{(s,k)}}^{(s,k)}\right\} \subset \Psi$ of the $N^{(s,k)}$ streets whose median axis is at least partially within the coverage region $\mathcal{C}_s(t_k)$, and we also indicate with $l_n^{(s,k)}$ the length of the portion of street $\psi_n^{(s,k)}, \forall n \in \left\{1, \ldots, N^{(s,k)}\right\}$, covered by $\mathcal{C}_s(t_k)$.

Following the derivation steps outlined above, it is possible to obtain the following expression for the expected energy cost of the opportunistic D2D-aided transmission, which we use as the desired estimation:

$$\hat{E}^{(s,k)}_{\text{D2D-aided}^*} \triangleq \mathbb{E}_{E^{(s,k)}_{\text{D2D-aided}^*}}(e) = \sum_{q=1}^{Q} \left(e_q^{(s,k)} \sum_{j=0}^{\infty} \left(p_{J^{(s,k)}}(j)\, p_{E^*}\left(e_q^{(s,k)} \mid j \right) \right) \right), \quad (3)$$

where $p_{J^{(s,k)}}(j) = \frac{1}{j!}\left(\sum_{n=1}^{N^{(s,k)}} \lambda_{\psi_n^{(s,k)}} l_n^{(s,k)}\right) \exp\left(\sum_{n=1}^{N^{(s,k)}} \lambda_{\psi_n^{(s,k)}} l_n^{(s,k)}\right)$.

Control Interval and Transmission Mode Selection - Considering the k-th control interval, we indicate the minimum among the expected energy cost associated to a direct opportunistic cellular transmission and the expected energy cost associated to an opportunistic D2D-aided one as

$$\hat{E}\left(s,k\right) = \min\left(\hat{E}_{\text{cell}}^{(s,k)}, \hat{E}_{\text{D2D-aided*}}^{(s,k)}\right). \tag{4}$$

The N_{CI} control intervals can be ranked, in ascending order, according to their energy cost $\hat{E}\left(s,k\right)$ $\forall k \in \{0,\ldots,N_{\text{CI}}-1\}$. The source node's strategy for the transfer of the content (i.e. of the N_c fragments) can be scheduled by selecting the N_c control intervals with the minimum expected energy cost. Clearly, the communication mode that will be used at the scheduled control interval k is the one which minimizes the expected energy cost in (4).

2.2 Execution Phase

The execution phase is in charge of implementing the communication modes selected in Sect. 2.1 at the scheduled control intervals, considering the real network conditions (i.e., the location of potential relays). In the control intervals for which a direct transmission was scheduled, the source node s transmits directly the fragment to the BS. In the control intervals for which an opportunistic D2D-aided cellular transmission was scheduled, the source node selects a relay among its neighbors. More specifically, it selects the relay with the lowest overall cost, i.e., including the source-to-relay D2D transmission cost and the relay-to-BS transmission cost. At execution time t_k it is possible to identify this relay. During the mode selection & scheduling phase, the source node s had determined the cost of the opportunistic D2D-aided transmission for each tile within the D2D coverage region $\mathcal{C}_s(t_k)$. This allows to establish a ranking of the locations (i.e. the tiles) in which it would be more desirable to have the relay. Note that, in Sect. 2.1, it was necessary to consider all the tiles since the source had no knowledge of where the potential relays would be located in the future. Then, in the execution phase, the source node selects as relay the neighbor that is located on the tile with the highest ranking (i.e., the lowest energy cost) among those tiles which have a neighbor on them. In case the source node finds no relays, it directly transmits the fragment to the BS.

3 Performance Evaluation

We have evaluated, using a Matlab-based simulator, the performance of the proposed scheme in a "Manhattan" grid scenario of 6 × 6 blocks. The widths of streets and buildings are set to 10 m and 90 m, respectively. The average height of the buildings is 20 m, and they have on average 4 floors. The BS is located at a height of 25 m on top of a building at the center of the scenario. A map-based channel model for urban macro-cell scenarios [13], which takes into account all the layout of the scenario and buildings described above, is used to compute the nominal channel gains for the cellular transmissions. The propagation losses for the D2D transmissions are modeled following the METIS Project's D1.4 on channel models [14]. This D2D model distinguishes between line-of-sight (LOS) and Non-LOS (NLOS) conditions. The mobility traces of the nodes in the scenario are obtained using the SUMO (Simulation of Urban MObility) simulator [15]. The nodes' speed is set to 1.5 m/s. At streets crossings, the nodes can turn right or left, or continue straight with equal probability. Different densities of nodes in the scenario are considered. Out of all the available nodes, the source nodes are selected randomly.

The evaluation has been conducted considering that the cellular and D2D technologies use the LTE spectrum band (a.k.a. in-band D2D) at 2.3 GHz. The control interval T_{CI} is set to 1 s. The considered traffic load guarantees that the cellular system can provide the required radio resources (i.e. Physical Resource Blocks) to the D2D and cellular links to transmit D_{CI} bits in a CI[3]. In our simulations, the traffic uploading requests follow a Poisson distribution with a rate $\lambda_{\mathrm{req}} = 1/10$. We considered contents with a size of $D_c = 24$ Mbits, made of $N_c = 6$ fragments of $D_{CI} = 4$ Mbits each. We considered $T_{\max}$ values in the set $\{10, 20, 30\}$ s.

The computation of the energy consumption of D2D and cellular transmissions takes into account both the nominal channel gain and random channel effects, including shadowing and multi-path fading, that are included through a suitable link margin (different for D2D and cellular transmissions). Following [11], we compute the energy consumed to transmit a single fragment (i.e. D_{CI} bits) as

$$E_{\mathrm{CI}} = n_u \tau_{\mathrm{PRB}} M \cdot (1/g) \mathcal{N}_0 B_{\mathrm{PRB}} \left(2^{(D_{\mathrm{CI}}/(n_u \tau_{\mathrm{PRB}} B_{\mathrm{PRB}}))} - 1 \right), \tag{5}$$

where g is the nominal channel gain. n_u is the number of PRBs used to transmit the D_{CI} bits in a control interval (assumed to be fixed). B_{PRB} and τ_{PRB} are the bandwidth and duration of a single PRB, that are equal to 180 KHz and 0.5 ms for LTE. $\mathcal{N}_0$ is the thermal noise power spectral density, and M is a suitable link margin calculated for the scenario under study[4].

For comparison purposes, besides the proposed scheme, the following schemes have been also evaluated under the conditions described above:

(i) Single-Hop (SH) traditional: In the SH traditional scheme, the source node does not implement any opportunistic networking scheme. Therefore, it uses the first N_c control intervals to upload the content to the BS.

[3] For example, considering an LTE system, each PRB carries a number of bits in the range from 16 to 720 (based on [16]). Assuming that a PRB carries 400 bits, there would be needed 10.000 PRBs to transmit a content fragment of size D_{CI} bits. In the considered control interval of 1 s, there are approximately {50.000, 100.000, 200.000, 500.000} PRBs for a LTE system of {5, 10, 20, 50} MHz bandwidth. In our simulations, we used a system bandwidth of 10 MHz.

[4] For the purposes of this work, we have computed, through offline simulations, suitable link margins for both cellular and D2D transmissions, obtaining values of 10 dB for D2D transmissions, and 4 dB for cellular transmissions.

(ii) Opportunistic cellular-only: For a fair comparison with the proposed scheme, the source nodes implementing the opportunistic cellular-only scheme uses the probabilistic model presented in Sect. 2.1 to select the N_c control intervals to complete the upload. Contrary to the proposed scheme, however, it only considers the costs associated to direct cellular transmissions.

(iii) Optimal scheme: The optimal scheme assumes the source nodes have full knowledge about the network conditions and other nodes' trajectory. Therefore, it can select the modes to use (either opportunistic cellular or opportunistic D2D-aided cellular) for each of the N_c control intervals that minimize the energy consumption. The implementation of this scheme is unfeasible in real networks and is utilized in this work to identify what would be the upper-bound of the proposed scheme.

For a fair comparison, the selected source nodes implement the four schemes under evaluation at the same position and time instant. The results reported in the next sub-sections are obtained over several simulation runs to guarantee the statistical accuracy of the results.

3.1 Mode Selection Accuracy

It is important to investigate how the proposed scheme adapts to the context conditions of the scenario to select the communication mode, and more specifically, to the node density. In Fig. 1, we report the average percentage share of the selected communication modes for the transmission of a fragment among opportunistic SH cellular and opportunistic D2D-aided cellular. We considered different values for the number of nodes present in the scenario, and three different values for the maximum time limit within which the transfer of the content needs to be completed. For example, when there are 100 nodes in the scenario, the opportunistic D2D-aided cellular mode is scheduled 54.2% of the times[5]. This percentage increases to 99% when the number of nodes in the scenario is 1500 nodes. The opportunistic D2D-aided communication mode is selected more frequently when the density of nodes in the scenario increases. This is the case because the proposed scheme takes this context information as an input for the estimation of the energy cost of the opportunistic D2D-aided transmissions. Practically speaking, the energy cost that the model estimates for the opportunistic D2D-aided transmissions reduces when it is more likely to find relays within the source node's D2D coverage region. This favors that one of the potential relays is under "good" conditions to the BS.

Regarding the effect of $T_{\max}$, a larger value of this parameter allows the source nodes to delay the start of the transmission to search for more efficient

[5] It has to be pointed out that for a scenario of the considered size, 100 nodes is a quite low number. For instance, in scenarios with the size considered in this study, the simulation guidelines reported in [17] suggest considering 1500 nodes for the test case "dense urban scenario societies". However, we believe that testing worst-case scenarios is also interesting to gain insights into the effectiveness and limits of the proposed scheme.

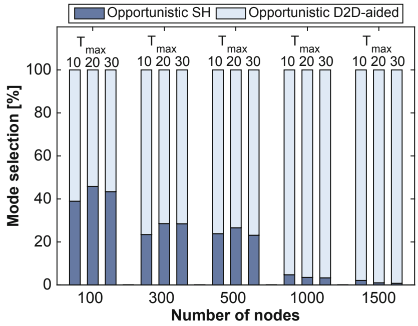


Fig. 1. Selected communication mode share

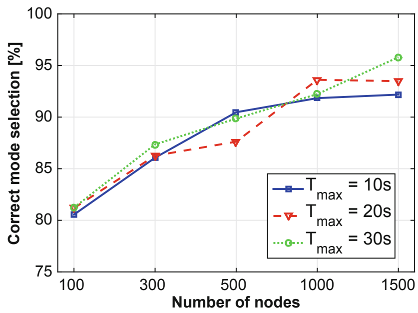
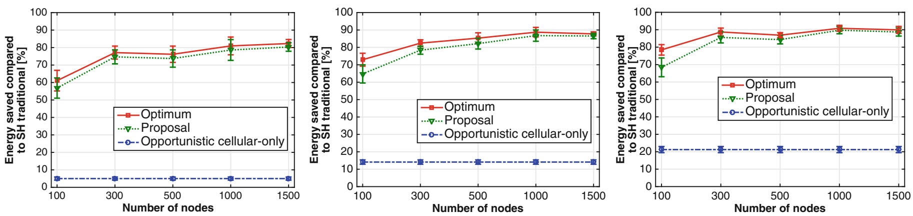


Fig. 2. Correct mode selection [%]

communication conditions. This allows to find more favorable conditions for both the opportunistic SH transmissions and the opportunistic D2D-aided ones. Therefore, the results reported in Fig. 1 show similar trends of the mode selection share as a function of $T_{\max}$. As we will see in the next subsection, however, $T_{\max}$ has an effect on the performance in terms of energy savings.

In Fig. 2, we show the accuracy of the proposed scheme in selecting the correct communication mode at the scheduled control interval. A correct selection is represented by the occurrence that a selection based on the actual conditions found at execution time would have provided the same choice performed by the proposed scheme in the mode selection & scheduling phase. A non-correct decision may arise since the proposed scheme selects the communication mode based on the probabilistic model, without knowing exactly the conditions the source node will find at execution time (i.e., the position of the potential relays) in the considered control interval. The results show that the accuracy of the proposed scheme in selecting the correct communication mode is above 80% for the scenarios under study, even under a very low node density.



(a) $T_{\max} = 10s$ (b) $T_{\max} = 20s$ (c) $T_{\max} = 30s$

Fig. 3. Energy consumption compared to traditional single-hop.

3.2 Energy Consumption Reduction

This section analyzes the reduction in average energy consumption achieved by the proposed scheme compared to the benchmark 'opportunistic cellular-only' and 'optimum' schemes described above. The performance of the 'SH traditional' scheme is used as a reference. The results reported in Fig. 3 show average energy reduction percentage with respect to 'SH traditional'. The plots in Fig. 3 also display the 95% confidence intervals obtained with our set of simulations.

The results reported for 'opportunistic cellular-only' show that the sole use of opportunistic networking in cellular networks already helps reducing the energy consumption compared to 'SH traditional' communications. For example, when $T_{\max}$ is set to 10 s (Fig. 3a), the 'opportunistic cellular-only' scheme reduces the energy consumption by 7% compared to 'SH traditional'. The benefits of integrating opportunistic networking in cellular networks increase with the available $T_{\max}$ since this allows the source nodes to search for more efficient communication conditions. In fact, the results reported in Fig. 3c show that the 'opportunistic cellular-only' scheme reduces the energy consumption by more than 20% compared to 'SH traditional' in the scenario in which $T_{\max}$ is set to 30 s. However, the scheme proposed in this work that, besides opportunistic cellular, also integrates D2D and opportunistic networking can achieve significant additional energy benefits. For instance, when $T_{\max}$ is set to 10 s (Fig. 3a), the proposed scheme reduces the energy consumption by 55% (in the worst case of 100 nodes) and up to 80% (with 1500 nodes) compared to 'SH traditional'. Since the proposed scheme also exploits opportunistic networking, it benefits from larger values of $T_{\max}$. In particular, Fig. 3c shows that with the proposed scheme the energy consumption is reduced by 65% (in the worst case of 100 nodes) and close to 90% (with 1000 or 1500 nodes) compared to 'SH traditional', in the scenario in which $T_{\max}$ is set to 30 s. The main reason for the reported energy reductions is that, in a urban scenario, as the one considered, NLOS links with the BS are quite frequent. If the source node is under NLOS with the BS, the effect of the combined exploitation of delay tolerance and the possibility to use an intermediate relay is to significantly increase the possibility to find a condition in which the final cellular transmission to the BS is under LOS, which requires a much lower transmit power. Regarding the performance trend with increasing node density, the energy reduction levels of the proposed scheme increase compared to 'SH traditional'. This is the case because with the increasing node density it is more likely to find a relay in a favorable position (and this is incorporated in the statistical model used to perform the mode selection & scheduling). Finally, it is interesting to observe that the gap with the performance of the 'optimal' scheme is quite small. The 'optimal' scheme only reduces by 10% or less the energy consumption compared to the proposed scheme under the worst-case node density, and the gap reduces with an increasing node density, with a ∼3% gap at 300 and 500 nodes, and a ∼1% gap at 1000 and 1500 nodes. It is important to remember that the 'optimum' scheme assumes the source nodes are able to predict, error-free, what is the best communication mode to use at each control interval (either opportunistic cellular or opportunistic D2D-aided) and its actual associated energy cost.

Therefore, the source nodes implementing the 'optimum' scheme can select communication modes and the control intervals that minimize the total energy consumption. The proposed scheme, that is designed for practical implementations, exploits instead context information available in cellular networks to make a probabilistic estimate of the energy costs, but can still achieve a performance quite close to the 'optimum' scheme.

4 Conclusions

This study has investigated the potential of integrating D2D and opportunistic networking in cellular networks to reduce the energy consumption in the uplink. We have proposed a probabilistic model that derives the communication mode and the time instant at which transmissions should take place in order to minimize the energy consumption. The proposed scheme exploits both opportunistic direct and D2D-aided transmissions across the time window allowed by a delay-tolerant application. The proposed scheme also divides contents into fragments and performs independent strategies for each fragment. To this aim, the proposed scheme uses context information available in cellular networks including density and distribution of nodes within the cell, statistical information about the channel gain, and the trajectory of the source node. The conducted evaluation has shown that the proposed scheme allows to select the correct transmission mode for each fragment (which minimizes the energy cost for the transmission), with very high accuracy (always above 80%). In terms of energy consumption reduction, the performance gains achieved by the proposed scheme are quite significant. The results show that the proposed scheme can significantly reduce the energy consumption (by up to 90% under the considered conditions) compared to a single-hop traditional scheme. In future works, we will expand the proposed technique by considering uncertainties in the source nodes' trajectory prediction and using a nesting mechanism which provides more freedom to the relays to decide how to upload the received data to the BS.

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