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Context-Aware Opportunistic Networking in Multi-Hop Cellular Networks

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Abstract – 5G networks will be required to efficiently support the growth in mobile data traffic. One approach to do so is by exploiting Device-to-Device (D2D) communications and Multi-Hop Cellular Networks (MCNs) in order to enhance the spectrum re-use and offload traffic over underlay networks. This study proposes to further improve the efficiency of transmitting mobile data traffic by integrating opportunistic networking principles into MCNs. Opportunistic networking can exploit the delay tolerance characteristic of relevant data traffic services in order to search for the most efficient transmission conditions in MCNs. The study first presents an analytical framework for two-hop opportunistic MCNs designed to identify their optimum configuration in terms of energy efficiency. Using this reference configuration, the paper then proposes a set of opportunistic forwarding policies that exploit context information provided by the cellular network. Numerical and simulation results demonstrate that opportunistic networking can significantly contribute towards achieving the capacity and energy efficiency gains sought for 5G networks. Under the evaluated conditions, the obtained results show that the proposed schemes can reduce the energy consumption compared to traditional cellular communications by up to 98% for delay tolerant services. In addition, the proposed schemes can increase the cellular capacity by up to 79% compared to traditional cellular communications.

Keywords – Multi-hop cellular networks (MCN); opportunistic networking; device-centric wireless; D2D; 5G.

1. Introduction

5G networks will face significant challenges to support the expected growth (by a factor of 500 to 1000) in mobile traffic in the next decade [1]. Such growth levels are expected to come from a 10 times increase in broadband mobile subscribers, and 50-100 times higher traffic per user. Leading international organizations also expect that 5G networks should support, compared to current 4G networks, 10 to 100 times more connected devices, 10 to 100 times higher user data rates, and 5 times smaller end-to-end latency. All this should be achieved while saving up to 90% of energy per provided service [1]. These expectations and forecasts have launched the race towards the definition and design of efficient future 5G networks. Relevant efforts currently focus on the use of higher frequency bands, the dense deployment of small cells and the design of advanced transmission technologies [2]. These approaches can be deemed as an evolution from the traditional cell-centric architectures. There is also a significant belief in the community [3] that future wireless networks need to explore and evolve from current cell-centric architectures to device-centric architectures that exploit the intelligence, communications and computing resources of smart mobile devices. This trend has been lately fostered by the identified benefits of Device to Device (D2D) communications that facilitate new value added services (including proximity based services), support critical public safety applications, help offload cellular traffic from the base stations, and increase the spatial frequency reuse and therefore the overall capacity of cellular networks [4]-[7]. In future device-centric wireless networks, smart mobile devices will provide wireless connectivity to other devices and will hence act as a bridge with the cellular infrastructure. The integration of cellular and ad-hoc or D2D communications is referred to as Multi-hop Cellular Networks (MCNs). MCNs will transform mobile devices into prosumers of wireless connectivity in an underlay network that if efficiently coordinated with the cellular network has the potential for significant capacity, energy efficiency and Quality of Service (QoS) benefits [8].

MCNs exploit the communications, computing and networking capabilities of smart devices. MCNs can also benefit from the mobility and storing capacity of mobile devices to implement opportunistic networking schemes that exploit the store, carry and forward paradigm. Traditionally, opportunistic networking has been proposed for disconnected networks that cannot always reliably ensure real-time end-to-end connections [9]. However, the authors believe that opportunistic networking can also be exploited in networks without disconnections (for example, in urban environments) in order to enhance the efficiency of device-centric wireless transmissions (whether D2D or MCN). In this case, two devices might not initiate a transmission (or even establish a connection) if such transmission is not sufficiently efficient, e.g. because of a low received signal level that would result in a high number of retransmissions and the use of low data rate transmission modes. Devices could hence benefit from waiting for more efficient transmission conditions to start their transmission. In this case, devices will reduce their energy consumption, while also improving the capacity of the network since less wireless resources will be needed to transmit a given amount of data. This opportunistic networking approach could result in some transmission delays, although it is not always the case as demonstrated in [10]. In any case, and according to Cisco estimates [11], delay tolerant services (including mobile video, social networking services, emails, and cloud services, among others) will represent a non-negligible portion of the expected mobile data traffic volume in the years to come. For example, Cisco estimates that mobile video will represent 69% of the mobile data traffic by 2018 [11]. In this context, efficiency-driven opportunistic networking principles could be designed for delay tolerant mobile data traffic, and integrated into device-centric wireless networks in order to enhance the efficiency and capacity of future 5G wireless networks. This is actually the objective of this study that focuses on device-centric wireless networks based on MCNs using mobile relays and D2D communications.

This study proposes novel opportunistic forwarding policies for MCNs and mobile delay tolerant services, and investigates their capacity and energy efficiency gains. The study focuses on two-hop uplink MCN communications where mobile devices with store, carry and forward capabilities relay the transmission between the source node and the base station. The emphasis is placed on two-hop wireless relaying due to the diminishing benefits when considering more than two hops for store, carry and forward relaying with the additional complexities and overhead to orchestrate the transmissions. The paper first presents an analytical framework that identifies the optimum mobile relay location, and the location at which the mobile relay needs to start forwarding the information to the cellular base station in order to minimize the total transmission energy consumption without degrading the end-user QoS. It might not always be feasible to implement the optimum configuration, for example, if there are no devices available at the optimum mobile relay location when needed. The study proposes then a set of opportunistic forwarding strategies that build from the optimum configuration and exploit context information obtained from the cellular network to facilitate their implementation. The strategies focus on relaxing the need to find a mobile relay located at the identified optimum location and time instant. In the first strategy, if no mobile relay is available at the identified optimum location and time instant, the source node waits for a mobile relay to reach the optimum location and then initiates the D2D transmission towards the mobile relay. In the second strategy, the source node increases the search area around the identified optimum location to find potential mobile relays. The proposed opportunistic forwarding strategies exploit context information already available in cellular systems (density and distribution of mobile nodes within the cell) to estimate the search area radius or the maximum time the source node should wait to guarantee with certain probability the presence of at least one mobile relay at the required location. The paper also evaluates the conditions under which each of these two strategies should be employed. The proposed opportunistic forwarding strategies have been designed with the initial objective to minimize the energy consumption. However, the study demonstrates that in addition to their significant energy benefits, the proposed strategies also increase the capacity compared to other forwarding schemes and traditional single-hop cellular communications where the information is directly transmitted from the source node to the cellular base station.

The rest of this paper is organized as follows. Section 2 reviews related studies. Section 3 introduces the concept of energy efficient opportunistic forwarding in MCNs using mobile relays and D2D communications, and formulates the analytical framework for deriving the optimum configuration that minimizes the energy consumption. Section 4 presents the two context-aware opportunistic forwarding proposals that relax the need to find mobile relays at the identified optimum location and time instant. These strategies are then evaluated in Section 5. Finally, Section 6 summarizes the main outcome of this study and concludes the paper.

2. Related Work

Opportunistic networking was initially proposed for disconnected wireless networks. In the absence of forwarding opportunities, mobile nodes could store the message and carry it until they can forward it to other nodes. Opportunistic networking can reduce the energy consumption [12] at the cost of possible higher transmission delays [13]-[14]. For example, the study reported in [15] investigates the problem of optimal opportunistic forwarding for Delay/Disruption-Tolerant Networks (DTN) under energy constraints (the study considers that the energy for transmitting a message is limited). To maximize the delivery probability while satisfying the energy constraint, the study controls the probability of transmitting a message upon the opportunistic connectivity between devices. Important efforts have also been devoted to estimate the periodicity in the encounters between mobile nodes [16], as well as the duration of opportunistic connections and the nodes' inter-contact time [17]-[18]. These studies have been further extended to consider the impact of duty-cycle operation that results in that nodes can miss contact opportunities when they operate under sleep state for saving energy [19]. In [20], the authors demonstrate that the performance of opportunistic networking can be improved when exploiting context information. In particular, the authors propose to exploit the spatial and temporal features of context information for more efficient forwarding decisions. The study proposes a social context-based routing scheme that is used to predict the context of nodes, so that devices know when and where they should start forwarding messages in order to minimize the transmission delay and network overhead.

Opportunistic networking principles can be extended to networks that do not suffer frequent disconnections. In fact, opportunistic networking can be utilized for searching for the most efficient transmission conditions between devices. For example, the adoption of opportunistic networking principles has been proposed to extend the coverage of cellular networks, offload cellular traffic using D2D communications, or increase the capacity [17]. The studies reported in [21] and [22] show that opportunistic policies can significantly enhance the efficiency of D2D transmissions by pausing communications under unreliable and low efficiency link quality conditions, and resume them when channel conditions improve. This feature was proven in [23] using queuing theory, and has been recently experimentally demonstrated in [10]. The benefits of integrating opportunistic networking and multi-hop cellular networks was first discussed in [24], where the authors present novel routing policies that use information about the relays' mobility to reduce energy consumption, increase spatial capacity, reduce co-channel interference, balance the load across cells, and switch-off low-utilization base stations. To do so, the authors define a graphical representation of the relays' mobility with time in a finite space-time network graph that includes all possible forwarding decisions. The graph's vertexes represent the location of the mobile relays and the graph's edges the communication links. Using the graph, a base station is able to establish end-to-end routes to achieve the desired outcome (reduce energy consumption, balance the load, etc.). The authors extend their prior study to cognitive cellular networks in [25], and demonstrate the importance of taking into account the power consumption of storage units in mobile relays when considering opportunistic networking.

Previous studies have shown that opportunistic networking and mobile relaying can reduce the energy consumption at the expense of some possible transmission delays. These technologies are then particularly suitable for delay tolerant services that offer the possibility to exploit the tolerable delay for an efficient integration of opportunistic networking into cellular networks. In this context, this study focuses on the use of opportunistic networking in MCNs to improve the transmission efficiency and reduce energy consumption, and not to handle disconnections like in traditional DTN scenarios. The authors presented in [26] an analytical framework for two-hop opportunistic MCN communications where a mobile node communicates with a base station using a mobile relay with store, carry and forward capabilities. This analytical framework derives the optimum locations at which the D2D and cellular transmissions should take place in order to reduce the energy consumption while satisfying the service QoS requirements. The presented framework assumed that it was possible to find mobile relays when needed at the derived optimum locations. To address this constraint, the authors first proposed a suboptimum solution that searches for mobile devices around the derived optimum location. This solution was first analyzed in [26] under a simple scenario where mobile devices are uniformly distributed within the cell. This solution is here further extended to more realistic scenarios where mobile devices are non-uniformly distributed. The solution in [26] addressed the possible lack of mobile relays at the identified optimum location and time instant by searching for mobile relays around the optimum location. An alternative solution is to wait for a mobile device to arrive at the derived optimum location [27]. An important issue that needs yet to be resolved is to determine when each of these two solutions should be employed if it is not possible to find a mobile relay at the identified optimum location and time instant. This paper addresses this critical aspect, and identifies the conditions under which each solution should be utilized to maximize efficiency, increase capacity, and satisfy the QoS requirements. To do so, this paper compares the performance of the two solutions under diverse scenarios with uniform and non-uniform distribution of nodes within the cell, and with varying spatial densities of nodes. The conducted analysis also studies the impact of the speed of mobile devices and the traffic characteristics.

3. Opportunistic Forwarding in MCN

This study considers the two-hop uplink MCN scenario reported in Figure 1 where a static Source Node (SN) communicates with a Base Station (BS) using a Mobile Relay (MR) with store, carry and forward capabilities. The study does not focus on any particular traffic service but considers that messages need to be transmitted before a deadline T in order not to degrade the end-user Quality of Experience (QoE). In this case, the time available to transmit the information from SN to BS can be computed considering: 1) the time needed for the D2D transmission from SN to MR (*D2D tx*), 2) the time that MR stores and carries the information (*Store and Carry*), and 3) the time needed by MR to transmit the information to the BS (*Cellular tx*). It is important noting that estimating the time the *D2D tx*, *Store and Carry* and *Cellular tx* processes need is in fact equivalent to identifying the MR location at which the D2D transmission should start (Opt_X_i), and the MR location at which the cellular transmission should start (Opt_Y_i). These locations are estimated in this study with the objective to minimize the overall energy consumption of end-to-end MCN communications[1].

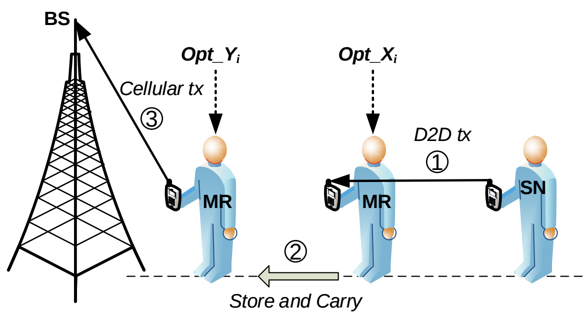

Figure 1. Two-hop opportunistic MCN scenario.

[1] Opportunistic MCN communications are configured in this study to reduce the total energy consumption. However, it will be later shown that opportunistic MCN communications can also increase the capacity even if initially configured to reduce the energy consumption.

3.1. Problem Formulation

The authors defined an optimization framework to identify the Opt_X_i and Opt_Y_i solutions that minimize the energy consumption in two-hop opportunistic MCN scenarios (eq. (1)-(4)) [26]. The multi-objective function in eq. (1) has been defined subject to the requirement that the message (of size *F*) is completely transmitted in the D2D (eq. (2)) and cellular (eq. (3)) connections, and the need that the end-to-end opportunistic MCN transmission is completed before the deadline *T* (eq. (4)). This deadline *T* is discretized in the optimization framework as $\{\tau_0, \tau_1 \ldots \tau_T\}$.

$$o.f: \min \begin{pmatrix} \underbrace{\sum_{\tau=\tau_0}^{\tau_{b-1}} \left(E_{D2D}\left(d_{SN-MR}, \tau\right) + \tau \cdot \left(P_R + P_W\right)\right) +}_{①} \\ \underbrace{\sum_{\tau=\tau_b}^{\tau_{c-1}} \tau \cdot P_{IDLE} +}_{②} \\ \underbrace{\sum_{\tau=\tau_c}^{\tau_{c+m}} \left(E_{cell}(d_{MR-BS}, \tau) + \tau \cdot P_W \right)}_{③} \end{pmatrix} \tag{1}$$

$st:$

$$\sum_{\tau=\tau_0}^{\tau_{b-1}} TR_{D2D}\left(d_{SN-MR}\right) \cdot \tau \geq F \tag{2}$$

$$\sum_{\tau=\tau_c}^{\tau_{c+m}} TR_{cell}\left(d_{MR-BS}\right) \cdot \tau \geq F \tag{3}$$

$$\tau_0 < \tau_{b-1} < \tau_b \leq \tau_{c-1} < \tau_c < \tau_{c+m} \leq \tau_T \tag{4}$$

The function in eq. (1) seeks minimizing the energy consumed in end-to-end opportunistic MCN transmissions. As a result, it considers the energy consumed at SN and MR in the *D2D transmission* ①, at MR in the *Store and Carry* process ② and at MR in the *Cellular transmission* to the BS ③. $\sum_{\tau=\tau_0}^{\tau_{b-1}} E_{D2D}\left(d_{SN-MR}, \tau\right)$ represents the energy consumed in the D2D transmission from SN to MR within the time interval $\{\tau_0, \tau_1 \ldots \tau_{b-1}\}$; the distance between the nodes at τ is considered to be equal to d_{SN-MR}. $\sum_{\tau=\tau_0}^{\tau_{b-1}} \tau \cdot \left(P_R + P_W\right)$ represents the sum of the storage power consumption at SN and MR while transmitting and receiving the information [25]; P_R and P_W are defined in Section 3.4. $\sum_{\tau=\tau_b}^{\tau_{c-1}} \tau \cdot P_{IDLE}$ represents the storage power consumption at MR while it moves towards the BS within the time interval $\{\tau_b, \tau_{b+1} \ldots \tau_{c-1}\}$. $\sum_{\tau=\tau_c}^{\tau_{c+m}} E_{cell}(d_{MR-BS}, \tau)$ represents the energy that MR consumes during the cellular transmission to the BS within the time interval $\{\tau_c, \tau_{c+1} \ldots \tau_{c+m}\}$. This energy is computed considering that the distance between MR and BS at τ is equal to d_{MR-BS}. On the other hand, $\sum_{\tau=\tau_c}^{\tau_{c+m}} \tau \cdot P_W$ represents the storage energy consumption at MR during its cellular transmission to the BS [25].

Two constraints need to be considered to ensure that the message (of size *F*) is completely transmitted from SN to MR (eq. (2)) and from MR to BS (eq. (3)). TR_{D2D} and TR_{cell} represent the throughput of the D2D and cellular transmissions, respectively. $\sum_{\tau=\tau_0}^{\tau_{b-1}} TR_{D2D}\left(d_{SN-MR}\right)\cdot\tau$ represents then in eq. (2) the transmitted D2D data within the time interval {τ_0, τ_1… τ_{b-1}}. $\sum_{\tau=\tau_c}^{\tau_{c+m}} TR_{cell}\left(d_{MR-BS}\right)\cdot\tau$ represents in eq. (3) the transmitted cellular data within the time interval {τ_c, τ_{c+1}… τ_{c+m}}. The data transmitted in the D2D and cellular connections is computed considering that the distance between SN and MR, and between MR and BS, is equal to d_{SN-MR} and d_{MR-BS} at τ. Finally, eq. (4) is defined so that the derived solution guarantees that the end-to-end MCN transmission is completed before the deadline *T*.

For a given location of the SN, the optimization framework presented in equations (1) to (4) derives the optimum configuration of two-hop opportunistic MCN communications that minimizes the overall energy consumption. This optimum configuration is given by the time instances τ_0, τ_{b-1}; τ_b, τ_{c-1}; τ_c and τ_{c+m} at which the *D2D transmission*, *Store and Carry* and *Cellular transmission* processes should take place, respectively. As previously explained, deriving such time instances is actually equivalent to finding Opt_X_i and Opt_Y_i. This optimization framework (represented by ϑ) can then be summarized as follows:

$$\begin{aligned}&\left[\tau_0,\tau_{b-1},\tau_b,\tau_{c-1},\tau_c,\tau_{c+m};Opt\_X_i,Opt\_Y_i\right]=\\&\arg\min\left(\vartheta\left(F,T,TR_{D2D},TR_{cell},E_{D2D},E_{cell},P_R,P_W,P_{IDLE}\right)\right)\end{aligned} \tag{5}$$

3.2. Transmission Energy Consumption

The energy consumed in the D2D and cellular transmissions is modeled using the WINNER pathloss model for urban scenarios with low antenna heights [28]. The signal power level at the receiver (P_{RX}) is computed as:

$$P_{RX}=G_{TX}+G_{RX}+P_{TX}-PL \tag{6}$$

where G_{TX} and G_{RX} represent the transmitter (TX) and receiver (RX) antenna gain, P_{TX} is the transmission power, and *PL* is the pathloss. The study considers that P_{TX} is the necessary transmission power to guarantee that P_{RX} is equal to the threshold received power level required for a successful communication between two nodes. P_{TX} can be computed as a function of the separation distance (*d*, in meters) between TX and RX:

$$P_{TX}(d)=\begin{cases}\dfrac{P_{RX}\cdot10^{4.1}\cdot\left(f/5\right)^2}{G_{TX}\cdot G_{RX}}d^{2.7} & if\ d<d_{bp}\\[2ex]\dfrac{P_{RX}\cdot10^{4.1}\cdot\left(f/5\right)^2}{G_{TX}\cdot G_{RX}\cdot d_{bp}^{1.73}}d^{4} & if\ d\ge d_{bp}\end{cases} \tag{7}$$

where *f* represents the carrier frequency (in GHz), and d_{bp} represents the breakpoint distance. d_{bp} is equal to $4\cdot(h_{TX}-1)\cdot(h_{RX}-1)/\lambda$. h_{TX} and h_{RX} represent the TX and RX antenna heights (in meters), and λ is the carrier wavelength (in meters).

The energy consumed in the D2D (E_{D2D}) and cellular (E_{cell}) transmissions can be estimated as:

$$E\left(d\right)=\left(e_{rx}+e_{tx}+e(d)\right)\cdot TR \tag{8}$$

where e represents the transmission energy consumption per bit, e_{tx} represents the energy consumption per bit in the transmitter electronics, and e_{rx} represents the energy consumption per bit in the receiver electronics. e is equal to P_{TX}/TR, where TR represents the throughput (TR_{D2D} or TR_{cell}). Equations (7) and (8) are defined considering Line-Of-Sight (LOS) propagation conditions. The energy consumption under Non-LOS (NLOS) conditions can be computed following a similar process.

3.3. Transmission Data Rate

This study (without loss of generality) considers an LTE system at 2GHz for the cellular transmissions, and IEEE 802.11g at 2.4GHz for the D2D transmissions[2]. The selection of these radio access technologies was driven by the availability of the models needed to create the analytical framework. However, it is important noting that the overall concept and the conclusions here reported do not depend on the selected technologies.

Using the model reported in [29], the cellular LTE throughput can be computed as a function of the distance (d, in meters) between MR and BS:

$$TR_{cell}\left(d\right)=r\left(N_{PRB},l_{MCS}\right)\cdot\left(1-p_{BLER}\left(N_{PRB},l_{MCS}\right)\right) \tag{9}$$

where $r(N_{PRB}, l_{MCS})$ represents the maximum instantaneous data rate as a function of the number of Physical Resource Blocks (N_{PRB}) and the Modulation and Coding Scheme index (l_{MCS}). N_{PRB} has been set to 6 following [30] and the 3GPP guidelines in [31]. l_{MCS} coincides with the 15 available Channel Quality Indicator (CQI) indexes available in LTE. The l_{MCS} indexes are set according to the distance to the BS; more robust MCS are needed as the distance increases[3]. The l_{MCS} indexes can be mapped to the Transport Block Size (TBS) using the table reported in [32]. As a result, $r(N_{PRB}, l_{MCS})$ can be computed as:

$$r\left(N_{PRB},l_{MCS}\right)=TBS/T_{TBS} \tag{10}$$

where T_{TBS} is TBS duration that is equal to 0.5ms in LTE.

$p_{BLER}(N_{PRB}, l_{MCS})$ in eq. (9) represents the Block Error Rate (BLER) experienced for the (N_{PRB}, l_{MCS}) allocation. Following indications in [29], we consider a target BLER of 10%. This results in that $p_{BLER}(N_{PRB}, l_{MCS})$ is set to 0.1 in eq. (9).

Using the model reported in [33], the D2D IEEE 802.11g throughput can be computed as a function of the distance (d, in meters) between SN and MR:

$$TR_{D2D}\left(d\right)=DataRate(d)\cdot Eff\cdot\left(1-PER\left(d\right)\right) \tag{11}$$

where *DataRate* is one of the IEEE 802.11g data rates: {54, 48, 36, 24, 18, 12, 9, 6; 11, 5.5, 2, 1} Mbps. Each IEEE 802.11g data rate corresponds to a combination of modulation and coding schemes (transmission mode). IEEE802.11g dynamically selects the data rate as a function of the experienced link quality conditions. *Eff* and *PER* in eq. (11) represent the Packet Error Rate and channel efficiency, respectively.

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[2] 3GPP considers IEEE 802.11 technologies as well as cellular technologies (e.g. LTE-Direct) for device-to-device communications [7].

[3] The cell is divided into 15 equally spaced and concentric rings identified by the MCS indexes.

The selection of IEEE 802.11g data rates has been empirically derived by the authors in [34] and can be approximated as:

$$DataRate(d)=\begin{cases}54 & d<78.47m\\ \dfrac{54}{\dfrac{1}{78.47}-\dfrac{1}{270.85}}\cdot\left(\dfrac{1}{d}-\dfrac{1}{270.85}\right) & 78.47m\le d<270.85m\\ 0 & 270.85m\le d\end{cases} \tag{12}$$

The piecewise function shown in (12) indicates in the first sub-function that IEEE 802.11g sets the *DataRate* to 54Mbps for SN-MR distances (*d*, in meters) shorter than 79m. For longer distances, more robust transmission modes are utilized, and hence the data rate is lower than 54Mbps.

The *PER* in eq. (11) was also empirically derived in [34], and can be approximated as:

$$PER\left(d\right)=\frac{0.75}{1+e^{-0.019\cdot\left(d-115.15\right)}} \tag{13}$$

(13) indicates that the PER augments with the SN-MR distance (*d,* in meters) even if more robust transmission modes are used for larger distances; there is an upper PER limit at 0.75.

Eff represents the IEEE 802.11g channel efficiency and indicates the effective time that the IEEE 802.11g channel is used to transmit data. *Eff* is estimated in [33] as:

$$Eff=\frac{t_d}{DIFS+t_{cont}+t_d+SIFS+t_{ack}} \tag{14}$$

where t_d and t_{ack} are the transmission time of data packets and ACK packets, respectively, t_{cont} is the contention period, and *DIFS* and *SIFS* are the inter-frame guard times.

3.4. Storage Energy Consumption

The energy consumed by storage units at mobile devices is considered in this study following the conclusions reached in [25]. Mobile devices automatically store received data packets in a DRAM unit. This study considers that the received information is transferred to an internal NAND flash unit to reduce the storage energy consumption [25]. As a result, the estimation of the storage energy consumption at mobile devices needs to consider the power state transitions of the DRAM and NAND flash storage units.

4. Context-aware Opportunistic Forwarding Proposals

Section 3 identified optimum configurations for two-hop opportunistic MCN communications. The derived optimum configuration assumes that an MR can be found when needed at the identified optimum location, which might not always be the case in a real world deployment. To address this scenario, this section presents novel context-aware opportunistic forwarding schemes designed to facilitate the selection of an MR when no device is available at the identified optimum location and time instant. The proposed solutions build from the optimum MCN configuration and MR location identified in Section 3, and exploit context information provided by the cellular infrastructure to search for candidate MRs. The first proposal (referred hereafter as 'Time-dependent opportunistic forwarding', DELAY in short) delays the start of the

D2D transmission until an MR is found at the identified optimum location. The second proposal (referred hereafter as 'Space-dependent opportunistic forwarding', AREA in short) increases the search area where to look for potential MRs around the optimum MR location.

4.1. Time-dependent Opportunistic Forwarding

The DELAY proposal uses the optimum MR location identified in Section 3, but delays the start of the D2D transmission until an MR is found at the identified optimum location. The space-time graph shown in Figure 2 is used to represent and compare the operation when considering the optimum configuration identified in Section 3 ('Optimum'), and the time-dependent proposal that delays the D2D transmission until an MR reaches the identified optimum location ('DELAY'). For the optimum configuration, the D2D transmission from SN_i to the MR located at the identified optimum location Opt_X_i is initiated at time instant τ_0. From this location (Opt_X_i), MR stores and carries the information until it reaches, at time instant τ_c, the identified location from which to start the cellular transmission (i.e. Opt_Y_i). The DELAY proposal considers the scenario in which SN_i cannot find an MR at the optimum location (Opt_X_i) at time instant τ_0. The proposal then delays the D2D transmission until an MR reaches the location Opt_X_i. t represents the time SN_i should delay the D2D transmission to guarantee with certain probability the arrival of at least one MR to the identified optimum MR location. The D2D transmission starts when this MR reaches Opt_X_i at time instant τ_0+t (Figure 2). MR would again store and carry the information before starting the cellular transmission to the BS. The cellular transmission cannot start at the location Opt_Y_i and time τ_c when implementing the DELAY proposal since SN_i had to delay the start of the D2D transmission. However, the complete transmission has to still end before the deadline T. In this case, MR would start the forwarding process to the cellular BS at location Y'_i (further away from the BS than Opt_Y_i) and time τ'_c.

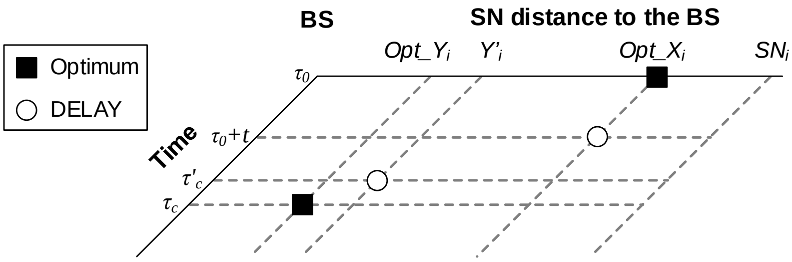


Figure 2. A graphical representation of two-hop opportunistic MCN communications for the optimum configuration and the DELAY proposal.

DELAY requires SN to delay the D2D transmission for t seconds until an MR reaches the optimum MR location derived in the optimization framework presented in Section 3. The time t has to be selected conditioned to the fulfillment of the following two conditions. It is first necessary to guarantee with certain probability that at least one mobile relay reaches the identified optimum MR location within t seconds. This study proposes to use cellular context information (spatial density and distribution of mobile nodes within a cell) to define and establish this probabilistic requirement. This information is already available in current cellular systems and can be obtained at no further cost. The second condition refers to the fact that the BS must completely receive the transmitted file before the deadline T, even despite the initial delay in the D2D transmission. This condition must be satisfied independently of whether SN has to exhaust or not the delay time t to find an MR at the identified optimum location. When it is not possible to define a time t that satisfies these two conditions, SN transmits the file to the BS using a traditional single-hop cellular connection instead of an opportunistic MCN one.

4.1.1. Uniform Distribution of Nodes within the Cell

This study first estimates the value of t considering a uniform distribution of nodes within the cell. To this aim, it is first necessary to calculate the probability that an MR reaches the identified optimum MR location (P_{Opt_Xi}). Following [35], this probability can be expressed using a Poisson distribution:

$$\begin{aligned} P_{Opt\_X_i} &= P\left(x > 0; \mu' t\right) \\ &= 1 - \exp\left(-\mu' t\right),\ \forall Opt\_X_i \in \left(1,\ldots,R\right) \end{aligned} \tag{15}$$

where μ' represents the average arrival rate of MRs to any location within the cell (and then also to the identified optimum MR location). μ' is equal to $\mu \cdot v/R$, where μ represents the average number of MRs uniformly distributed within the cell, v the nodes' speed, and R the cell radius. t in eq. (15) represents the inter-arrival delay time or the time to the next arrival of an MR to any location within the cell. In this context, the time t that guarantees with probability δ (i.e. $P_{Opt\_Xi} = \delta$) the arrival of an MR at Opt_X_i can be expressed as:

$$t = \frac{R \cdot \ln\left(1-\delta\right)}{-\mu \cdot v} \quad iff\ \exists Y'_i = \underset{\tau'_{b-1} = \tau_{b-1} + t}{\arg\min} \left(\vartheta(\ldots)\right) \tag{16}$$

The time t that guarantees the arrival of at least one MR at the identified optimum MR location can be found if and only if (*iff*) the condition shown in (16) is also fulfilled. This condition requires that the optimization problem ($\vartheta(\ldots)$ in eq. (16)) can find a suboptimum location (Y'_i) at which the MR should start the cellular transmission to the BS. This location is obtained considering that the D2D transmission would finish at time instant $\tau_{b-1}+t$ (the optimum configuration needs τ_{b-1} seconds to conclude the D2D transmission from SN to MR). If this condition is met, it is possible to establish the two-hop opportunistic MCN link to transmit the information from SN to the BS before the deadline T. If not, SN directly transmits the information to the BS using a traditional single-hop cellular connection.

4.1.2. Non-uniform Distribution of Nodes within the Cell

This study also estimates the time t for a non-uniform distribution of nodes within the cell. Without loss of generality, we consider decreasing spatial densities of nodes as we move away from the BS. Following [36], the non-uniform distribution of users in the cell is modeled using a truncated Normal distribution centered at the position of the cellular BS. The truncated Normal distribution is a piecewise-defined function [35]:

$$P\left(x; s, \sigma, a, b\right) = \begin{cases} \dfrac{\phi\left(\dfrac{x-s}{\sigma}\right)}{\sigma \cdot Z}, & if \quad x \in [a,b] \\ 0, & if \quad x \notin [a,b] \end{cases} \tag{17}$$

where $\varnothing(\xi)$ represents the probability density function of the standard Normal distribution. The Normal distribution of a random variable x characterized by the parameters s (mean) and σ^2 (variance) can be expressed as [35]:

$$P(x; s, \sigma) = \frac{1}{\sqrt{2 \cdot \pi\sigma}} \exp\left(-\frac{(x-s)^2}{2\sigma^2} \right), \quad -\infty \le x < \infty \tag{18}$$

In eq. (17), Z represents the Cumulative Distribution Function (CDF) of x varying within an upper ($b \setminus x \in [-\infty, b]$) and lower ($a \setminus x \in [a, \infty]$) bounds:

$$Z = \Phi\left(\frac{b-s}{\sigma}\right) - \Phi\left(\frac{a-s}{\sigma}\right) \tag{19}$$

with the CDF defined as:

$$\Phi(x) = F(x) = P(X \le x) = \int_{-\infty}^{x} P(x; s, \sigma)\, dx \tag{20}$$

Using eq. (17), it is then possible to calculate the probability to find one MR at the identified optimum MR location (Opt_X_i):

$$P_{Opt\_X_i} = \int_{Opt\_X_i - \varepsilon/2}^{Opt\_X_i + \varepsilon/2} P(x; s, \sigma, a, b)\, dx \tag{21}$$

where ε represents the spatial discretization unit. Using eq. (21), the average spatial density of nodes at Opt_X_i can be expressed as $\mu_{Opt\_Xi}=(\mu/R)\cdot P_{Opt\_Xi}$, where μ/R is the average spatial density of nodes in the cell. Following [37], the truncated Normal distribution can be approximated by a series of discrete Poisson distributions. In this case, the analysis for a non-uniform distribution of nodes within the cell can be treated similarly to the scenario where nodes were uniformly distributed within the cell (Section 4.1.1). As a result, we can calculate the time t the SN needs to delay the D2D transmission to guarantee with probability δ the arrival of an MR at Opt_X_i under non-uniform distribution of nodes within the cell as:

$$t = \frac{R \cdot \ln(1-\delta)}{-\mu \cdot P_{Opt\_X_i} \cdot v} \; iff \; \exists Y'_i = \underset{\tau'_{b-1} = \tau_{b-1} + t}{\arg\min} \left(\vartheta(\ldots)\right) \tag{22}$$

It is important noting that eq. (22) depends on P_{Opt_Xi}. This results in that t varies with the optimum MR location within the cell, which was not the case for uniform distribution of nodes within the cell (eq. (15) and (16)). Eq. (22) also requires that the optimization problem (ϑ) can find a suboptimum location (Y'_i) at which the cellular transmission should start. Otherwise, the SN would communicate with the BS using a traditional single-hop cellular connection.

4.2. Space-dependent Opportunistic Forwarding

The AREA proposal addresses the scenario in which an MR cannot be found when needed at the identified optimum location by increasing, around the optimum MR location, the search area where to look for potential MRs. The search area is defined using context information provided by the cellular infrastructure (spatial density and distribution of mobile nodes within the cell). If more than one MR is located within the search area, SN selects the one that is closer to the optimum location *Opt_X*$_i$. Figure 3 illustrates the search area around the optimum location *Opt_X*$_i$. r denotes the radius of the search area around *Opt_X*$_i$. X'_i represents the location of the selected MR within the search area, and Y'_i the location at which the selected MR will start the cellular transmission to the BS. The position at which the selected MR will start the cellular transmission to the BS (closer or further away to the BS than the optimum configuration) depends on the initial location of the selected MR (i.e. X'_i).

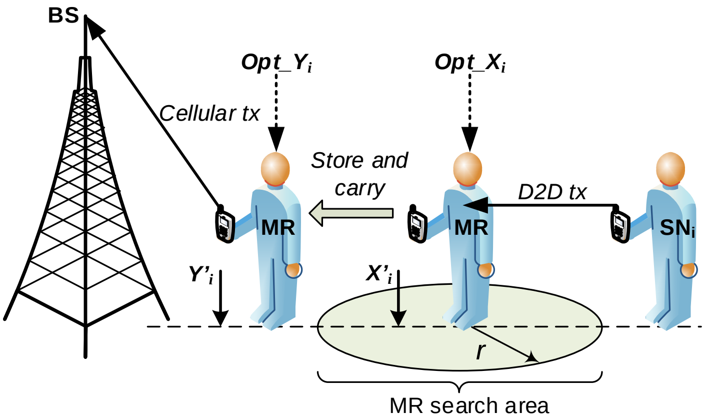


Figure 3. Two-hop opportunistic MCN communications for the optimum configuration and the AREA proposal.

The area of interest to find potential MRs around the identified optimum MR location needs to fulfill the following two conditions. The first condition refers to the fact that the defined area must guarantee the presence of at least one MR with certain probability. This probability is here computed using cellular context information, in particular, the average spatial density and the distribution of mobile nodes within the cell. The second condition is that the defined search area must satisfy the established QoS restriction, i.e. independently of the location of selected MR within the search area, the information must be completely received at the BS before T. When it is not possible to find a search area that fulfills these two conditions, SN communicates with the BS using a traditional single-hop cellular link.

4.2.1. Uniform Distribution of Nodes within the Cell

The radius of the MR search area is first estimated considering that mobile devices are uniformly distributed within the cell. To this aim, this study first estimates the probability (P_{Opt_Xi}) to find at least one MR around the identified optimum location (*Opt_X*$_i$). Following [35], this probability can be expressed using a Poisson distribution:

$$\begin{aligned} P_{Opt\_X_i} &= P\left(x > 0; \frac{\mu}{R}\cdot\phi\right) \\ &= 1 - \exp\left(-\frac{\mu}{R}\cdot\phi\right),\ \forall Opt\_X_i \in (1,\ldots,R) \end{aligned} \tag{23}$$

where μ/R is the average spatial density of mobile nodes within the cell of radius R, and $\varnothing$ is the diameter of the MR search area (equal to $2r$). It is important noting that eq. (23) is valid for any *Opt_X*$_i$ location within the cell. Following eq. (23), it is possible to estimate the radius r that guarantees with probability δ the presence of at least one MR around *Opt_X*$_i$:

$$r = \frac{R \cdot \ln(1-\delta)}{-2 \cdot \mu} \quad iff \ \exists Y'_i = \underset{\forall X'_i \in o(Opt\_X_i, r)}{\arg\min} \left(\vartheta(\ldots) \right) \tag{24}$$

Eq. (24) requires that for every possible location of the MR (X'_i) within the search area, the optimization problem (represented by θ in eq. (24)) is capable to find the location (Y'_i) at which the MR has to start the cellular transmission to the BS in order to minimize the energy consumption and guarantee that the transmission is completed before *T*. If it is not possible to find Y'_i for every possible X'_i within the search area, SN will transmit the information directly to the BS using a traditional single-hop cellular connection.

4.2.2. Non-uniform Distribution of Nodes within the Cell

The search area (defined by the radius *r* around Opt_X_i) has also been computed when the distribution of users within the cell is non-uniform. We consider again a non-uniform distribution in which the spatial density of nodes is higher close to the BS. This distribution is mathematically modeled by means of a truncated Normal distribution (eq. 17). Eq. (21) estimates the probability P_{Opt_Xi} that one MR is located at the identified optimum MR location. Using eq. (21), the probability to find one MR within the search area can be defined as a function of *r*:

$$P_{SearchArea}(r) = \int_{Opt\_X_i - \varepsilon/2 - r \cdot \varepsilon}^{Opt\_X_i + \varepsilon/2 + r \cdot \varepsilon} P(x; \mu, \sigma, a, b)\, dx \tag{25}$$

where ε represents the spatial discretization unit. If we consider that there are on average μ MRs within the cell, the probability to find at least one MR within the search area around the identified optimum MR location Opt_X_i can be calculated as $(1-(1-P_{SearchArea})^{\mu})$. The minimum radius *r* ($r \in \mathbb{N}$) around Opt_X_i that guarantees with probability δ the presence of at least one MR can then be defined using the following conditions:

$$\begin{aligned} &\left(1-\left(1-P_{SearchArea}(r-1)\right)^{\mu}\right) < \delta \\ &and \left(1-\left(1-P_{SearchArea}(r)\right)^{\mu}\right) \geq \delta \qquad iff \ \exists Y'_i = \underset{\forall X'_i \in o(Opt\_X_i, r \cdot \varepsilon)}{\arg\min} \left(\vartheta(\ldots) \right) \end{aligned} \tag{26}$$

It should be noted that the same condition to the one analyzed in eq. (24) must be satisfied in eq. (26) in order to define the MR search area $o(Opt\_X_i, r \cdot \varepsilon)$. If the condition is not met, the SN will again transmit the information directly to the BS through a traditional single-hop cellular link.

5. Performance Evaluation

5.1. Worst Case Conditions

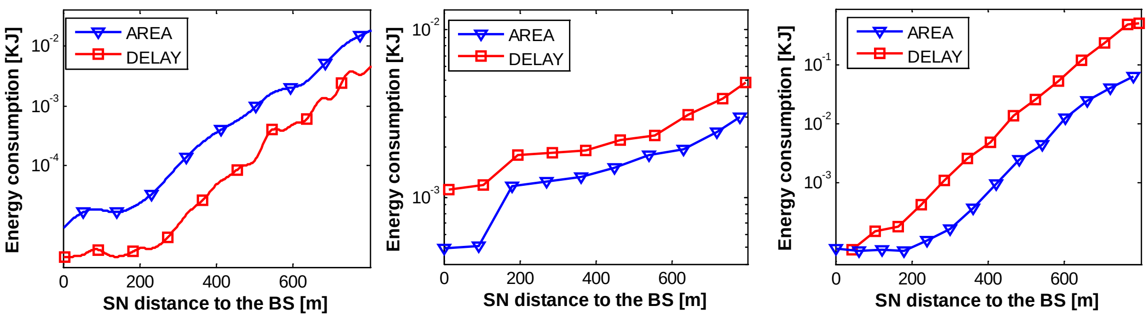
This section is aimed at numerically comparing the performance of the two proposed context-aware opportunistic forwarding strategies considering their worst case operating conditions. In particular, we consider that the DELAY scheme needs to wait for time *t* to elapse before a MR reaches the optimum MR location (*Opt_Xi*), and that AREA founds the MR at the limit of the search area. The evaluation under these worst case conditions allows identifying the minimum energy gains that the proposed strategies can achieve with respect to traditional single-hop cellular communications.

The comparison is first conducted considering a uniform distribution of nodes within the cell. The probability δ used to guarantee the presence of the MR at the identified location and time instant is set to 0.9. The performance has been evaluated in Matlab for all possible distances between SN and BS. The study considers a cell with a radius of 800m. The cell is divided into 15 equally spaced and concentric rings with a LTE transmission mode assigned to each ring (Section 3.3). The energy consumption values for the DRAM and NAND flash storage units have been obtained from [38] and [39] respectively. The file that the static SN needs to upload to the BS has initially a nominal size of 10Mb. The study considers the following range of deadlines T={60s, 100s, 150, 200s}. We consider that the MR is in line with the SN, and move towards the BS with a speed of 2m/s. The rest of parameters are summarized in Table 1.

Parameter	Description	Value
R	Cell radius	800m
BW	LTE system bandwidth	5MHz
G_{TX}, G_{RX}	Transmitter and receiver antenna gain	1
e_{tx}, e_{rx}	Energy consumed per bit in the transmitter/receiver electronics	50×10^{-9}J/b
P_{RX}	Power reception threshold	-62dBm
h_{SN}, h_{MR}, h_{BS}	Antenna height of SN, MR and BS	1.5m, 1.5m, 10m
DRAM P_R, P_W, $P_{Idle\_self\text{-}refresh}$	DRAM power consumed for Reading, Writing and in Idle_self-refresh state	252mW, 252mW, 1.35mW
NAND Eff_{Read}, Eff_{Write}, P_{Idle}	NAND efficiency for Reading and Writing, and Power consumed in Idle state	1.83nJ/b, 11.92nJ/b, 0.4mW
Transf_DF, *Transf_FD*	Transfer speed from the DRAM to the NAND flash and vice versa	4.85 MiB/s, 927.1 KiB/s

Table 1. Evaluation parameters.

Figure 4 compares the energy consumed by DELAY and AREA as a function of the distance between SN and BS. The results are depicted in logarithmic scale, and have been obtained for an average spatial density of users within the cell equal to μ/R=0.03MRs/m. Figure 4.a represents the energy consumed in the D2D transmission from SN to MR, while Figure 4.b represents the energy consumed in the store and carry process, and Figure 4.c the energy consumed in the cellular transmission from MR to BS. Figure 4.a shows that the DELAY proposal reduces the energy consumed in the D2D transmission with respect to AREA. However, AREA reduces the energy consumed in the store and carry (Figure 4.b) and cellular transmission (Figure 4.c) processes with respect to DELAY. The delay introduced by DELAY on the D2D transmission results in that MR starts the cellular transmission to the BS at a higher distance to the BS than the AREA scheme. This results (Figure 4.c) in that DELAY increases the time MR needs to upload the information to the BS, and therefore the energy consumed in the cellular transmission to the BS. The comparison of Figure 4.a and Figure 4.c shows that the reduction in energy consumed in the D2D transmission process by DELAY cannot compensate the increase in the energy consumed during the cellular transmission. The total energy consumed under the evaluated worst-case scenario and conditions is depicted in Figure 5. Both schemes decrease the energy consumption compared to traditional single-hop cellular communications. On average, AREA reduces the energy consumption compared to single-hop cellular communications by 91.8%, and DELAY by 88.1%. The results also show that AREA achieves better energy performance than DELAY. In fact, Figure 5 shows that the AREA proposal can reduce, on average, the total energy consumption compared to DELAY by 17.4%. This trend is observed for (almost) all the distances between SN and BS[4], and for different values of the deadline *T*. However, we observe that the differences between AREA and DELAY decrease as the deadline *T* increases. For example, if we increase *T* from 60s to 100s, 150s and 200s, the reduction in average energy consumption obtained by AREA compared to DELAY is equal to 14.4%, 9.2%, and 6.2%, respectively. As the deadline *T* increases, DELAY compensates the delay experienced for the D2D transmission, which allows reducing the distance at which MR starts the cellular transmission to the BS, and therefore the energy consumption. The reduction in the differences between the AREA and DELAY proposals are also observed if we increase the spatial density of nodes, the speed at which MR moves, or the size of the data file. Figure 6.a compares the total energy consumed when the spatial density of nodes is increased to 0.09MRs/m, Figure 6.b when the speed is increased to 10m/s (e.g. the MR is located inside a vehicle), and Figure 6.c when the file size is increased to 50Mb. The average reduction in energy consumption achieved by AREA compared to traditional single-hop cellular communications is equal to 94.7% in Figure 6.a, 99% in Figure 6.b, and 95% in Figure 6.c. The average reduction in energy consumption achieved by DELAY compared to traditional single-hop cellular communications is equal to 93.4% in Figure 6.a, 98% in Figure 6.b, and 93.5% in Figure 6.c.



a) *D2D transmission* b) *Store and Carry (SC)* c) *Cellular transmission*

Figure 4. Comparison of the DELAY and AREA energy consumption (uniform distribution of nodes within the cell, *v*=2m/s, *T*=60s, *F*=10Mb, *μ/R*=0.03MRs/m). The deadline *T* determines the location at which MR should start the cellular transmission to the BS.

[4] Under a uniform distribution of mobiles within the cell, *t* and *r* are constant for any location of the SN within the cell following eq. (16) and (24).

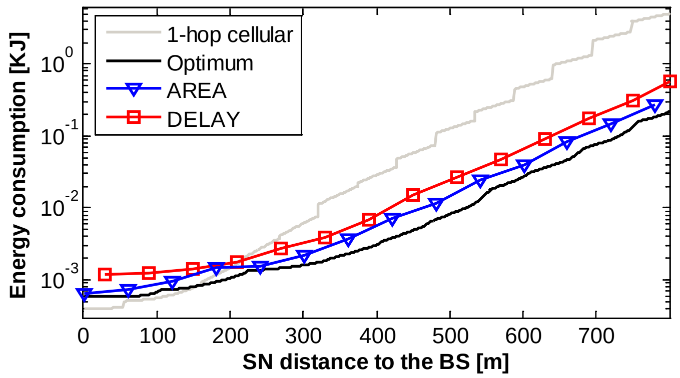
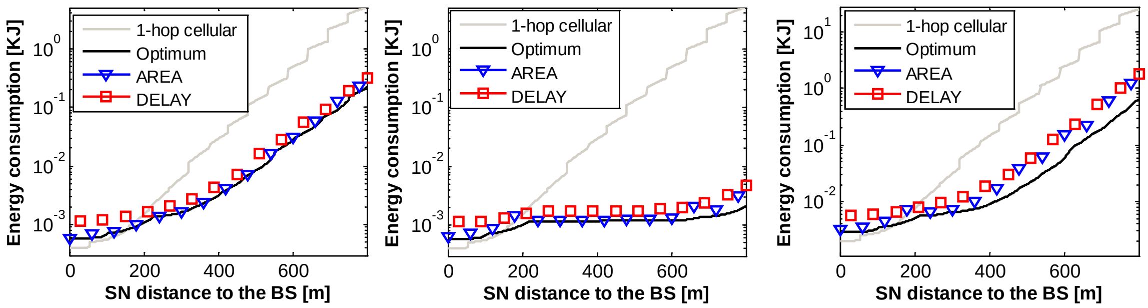


Figure 5. Total energy consumption (uniform distribution of nodes within the cell, *v*=2m/s, *T*=60s, *F*=10Mb, *μ/R*=0.03MRs/m).



a) *v*=2m/s, *T*=60s, *F*=10Mb, *μ/R*=0.09MRs/m

b) *v*=10m/s, *T*=60s, *F*=10Mb, *μ/R*=0.03MRs/m

c) *v*=2m/s, *T*=60s, *F*=50Mb, *μ/R*=0.03MRs/m

Figure 6. Total energy consumption (uniform distribution of nodes within the cell).

Figure 7 compares the total energy consumed when MRs are not uniformly distributed within the cell[5]; *μ/R* is set equal to 0.03MRs/m and the spatial distribution of users results in that approximately 68% of the nodes are located at distances to the BS smaller than 300m. A non-uniform distribution of users within the cell results in that *t* and *r* increase with the distance between SN and BS in order to compensate the smaller density of users when the distance to the BS increases. In this context, the AREA proposal considerably increases the energy consumed in the D2D transmission (and therefore the total energy consumption) with the SN distance to BS, and the DELAY proposal might exhaust the available deadline *T* without completely transmitting the file of size *F* because of the time it had to wait for an MR to arrive at the identified optimum location. It is important to remember that the current numerical evaluation considers a worst case scenario in which AREA selects the MR at the limit of the search area around the optimum MR location, and DELAY needs to wait for *t* to elapse before an MR reaches the optimum MR location. In any case, the results in Figure 7 clearly show that AREA and DELAY improve the energy consumption compared to traditional single-hop cellular communications. On average, AREA reduces the energy consumption compared to single-hop cellular communications by 40%, and DELAY by 26%. The benefits of the AREA and DELAY

[5] The results are presented for SN distances to BS higher than 400m since the two schemes achieve very similar results for smaller distances.

proposals under worst case conditions reduce when SN is located at the cell edge. Figure 7 shows that AREA is challenged to establish an efficient opportunistic MCN link for SN distances to the BS higher than 715m as a result of the large distances between SN and MR. DELAY experiences the same challenge for SN distances to the BS higher than 555m. If we increase *T* from 60s to 100s, 150s or 200s, the differences between AREA and DELAY decrease. For example, if we increase *T* from 60s to 100s, 150s and 200s, the SN distances to the BS from which DELAY cannot establish an efficient opportunistic MCN link (and needs to start a traditional single-hop cellular transmission) increase to 650m, 715m and 730m respectively. These distances do not change for AREA when *T* is increased (remain equal to 715m) since AREA is challenged by the large distances between SN and MR. Under a non-uniform distribution of nodes within the cell, we can also observe that the differences between DELAY and AREA reduce if we increase the spatial density of nodes, the speed at which MR moves or the size of the file. Figure 8.a compares the total energy consumed when the spatial density of nodes is increased to 0.09MRs/m, Figure 8.b when the speed is increased to 10m/s (in this scenario AREA shows better energy performance than DELAY), and Figure 8.c when the file size is increased to 50Mb. The average reduction in energy consumption achieved by AREA compared to traditional single-hop cellular communications is equal to 91.3% in Figure 8.a, 50% in Figure 8.b, and 32% in Figure 8.c. The average reduction in energy consumption achieved by DELAY compared to traditional single-hop cellular communications is equal to 53.8% in Figure 8.a, 52.3% in Figure 8.b, and 13.8% in Figure 8.c.

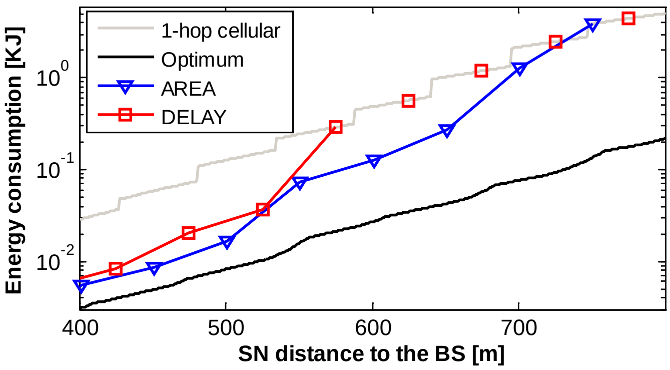
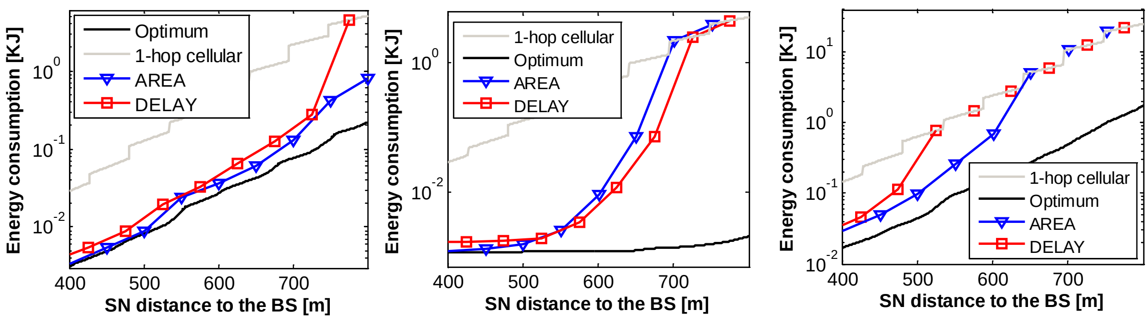


Figure 7. Total energy consumption (non-uniform distribution of nodes within the cell, *v*=2m/s, *T*=60s, *F*=10Mb, *μ/R*=0.03MRs/m).



a) *v*=2m/s, *T*=60s, *F*=10Mb, *μ/R*=0.09MRs/m

b) *v*=10m/s, *T*=60s, *F*=10Mb, *μ/R*=0.03MRs/m

c) *v*=2m/s, *T*=60s, *F*=50Mb, *μ/R*=0.03MRs/m

Figure 8. Total energy consumption (non-uniform distribution of nodes within the cell).

The conducted evaluation of the context-aware opportunistic forwarding proposals has shown that AREA and DELAY can notably reduce the energy consumption compared to traditional single-hop cellular communications even under worst case conditions. This is observed for all scenarios and conditions (Figure 5 to Figure 8). The two proposals better approximate the energy performance achieved with an optimum configuration of opportunistic MCN communications under a uniform distribution of users. The results have also shown that AREA can reduce the energy consumption compared to DELAY under a uniform distribution of users in the cell. This trend is also generally observed under a non-uniform distribution of users within the cell; DELAY only achieves better energy performance at larger distances to the BS under certain conditions (high deadline *T* and MR speed).

5.2. Energy Efficiency

The previous section numerically evaluated the energy performance of the proposed context-aware opportunistic forwarding schemes under defined worst-case conditions. The conducted evaluation allows identifying minimum energy performance bounds. This section seeks to complement the previous study with an evaluation that covers various and more general possible operating conditions. In other words, the AREA scheme is not bounded to select an MR at the border of the search area, and DELAY does not have to wait *t* seconds before an MR is found at the optimum location. The AREA and DELAY proposals are also configured so that if no MR can be found at the identified locations and within the estimated timeframe, then SN directly transmits the information to the BS using traditional single-hop cellular communications. The evaluation here reported also includes additional reference schemes for comparison, and introduces variants of the AREA and DELAY schemes.

The AREA and DELAY variants are defined based on how the cellular infrastructure provides the context information required to calculate *t* and *r*. The original AREA and DELAY proposals described in Section 4 consider that the context information (spatial density and distribution of users within the cell) is provided per cell. However, this context information could also be provided for each concentric ring that defines a cell[6]. In this study, we consider a total of 15 rings per cell with each ring characterized by the use of a different LTE transmission mode (see Section 3.3). When the context information is provided per ring rather than per cell, we denote the context-aware opportunistic forwarding schemes as AREA-Ring or DELAY-Ring. The original DELAY scheme and DELAY-Ring estimate *t* using the expression derived for a uniform distribution of nodes within the cell (eq. (16)). When the context information is provided per ring, the spatial density of users (μ/R) in eq. (16) is replaced by φ_i/l^i_r. φ_i represents the average number of nodes in the ring *i* where the optimum MR location is situated, and l^i_r the ring length. The average number of MRs within the cell can then be calculated as $\mu = \sum_{i=1}^{N} \varphi_i$ and the cell radius as $R = \sum_{i=1}^{N} l_r^i$, with $i \in \{1...N\}$ and *N* representing the number of rings in the cell (*N*=15 in this study). The original AREA scheme and AREA-Ring estimate *r* using the expression derived for a uniform distribution of nodes within the cell (eq. (24)). When the context information is provided per ring, the spatial density of users (μ/R) in eq. (24) is also replaced by φ_i/l^i_r. It should be noted that the AREA and DELAY variants utilize the same expressions of *r* and *t* under uniform and non-uniform user distributions.

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[6] Standards such as LTE or HSPA divide cells into concentric rings. Different transmission modes are used per ring based on parameters such as the signal strength or the Channel Quality Indicator (CQI).

This study compares the performance of the AREA and DELAY proposals against that obtained with traditional single-hop cellular communications ('1-hop cellular') and the optimum configuration of opportunistic MCN communications ('Optimum'). The performance is also compared against other reference schemes. The '1-hop Direct-contact' scheme considers that the SN can store and carry the information before transmitting it to the BS, and does not use any mobile relay [12]. 'MR closest to SN' and 'MR closest to BS' refer to two two-hop opportunistic MCN schemes in which SN selects the MR closer to its location [40] and the MR that provides the higher progress towards the BS [41], respectively. For a fair comparison with the proposed schemes, the configuration of the reference schemes is also derived following a similar optimization process to that reported in Section 3.1 that seeks minimizing the energy consumption. For example, the optimization process identifies for the 'MR closest to BS' scheme the MR location that provides the highest progress towards BS and is able to upload the information before the deadline T. The optimization process also derives the location at which MR should start the cellular transmission to the BS.

The performance of all schemes is evaluated considering a single cell scenario that has been simulated using a discrete-event simulator implemented in Matlab. The implemented scenarios consider both uniform and non-uniform distribution of MRs in the cell. To create uniform distributions of nodes within the cell, MRs appear at the cell edge following a Poisson process with a rate equal to $\mu \cdot v/R$, and move towards the BS at a predefined constant speed. Non-uniform distributions of nodes with higher spatial densities close to BS are here created by placing initially MRs at intermediate locations between the BS and the cell edge, and using the additive property of Poisson processes. The results here presented have been obtained for a large number of experiments (minimum 80 experiments for each result) in order to ensure that the standard error of the mean (i.e. the standard deviation of the estimated mean with respect to the mean obtained in each experiment) is always below 0.01.

Table 2 reports the reduction (in percentage) of the average energy consumption achieved with the different schemes compared to traditional single-hop cellular communications. The depicted results clearly show that the use of opportunistic forwarding schemes helps reducing the energy consumption, with the benefits increasing when adequately combining opportunistic networking and MCN communications. Only the 'MR closest to BS' technique consumes more energy in some of the considered scenarios than single-hop cellular communications (negative values in Table 2). This is the case because of the high energy consumed during the D2D transmission as a result of selecting the MR as close as possible to the BS. The higher energy benefits would be achieved if the 'Optimum' reference configuration could be possible (Table 2). The results depicted in Table 2 for the 'Optimum' configuration correspond to the numerical results obtained in Section 5.1. These results assume that it is always possible to find a MR at the identified optimum location and time instant. This assumption is made to obtain a maximum performance bound with which to compare the energy benefits that can be obtained with the context-aware proposals. However, this assumption might not always be feasible. In fact, the probability that SN could find an MR at the required optimum location and time instant was less than 0.3 when the spatial density of users in the cell was 0.125 MRs/m. This probability decreased to 0.1 when μ/R was equal to 0.03 MRs/m.

Technique	μ/R= 0.125 MRs/m		μ/R= 0.03 MRs/m	
	F=10Mb, *v*=2m/s, *T*=30s	*F*=10Mb, *v*=10m/s, *T*=30s	*F*=10Mb, *v*=2m/s, *T*=30s	*F*=10Mb, *v*=2m/s, *T*=60s
AREA	86.3	89.6	83.5	88.1
AREA – Ring	88.0	98.2	87.1	91.4
DELAY	84.5	94.6	66.1	85.1
DELAY – Ring	86.9	99.0	66.1	86.3
MR closest to BS	-129.1	45.3	-11.3	-8.0
MR closest to SN	23.8	96.1	28.2	75.2
1-hop Direct-contact	64.3	96.9	64.3	71.8
Optimum	91.7	99.0	91.7	95.6

a) Uniform spatial distribution of MRs within the cell

Technique	μ/R= 0.125 MRs/m		μ/R= 0.03 MRs/m	
	F=10Mb, *v*=2m/s, *T*=30s	*F*=10Mb, *v*=10m/s, *T*=30s	*F*=10Mb, *v*=2m/s, *T*=30s	*F*=10Mb, *v*=2m/s, *T*=60s
AREA	51.7	56.9	54.1	55.5
AREA – Ring	87.1	95.7	73.9	80.5
DELAY	52.0	68.1	38.3	50.9
DELAY – Ring	68.8	96.1	42.3	60.6
MR closest to BS	-117.9	47.0	-28.9	-21.9
MR closest to SN	39.4	96.8	53.0	76.1
1-hop Direct-contact	60.1	96.9	60.1	71.8
Optimum	91.7	99.0	91.7	95.6

b) Non-uniform spatial distribution of MRs within the cell

Table 2. Reduction (in percentage) of the total average energy consumption achieved with opportunistic MCN compared to single-hop cellular.

Table 2 shows that the AREA and DELAY proposals can also achieve significant energy gains compared to traditional single-hop cellular communications. These gains can actually be very close to those that would be obtained with a potential optimum configuration under certain scenarios and conditions. In particular, AREA and DELAY increase their energy gains with the density of MRs within the cell and the MRs' speed[7]. This trend is observed independently of whether MRs are distributed uniformly or not within the cell. Higher *T* deadlines also tend to improve the performance of AREA and DELAY since the schemes have more time to exploit the benefits of opportunistic networking. A closer comparison of the AREA and DELAY schemes shows that AREA is particularly suitable under low density of users or a small *T* deadline. When the spatial density of users and *T* decrease, DELAY reduces its hit rate (Table 3) because the time SN needs to wait for an MR to reach the optimum MR location does not allow establishing the two-hop opportunistic MCN connection before *T* expires. The hit rate is defined as the average percentage of SN-BS links established using two-hop opportunistic MCN communications. The results in Table 3 show that AREA's hit rate is not that highly influenced by the *T* parameter, and explain why AREA outperforms DELAY for low values of *T*. When *T* increases to 60 seconds, DELAY and AREA achieve closer energy efficiency levels. This is due to the fact that higher *T* values allow DELAY to compensate the longer delays

[7] Increasing these two parameters helps reducing the time *t* SN needs to delay the D2D transmission (eq. (16)) and the radius *r* around the optimum MR location (eq. (24)).

experienced for the D2D transmission as a result of the need to wait for an MR to reach the optimum MR location[8].

Technique	μ/R=0.125 MRs/m		μ/R= 0.03 MRs/m	
	F=10Mb, *v*=2m/s, *T*=30s	*F*=10Mb, *v*=10m/s, *T*=30s	*F*=10Mb, *v*=2m/s, *T*=30s	*F*=10Mb, *v*=2m/s, *T*=60s
AREA	94.1	92.1	90.3	89.4
AREA – Ring	96.5	99.4	97.4	96.5
DELAY	93.0	96.7	79.1	89.0
DELAY – Ring	96.1	99.9	78.9	93.5

a) Uniform spatial distribution of MRs within the cell

Technique	μ/R=0.125 MRs/m		μ/R= 0.03 MRs/m	
	F=10Mb, *v*=2m/s, *T*=30s	*F*=10Mb, *v*=10m/s, *T*=30s	*F*=10Mb, *v*=2m/s, *T*=30s	*F*=10Mb, *v*=2m/s, *T*=60s
AREA	80.0	78.3	80.1	77.6
AREA – Ring	96.1	95.7	94.6	95.2
DELAY	80.9	85.9	67.0	76.5
DELAY – Ring	91.8	98.9	65.7	83.9

b) Non-uniform spatial distribution of MRs within the cell

Table 3. Hit rate: percentage of SN-BS links established using two-hop opportunistic MCN communications.

The results depicted in Table 2 show that a higher mobility of MRs improves the energy gains of AREA and DELAY, with the largest improvements obtained for DELAY. Increasing the MRs speed results in that the cellular transmission from MR to the BS will start closer to the BS where higher cellular data rates are possible. However, it can also negatively impact AREA if the distance between SN and the selected MR exceeds the D2D communications range. This risk increases at higher speeds, which explains the slight negative impact of the MRs' speed on AREA's hit rate (Table 3). These trends are observed under uniform and non-uniform distribution of users in the cell. However, non-uniform distributions of users in the cell reduce the energy gains of both schemes. A non-uniform distribution of users in the cell results in a lower density of nodes with increasing distances to the BS. A varying user density across the cell influences the estimation of the t and r parameters. Providing the context information per cell in the case of non-uniform MRs distribution cannot take into account this variation, and can hence result in frequent incorrect estimations of t and r. The results depicted in Table 3 show that when the distribution of users per cell varies from a uniform one to a non-uniform one, the hit rate decreases. AREA and DELAY do not establish opportunistic MCN links to transmit the information from SN to BS when they cannot find an MR at the identified locations and within the estimated timeframe. A lower percentage of SN-BS links established

[8] For this scenario, the AREA and DELAY proposals show slightly lower energy performance than under worst case conditions (Section 5.1) where it was assumed that an MR was always found at the limit of the search area (AREA) or at the optimum MR location after t seconds elapse (DELAY). The numerical results here reported consider that if no MR can be found at the identified locations and within the estimated timeframe, then SN directly transmits the information to the BS using traditional single-hop cellular communications. This operational difference explains why these results do not have to be equal or higher than those reported in Section 5.1 under worst case conditions.

using opportunistic MCN links[9] decreases the energy gains of the AREA and DELAY proposals compared to traditional single-hop cellular communications (Table 2); the gains are still very significant and above 50% in most cases.

Table 3 shows that providing the context information per ring rather than per cell results in that AREA and DELAY increase their hit rate even under non-uniform user distributions per cell. In fact, the AREA-Ring and DELAY-Ring schemes can achieve hit rate levels with non-uniform distributions close (or even higher) to that obtained by AREA and DELAY under uniform user distributions per cell. Table 3 also shows that the impact of whether the context information is provided per cell or ring is higher for non-uniform user distributions than for uniform ones. As previously explained, this is the case because using context information per cell can result in incorrect estimations of the *t* and *r* parameters when users are non-uniformly distributed in the cell. Providing the context information per ring rather than per cell significantly improves the hit rate (Table 3) and the energy gains compared to traditional single-hop cellular communications (Table 2) independently of the user distribution. The results in Table 2 show that under a uniform distribution of users, the differences between AREA-Ring and DELAY-Ring appear only for a low density of users. In this case, AREA-Ring outperforms DELAY-Ring, with higher differences observed for the lowest *T* value. This is due to the fact that DELAY needs to wait for an MR to reach the optimum MR location, with the D2D delay increasing with the lower density of users per cell. This delay, and decreasing the *T* deadline, results in the reduction of the hit-rate performance shown in Table 3. AREA-Ring also outperforms DELAY-Ring for non-uniform user distributions. In this case, the differences appear even for the higher density of users evaluated. The use of the context information per ring provides a better indication of how users are distributed within the cell, which allows better adjusting *t* and *r*.

5.3. Capacity

The previous sections have demonstrated that the use of opportunistic MCN communications can significantly improve the energy efficiency of traditional single-hop cellular communications. The higher energy gains can be achieved with the AREA and DELAY proposals. These proposals can obtain energy gains close to that reached with an optimum energy configuration of opportunistic MCN communications if adequately configured, e.g. using context information per ring in the case of non-uniform user distributions. The observed energy gains result from a more efficient use of radio resources. Indeed, opportunistic MCN communications provide the means to decide when to establish a communications link based on its efficiency and quality. Table 4 demonstrates that the efficient use of radio resources that results from the combination of opportunistic networking and MCN for delay tolerant services can also provide very significant cellular capacity gains compared to traditional single-hop cellular communications. The capacity gain is measured in this study as the reduction of the time needed to complete the MR-BS cellular transmission in the case of two-hop opportunistic MCN communications compared to the time needed by traditional single-hop cellular communications to complete the SN-BS cellular transmission. The 'MR closest to BS' reference scheme is the one achieving higher capacity gains. This is the case because the MR is selected as close as possible to the BS, and therefore the scheme can minimize the time needed to upload the information to the BS. However, it is important to remember that this scheme

[9] Especially those close to the cell edge where opportunistic networking shows higher energy efficiency.

actually consumed even more energy than traditional single hop cellular communications (Table 2). This is due to the fact that selecting an MR as close as possible to the BS significantly increases the energy consumption in the D2D transmission due to the lower quality/efficiency conditions for the D2D link. Table 4 also shows that the '1-hop Direct-contact' reference scheme can increase the capacity compared to traditional single-hop cellular communications. However, its capacity gains are in general below the ones obtained with opportunistic forwarding schemes as it does not take advantage of the D2D transmission to start the cellular transmission closer to the BS. Similar trends are observed in terms of the impact of user density, MR speed, deadline *T* and context information (per cell or per ring) on the AREA and DELAY capacity performance and comparison (Table 4) as they were observed for the energy consumption (Table 2).

Technique	μ/R= 0.125 MRs/m		μ/R= 0.03 MRs/m	
	F=10Mb, *v*=2m/s, T=30s	*F*=10Mb, *v*=10m/s, T=30s	*F*=10Mb, *v*=2m/s, T=30s	*F*=10Mb, *v*=2m/s, T=60s
AREA	63.1	72.6	61.1	66.3
AREA – Ring	64.2	78.5	63.5	68.6
DELAY	61.1	76.1	49.3	62.8
DELAY – Ring	62.6	78.9	49.3	63.5
MR closest to BS	74.7	81.8	72.4	76.6
MR closest to SN	18.5	72.4	20.5	48.3
1-hop Direct-contact	41.1	73.6	41.1	48.3
Optimum	66.9	79.1	66.9	72.1

a) Uniform spatial distribution of MRs within the cell

Technique	μ/R= 0.125 MRs/m		μ/R= 0.03 MRs/m	
	F=10Mb, *v*=2m/s, T=30s	*F*=10Mb, *v*=10m/s, T=30s	*F*=10Mb, *v*=2m/s, T=30s	*F*=10Mb, *v*=2m/s, T=60s
AREA	42.2	50.5	43.2	45.7
AREA – Ring	63.0	76.7	57.7	65.1
DELAY	41.7	58.4	31.0	40.8
DELAY – Ring	51.6	76.9	33.9	61.2
MR closest to BS	73.7	81.6	63.9	70.2
MR closest to SN	25.4	73.5	36.6	53.7
1-hop Direct-contact	41.4	73.6	41.4	48.3
Optimum	66.9	79.1	66.9	72.1

b) Non-uniform spatial distribution of MRs within the cell

Table 4. Capacity gains with respect to single-hop cellular communications.

5.4. Simulations

This section extends the previous studies with the analysis of opportunistic MCN communications by means of simulations in NS2. Simulations can complement the previous numerical evaluations as they can account for relevant factors such as interference. Interference can be particularly relevant for D2D communications operating at the 2.4GHz ISM band. This study focuses on the AREA proposal since previous results already showed that AREA generally outperforms DELAY (see Section 5).

The simulator implements mobile nodes that use an IEEE 802.11g interface at 2.4GHz for D2D communications. The simulator includes the IEEE 802.11s' discovery process that is enabled through the periodic broadcast exchange of beaconing messages among neighboring nodes. Beacon messages include location information of the mobile nodes. Using the IEEE 802.11s' discovery process, mobile nodes keep updated tables of 1-hop neighbor nodes (including their locations) that are candidates to establish D2D links. This information is exploited by AREA to select the adequate MR within the search area. The simulator implements the WINNER pathloss model for urban scenarios (Section 3.2) and the 'store and carry' process (Section 3.4). The simulator implements an LTE cell with 15 concentric rings that coincide with the available CQI indexes in LTE (Section 3.3). The simulated scenario uniformly distributes mobile nodes within the cell. The nodes move towards the BS at 2m/s. The same scenario has been reproduced in NS2 and Matlab to confirm the trends observed in the numerical evaluations. The simulations also consider the case in which the SN wants to upload a file to the BS using a MR with store, carry and forward capabilities. However, the simulations consider simultaneous traffic sessions from different SNs. This allows accounting for the impact of interferences, which are expected to be particularly relevant for IEEE802.11-based D2D communications. A large number of simulations have been carried out varying the location of the SNs within the cell. The rest of parameters are summarized in Table 1.

Table 5 reports the reduction (in percentage) of the average energy consumption achieved with the AREA proposal compared to conventional single-hop cellular communications. The results are reported for simulations carried out in NS2 and the previous evaluations using Matlab. The results confirm for both evaluations that opportunistic MCN communications reduce the energy consumption compared to conventional single-hop cellular communications. The simulation results are shown for different simultaneous traffic sessions. This parameter refers to the number of simultaneous traffic sessions that take place while SN is transferring the information from SN to MR, and that can interfere this transmission (i.e. it is not related to the total number of simultaneous traffic sessions in the cell, but only considers those sessions that can interfere a transmission from SN to MR). It is important noting that the results obtained with a single interfering traffic session are in line with those reported in the numerical evaluations. This is the case because the operation of AREA is not affected by other simultaneous transmissions. In this case, the D2D link of the opportunistic MCN connection experienced, on average, a packet collision rate of 0.49% in the scenario characterized by the presence of a single traffic session. The packet collision rate has been measured as the ratio between the number of data packets that suffer collisions and the total number of transmitted data packets. Table 5 also shows that the energy benefits of AREA with regards to single-hop cellular communications slightly reduce when the simultaneous traffic sessions increase; the gains achieved are still higher than 90%. This slight decrease is due to higher interference levels experienced for the D2D transmissions that result in an increase of the packet collision rate. For example, the packet collision rate experienced in the D2D link is 3.3%, 4.8% and 7.25% when considering 3, 5 and 9 simultaneous traffic sessions, respectively. As the packet collision rate increases, the D2D link requires more time to conclude the transmission of the file since additional retransmissions are needed. The larger D2D transmission time and the retransmissions result in an increase of the D2D energy consumption.

Technique	Simulations				Numerical
	Simultaneous traffic sessions				
	1	3	5	9	
AREA	94.9	94.4	93.5	91.4	95.1
AODV	78.0	58.2	51.8	37.7	-

Table 5. Reduction (in percentage) of the total average energy consumption compared to single-hop cellular (uniform spatial distribution of MRs within the cell, *v=2m/s, T=60s, F=10Mb, μ/R=0.09MRs/m*).

Additional simulations were performed considering the case in which the SN to BS transmissions were done using ad-hoc routing protocols, in particular using the AODV (Ad hoc On-Demand Distance Vector) protocol [42][10].

The results reported in Table 5 show the reduction (in percentage) of the average energy consumption achieved with the AODV protocol compared to conventional single-hop cellular communications. The obtained results show that AODV can reduce the energy consumption, with the benefits decreasing with the number of simultaneous traffic sessions. These simultaneous sessions, and the resulting interference, have a higher impact for AODV than for the AREA proposal that benefits from the store, carry and forward process. This is the case because AODV requires multiple intermediate D2D transmissions to communicate SN with the BS (the number of hops increases with the distance of SN to the BS). In this case, the interference and packet collisions have an impact on the quality experienced in each hop between SN and BS. The packet collision rate experienced in the AODV multi-hop routes was 2.9%, 6.6%, 10.8% and 15.2% when the number of simultaneous traffic sessions was equal to 1, 3, 5 and 9, respectively. These values are significantly higher than those observed for the AREA proposal that can provide higher energy gains than ad-hoc routing protocols such as AODV.

6. Conclusions

This study has proposed and analyzed the integration of opportunistic networking principles into multi-hop cellular networks for the case of delay tolerant services. A set of context-aware opportunistic forwarding schemes for MCN communications are proposed that exploit the store, carry and forward capabilities of mobile devices. The proposed schemes are based on a reference optimum configuration of opportunistic MCN communications analytically derived with the objective to minimize the energy consumption. The set of derived schemes exploit context information available in cellular networks to identify adequate mobile relays taking into account the identified optimum configuration. If no MR can be found at the identified optimum location and time instant, the AREA proposal expands the MR search area around the optimum location using information about the spatial density and distribution of mobile nodes within the cell. The DELAY proposal uses the same context information to identify for how long the D2D transmissions from the source node can be delayed to find an MR at the identified optimum location. The conducted numerical evaluations have shown that the integration of

[10] The study does not limit the number of hops that AODV can utilize to establish the route from SN to the BS. Mobile nodes use their IEEE 802.11g interfaces in the route search process. Once the route has been established, mobile nodes communicate between them using IEEE 802.11g D2D transmissions. The last hop to the BS is carried using a LTE connection.

opportunistic networking principles into MCN yields significant energy savings and capacity gains compared to traditional single-hop cellular communications. The AREA proposal generally outperforms the DELAY scheme. Both schemes benefit from the provision of context information per ring rather than per cell. In this case, the proposals, and in particular the AREA scheme, can achieve energy and capacity performance levels close to those that could be obtained under an optimum configuration of opportunistic MCN communications. In this case, the context-aware schemes can reduce the energy consumption compared to traditional single-hop cellular communications by up to 98% for delay tolerant services, and increase the cellular capacity by up to 79%. These results demonstrate that opportunistic networking and MCN can significantly contribute towards achieving the capacity and energy efficiency gains sought for 5G networks. The authors are now working on the implementation of the proposed opportunistic forwarding policies in hardware units. The experimental work that is currently under preparation builds on previous experimental contributions from the authors ([8]and [10]) and other studies available in the literature. Of particular relevance is for example the opportunistic networking solution developed by Spacetime Networks Oy. The solution builds from the results of the Scampi European project. This project developed the Liberouter framework [43]-[44], a complete system that includes low-cost applications that transform mobile devices (Android-based) into routers to assist in message forwarding. As a future avenue of research the proposed opportunistic scheme can be deemed a natural fit in emerging C/U-split architectures, where control (C) and user/data (U) forwarding planes are physically and/or logically decoupled [45]. In split-architectures, a macro BS is responsible for the control plane and high capacity small cells are responsible for the forwarding plane; in that setting, the macro-BS could orchestrate delay-tolerant transmissions based on the store-carry and forward networking paradigm.

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