Context-Based Opportunistic Forwarding in Multi-hop Cellular Networks using Mobile Relays

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ABSTRACT
Multi-hop Cellular Networks can help address the increasing data demand and expected capacity constraints of cellular systems through the integration of cellular and relaying technologies. Multi-hop Cellular Networks using Mobile Relays (MCN-MR) are characterized by a decentralized and cooperative operation that provides new networking opportunities but also significant management challenges. In this context, this work investigates the use of opportunistic store-carry and forward schemes in MCN-MR networks to increase energy efficiency in the provision of delay tolerant services. In particular, the paper identifies for a two-hop MCN-MR scenario the optimum mobile relay location and the location from which the relay should start forwarding the information to the cellular base station in order to minimize the overall energy consumption. Taking this optimum configuration as a reference benchmark, the paper proposes then a scheme that relaxes the requirement to operate under the identified optimum configuration, and exploits context information provided by the cellular infrastructure. The proposed scheme is compared against other forwarding approaches, and the obtained results demonstrate the capacity of opportunistic forwarding in MCN-MR to reduce energy consumption for delay tolerant services.

Categories and Subject Descriptors
B.8.2 [**Performance and Reliability**]: Performance Analysis and Design Aids. C.1.3 [**Processor Architectures**]: Other Architecture Styles - *cellular architecture (e.g., mobile), heterogeneous (hybrid) systems*. C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design - *store and forward networks, wireless communication*.

Keywords
Multi-hop cellular networks; opportunistic networking; energy efficiency; Store-Carry & Forward (SC&F); mobile relaying; Peer to Peer (P2P) communications.

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1. INTRODUCTION
The growth in data traffic represents a significant challenge for cellular operators. To address it, cellular operators are currently relying on new radio access technologies, advanced physical layer techniques, and the deployment of small cells. An alternative to the traditional infrastructure-centric cellular solutions are Multi-hop Cellular Networks (MCN). MCN are based on the integration of cellular and relaying technologies. Several studies have demonstrated the potential of MCN in terms of capacity, energy-efficiency, and traffic offloading [1]. Such benefits are expected from the substitution of long-distance, and generally Non-Line of Sight (NLOS), cellular links with multi-hop transmissions with improved link budgets. The introduction of relaying techniques into cellular standards has initially focused in fixed relays. On the other hand, the use of mobile relays in MCN networks (MCN-MR) offers additional networking possibilities through a collaborative use of the resources of deployed mobile devices [2]. For example, MCN-MR can benefit from the adoption of opportunistic networking solutions. Opportunistic schemes exploit the node's mobility and the store, carry and forward paradigm to establish communication links between mobile relays based on contact opportunities at the expense of some end-to-end transmission delay [3]. The integration of opportunistic networking and MCN-MR represents then an interesting option to provide quality of service while improving energy-efficiency of the increasing proportion of cellular data traffic that can be deemed as delay tolerant, e.g. updates to social networking, emails, firmware and software updates, cloud services, etc. [4]. It is interesting noting that the latest Cisco's global mobile data traffic forecast places these services and applications in the top-ranking of user applications driving the higher mobile data consumption [5]. In this context, this paper investigates the capacity of opportunistic store-carry and forward techniques to reduce the energy consumption of delay tolerant services in MCN-MR networks. To this aim, the paper first presents a mathematical framework to identify the optimum mobile relay location, and the location at which the relay needs to start forwarding the information to the cellular network in order to minimize the overall energy consumption in a two-hop MCN-MR scenario. Taking this optimum configuration as a reference benchmark, the paper proposes then a scheme that relaxes the requirement to operate under the identified optimum configuration, and exploits context information provided by the cellular infrastructure to search for potential mobile relays that reduce the energy consumption. In particular, the proposed scheme exploits context information (currently available in cellular systems) about the density and distribution of mobile relays within a cell. The conducted study demonstrates the capacity of opportunistic forwarding in MCN-MR to reduce

energy consumption for delay tolerant services, and the benefits achieved by the proposed context-based scheme compared to other forwarding approaches.

2. RELATED WORK

Several studies have investigated the impact of mobile relaying and opportunistic networking into energy consumption. The work presented in [6] considers a scenario where a cell is divided into concentric rings, and only mobile devices inside the inner-most ring are allowed to send data to the cellular base station. On the other hand, mobile relays located in outer rings are in charge of relaying data to inner rings. The study shows it is possible to reduce the energy consumption with an adequate selection of the rings' size. In opportunistic networks, multi-hop routes are established based on connectivity opportunities and the mobile nodes' inter-contact time. If no suitable forwarding opportunity exists, the mobile nodes can store the message until such opportunity arises. The study reported in [7] showed that this store, carry and forward approach can reduce the energy consumption despite an increase in the transmission delay. The benefits of integrating MCN and opportunistic networking are discussed in [4], where the authors present novel routing policies that use information about the relays' mobility to reduce energy consumption [8], increase spatial capacity, reduce co-channel interference, balance the load across cells, and switch-off low-utilization base stations [9]. The authors derive the opportunistic routing policies by formulating a finite space-time network graph where the vertexes represent the location of the mobile relays with time, and the edges the transmission links. The resulting network graph includes all possible routes for forwarding information towards a cellular base station. The authors show that the energy-efficiency benefits achievable with the integration of cellular and opportunistic communications increase with the time available to transmit the information towards the destination node. The study is further extended in [10] where the authors highlight the importance of considering the power consumption of storage units in mobile relays for the study of opportunistic networks.

3. OPTIMUM OPPORTUNISTIC FORWARDING IN MCN-MR NETWORKS

The previous studies have demonstrated the energy benefits resulting from the integration of opportunistic store-carry and forward mechanisms in cellular networks at the expense of some possible end-to-end transmission delays. Such integration offers the possibility for mobile devices to delay the transmission of the information to the base station. In the case of delay tolerant services, a key aspect is then how to manage the available time to achieve the desired outcome, which in the case of this study is to reduce the energy consumption.

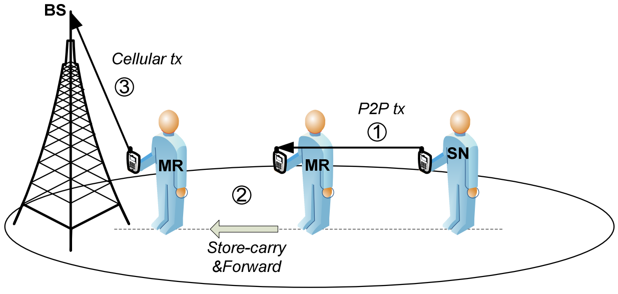


Figure 1. 2-hop opportunistic MCN-MR scenario.

Building from the existing results, this paper goes a step further to identify the optimum mobile relay location and the location at which the relay needs to start forwarding the information to the cellular base station in order to minimize the overall energy consumption. To this aim, the paper considers the processes involved in the integration of opportunistic and cellular communications: selection of the mobile relay node, store-carry and forward process, and the cellular communication with the base station. The paper focuses on a two-hop MCN-MR scenario in which the Source Node (SN) is static and wants to transmit information to the Base Station (BS) using a Mobile Relay (MR) with store, carry and forward capabilities; Figure 1 illustrates the scenario under study. In this context, the time needed to transmit the information from the SN to the BS is computed based on: 1) the time needed for the ad-hoc transmission from SN to MR (*P2P tx*), 2) the time that the MR stores and carries the information (*Store-carry & Forward*), and 3) the time needed by the MR to transmit the information to the BS (*Cellular tx*). It is important noting that estimating the time needed to transmit the information from the SN to the BS requires determining the location of the MR when the P2P and cellular transmissions start. This section focuses then on estimating these two locations with the final objective to reduce the total energy consumption.

The process to minimize the total energy consumption is conducted following a multi-objective constrained optimization problem. To this aim, the objective function shown in (1) has been defined together with two constraints (eq. 2 and 3) and the requirement that the BS receives the information before a deadline T that is service dependent (eq. 4). This deadline is discretized in (1) as $\{\tau_0, \tau_1 \ldots, \tau_\Gamma\}$. The objective function (1) is defined considering the energy consumed by the processes involved in 2-hop opportunistic MCN-MR communications (see Figure 1): the *P2P tx* ①, the *Store-carry & Forward* process ② and the *Cellular tx* ③. $\sum_{\tau=\tau_0}^{\tau_{b-1}} E_{adhoc}\left(d_{SN-MR},\tau\right)$ in (1) represents the energy consumed in the P2P ad-hoc transmission between the SN and MR nodes within the time interval $\{\tau_0, \tau_1, \ldots, \tau_{b-1}\}$, and considering that the SN and MR nodes are separated by $d_{SN\text{-}MR}$ at τ. P_R, P_W and P_{IDLE} refer to the power consumed in the process to store and carry information on mobile devices. These three variables are defined in Section 3.1. $\sum_{\tau=\tau_c}^{\tau_{c+m}} E_{cell}\left(d_{MR-BS},\tau\right)$ represents the energy consumed in the cellular transmission between the MR and the BS within the time interval $\{\tau_c, \tau_{c+1}, \ldots, \tau_{c+m}\}$, and considering that the MR and BS nodes are separated by $d_{MR\text{-}BS}$ at τ. The objective function includes two constraints for the message (of size F) to be completely transmitted in the P2P (eq. 2) and cellular (eq. 3) transmissions. Thr_{adhoc} and Thr_{cell} represent the P2P and cellular transmission rates respectively. Constraint (4) ensures the communication processes are conducted before the deadline T.

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

$$st:$$

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

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

$$0 \le \tau_0 < \tau_{b-1} < \tau_b \le \tau_{c-1} < \tau_c < \tau_{c+m} \le T \tag{4}$$

Following the previous discussion, identifying the optimum mobile relay location (Opt_X_i) and the location at which the relay needs to start forwarding the information to the cellular network (Opt_Y_i) in order to minimize the overall energy consumption, is equivalent to finding τ_{b-1}, τ_{c-1} and τ_{c+m} in (1). In this context, the optimization process (ϑ) could be summarized as follows:

$$\begin{aligned}&\left[\tau_{b-1},\tau_{c-1},\tau_{c+m},Opt\_X_i,Opt\_Y_i\right]=\\&\vartheta\left(F,T,Thr_{adhoc},Thr_{cell},E_{adhoc},E_{cell},P_R,P_W,P_{IDLE}\right)\end{aligned} \tag{5}$$

3.1 Estimation of the energy consumption

Following the study presented in [8], the energy consumed in the ad-hoc (E_{adhoc}) and cellular (E_{cell}) transmissions can be expressed as follows:

$$E(d)=\begin{cases}(e_r+e_t+e_{LOS}\cdot d^2)\cdot Thr & if\ d<d_{brake}\\(e_r+e_t+e_{MP}\cdot d^4)\cdot Thr & if\ d\ge d_{brake}\end{cases} \tag{6}$$

where e_t and e_r represent the energy consumption per bit in the transmitter and receiver electronics respectively, and Thr is the transmission rate (Thr_{adhoc} or Thr_{cell}). The distance between the transmitter and receiver is d, and $d_{brake} = 4\pi\cdot h_T\cdot h_R/\Lambda$ is the critical distance (h_T and h_R are the transmitter and receiver antenna heights, and Λ is the carrier wavelength, all of them in m). For $d < d_{brake}$, the parameter e_{LOS} represents the energy consumption per bit with Line-of-Sight (LOS) propagation conditions. e_{MP} is the energy consumption per bit under MultiPath (MP) fading conditions for $d \ge d_{brake}$.

The energy consumed by the store and carry process is also considered in the optimization process following the conclusions reached in [10]. Mobile devices automatically store data packets received from the wireless interface in the DRAM storage unit. The information could be transferred to internal units such as NAND flash if considered appropriate given their lower energy consumption (the time that the information is stored, and the transfer speed and power cost are factors to evaluate). However, the information needs to be transferred back to the DRAM when the mobile device starts the forwarding process. This work considers that the information is always transferred from DRAM to NAND flash[1]. The power state transitions of the two storage units during these processes are depicted in Figure 2 [10]. P_R includes the power consumed by the DRAM and NAND flash when these storage units Read (R) and Write (W) the information, as well as the power consumed for transferring the information from DRAM to NAND flash (*Transf_DF*). P_{IDLE} includes the power consumed by the NAND flash that is storing the information in *Idle* state, and the power consumed by the DRAM that is in *Idle_self-refresh* state. Finally, P_W is the power consumed by the two storage units when they transfer the information back to the DRAM for transmission.

[1] It is out of the scope of this paper to determine when it is worth transferring data from DRAM to NAND.

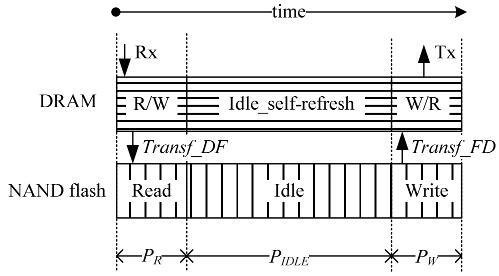


Figure 2. Transition states of the storage units as a function of the time when the information is transferred from DRAM to FLASH memories, and sent back to DRAM.

The P2P tx (①) part of the objective function (1) includes P_W and P_R. These two variables represent the storage power consumption at the SN while transmitting the information, and at the MR while receiving it during the time that the ad-hoc transmission takes place, i.e. within the time interval $\{\tau_0, \tau_1, \ldots, \tau_{b-1}\}$. Part ② of (1) includes P_{IDLE}, which represents the power consumption at the MR when it stores and carries the information. This process takes place within the time interval $\{\tau_b, \tau_{b+1}, \ldots, \tau_{c-1}\}$. Part ③ of (1) represents the cellular transmission from the MR to the BS. This part includes then the storage energy consumption for transmitting the information (P_W) during the time interval $\{\tau_c, \tau_{c+1}, \ldots, \tau_{c+m}\}$.

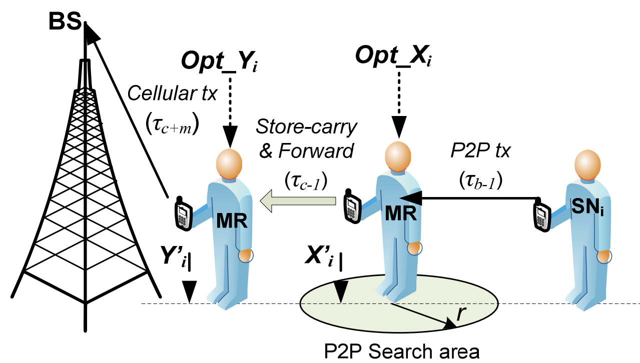


Figure 3. Optimum and suboptimum configurations in 2-hop opportunistic MCN-MR communications.

4. CONTEXT-BASED OPPORTUNISTIC FORWARDING

The optimization process presented in Section 3 allows identifying the optimum location of the MR and the optimum location at which the MR should start forwarding the information to the BS in order to minimize the overall energy consumption. The overall energy consumption computed when a MR is found at the identified optimum location can be used to establish an energy-efficiency performance bound. However, in a practical setting, it can happen that a MR cannot be found at the identified optimum location in the corresponding time instant, which has an impact on the overall energy consumption. In this case, alternative approaches are needed to select the MR. This section presents then a suboptimum opportunistic forwarding solution to select the MR taking as reference point the optimum location identified in Section 3. The solution leverages the optimization framework presented in (1)-(4), but increases the search area where to look for potential MRs around the optimum MR location identified in Section 3. Figure 3 represents the 2-hop opportunistic MCN-MR scenario considering the optimum configurations identified in Section 3, and the new suboptimum approach that increases the area where to look for a MR. For the optimum configuration, the *P2P tx* (that is completed in the time instant τ_{b-1}) takes place from SN_i to a MR located at Opt_X_i. The MR stores and carries the information from Opt_X_i, and initiates the *Cellular tx* at time instant τ_{c-1} when reaching the Opt_Y_i location. The cellular transmission finishes at time instant τ_{c+m}. In the suboptimum case, SN_i is not able to find a MR at the desired location (Opt_X_i), and looks for potential MRs around Opt_X_i. *r* represents the radius of the search area around Opt_X_i (additional details are presented below). SN_i might then find a MR within this search area at the suboptimum location X'_i. If the SN finds more than one MR within the search area, it would select the one that is closer to the optimum location Opt_X_i (if several MRs are available at the same minimum distance to the optimum location, one of them is chosen randomly). Figure 3 also represents the locations at which the *P2P tx* (X'_i) and *Cellular tx* (Y'_i) would take place in the case of the suboptimum approach.

4.1 Search area for potential MRs

The area where to look for potential MRs around the identified optimum MR location has to fulfill two conditions. First, the search area should guarantee with certain probability the presence of at least one MR. To this aim, this paper proposes to exploit context information provided by the cellular network, in particular, statistical information about the spatial density and distribution of mobile nodes within the cell. The second condition is that the BS must still receive the complete data before the deadline *T* despite the suboptimum location of the MR. This condition must be satisfied for any possible MR location within the search area. It might then happen that the search area is so large that the end-to-end MCN-MR transmission cannot be completed before the deadline *T*. This may be due for example to a significant increase of the *P2P tx* time when the distance from SN to the suboptimum MR is much larger than the distance from SN to the optimum MR. It might also happen that the distance between the suboptimum MR and SN exceeds the *P2P tx* radio coverage limit. If the two conditions established for determining the MR search area are not fulfilled, a satisfactory opportunistic MCN-MR transmission is considered unfeasible, and the SN directly transmits the information to the cellular BS through a traditional single-hop cellular link.

As established in the 3GPP reference system scenarios, mobile devices are considered to be uniformly distributed within a cell [11]. In this case, the probability to find at least one MR around the identified optimum location (Opt_X_i) can be calculated as follows [12]:

$$P_{Opt\_X_i} = P\left(x>0;\frac{\mu}{R}\cdot\phi\right) = 1 - P\left(x=0;\frac{\mu}{R}\cdot\phi\right) = 1-\frac{\left(\frac{\mu}{R}\cdot\phi\right)^0\cdot\exp\left(-\frac{\mu}{R}\phi\right)}{0!} = 1-\exp\left(-\frac{\mu}{R}\phi\right),\ \forall Opt\_X_i \in (1,\ldots,R) \quad (7)$$

where μ represents the average number of MRs uniformly distributed within a cell of radius *R*, and *Ø* corresponds to the diameter of the search area.

It is important noting that the expression in (7) is valid for any Opt_X_i location within the cell. The radius *r* around Opt_X_i that guarantees with probability δ the presence of at least one MR (8) can then be expressed as shown in (9):

$$P_{Opt\_X_i} = 1-\exp\left(-\frac{\mu}{R}\phi\right) = \delta \quad (8)$$

$$r = \frac{R\cdot\ln(1-\delta)}{-2\cdot\mu}\ \mathit{iff}\ \exists\left[X'_i, Y'_i, \ldots\right] = \underset{\forall X'_i \in o(Opt\_X_i, r)}{\arg\min}\left(\vartheta(\ldots)\right) \quad (9)$$

considering that the diameter of the search area (*Ø*) is equal to 2*r*.

As shown in (9), the radius *r* that guarantees the presence of at least one potential MR around the optimum MR location is proportional to the cell radius *R* and inversely proportional to the spatial density of MRs within the cell μ/R. In addition, *r* increases with the probability δ guaranteeing the presence of at least one MR in the search area. It is important noting that the derived radius *r* represents the radius of the search area where to look for potential MRs if and only if (*iff*) the condition shown in (9) is also fulfilled. The condition requires that there exists a solution ($[X'_i, Y'_i, \ldots]$) of the optimization problem (ϑ) presented in (1)-(4) for every possible location of the MR (X'_i) within the search area. If this condition is met, it is possible to define the search area for potential MRs *o(Opt_Xi, r)* centered in Opt_X_i (location of the optimum MR) and with radius *r*. If there is any MR location within *o(Opt_Xi, r)* where it is not possible to derive a solution of the optimization problem, the SN will transmit the information directly to the BS through a traditional single hop cellular link. On the other hand, if several MRs are found within the search area, SN will select the one closer to the optimum MR location Opt_X_i.

5. EVALUATION ENVIRONMENT

The performance of the proposed optimum and context-based opportunistic forwarding schemes in MCN-MR is evaluated in the scenario characterized by the parameters summarized in Table 1. The evaluation reported in this section considers HSPA at 2.1GHz for the cellular transmissions and IEEE 802.11g at 2.4GHz for the P2P ad-hoc transmissions[2]. It is important noting that the conclusions of the study are not dependent on the selected radio access technologies; the selection is based on the availability of models for both technologies. In fact, the study could be reproduced or adapted to other radio access technologies.

The cellular operation is adapted based on the experienced channel conditions using Adaptive Modulation and Coding (AMC) schemes. Following the model reported in [14], the cellular transmission rate of the communication from MR to BS is modeled as follows:

$$Thr_{cell}(d) = K\cdot C\cdot\log_2\left(M(d)\right)\cdot BW \quad (10)$$

where *BW*, *M* and *C* represent the bandwidth, modulation constellation size and coding rate, respectively. *M* and *C* are selected according to the distance between the mobile device and the BS (the higher the distance, the lower the signal strength, and more robust modulation and coding schemes are needed). In this study, we consider seven possible combinations of modulation and coding schemes with a maximum transmission rate of 7Mbps. *K* represents an attenuation factor that limits the cellular data rate, and includes, among others, the effect of transmission failures, retransmissions, and interference [14].

[2] It is interesting noting that 3GPP is recently considering 802.11 technologies as an alternative to cellular ones (e.g. LTE-Direct) for D2D communications in order to offload cellular traffic [13].

Table 1. Scenario parameters

Parameter	Description	Value
F	Message size	10Mb
T	Transmission deadline	40s
R	Cell radius	1000m
λ	Spatial MR densities: MRs per m	{0.1, 0.05}
δ	Probability to guarantee the presence of at least one MR in the search area	{0.8, 0.9}
AMC	Available modulation and coding schemes	BPSK (r=1/3) QPSK (r=1/3, 1/2, 2/3) 16QAM (r=1/2, 2/3, 5/6)
Max UL Thr	Maximum UL tx rate	7Mbps
BW	System bandwidth	10MHz
e_t, e_r	Energy consumed per bit by the transmitter/receiver	50×10^{-9}J/b
h_{SN}, h_{MR}, h_{BS}	Antenna height of the SN, MR and BS	1.5m, 1.5m, 10m
v	Mobile speed	2m/s
DRAM P_R, P_W, P_{Idle}	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
Trans_DF, Transf_EF	Transfer speed from the DRAM to the NAND flash and vice versa	4.85 MiB/s, 927.1 KiB/s

Based on the model reported in [15], the IEEE 802.11g transmission rate for the P2P ad-hoc communication from SN to MR can be expressed as follows:

$$Thr_{adhoc}\left(d\right) = DataRate\left(d\right) \cdot Eff \cdot \left(1 - PER\left(d\right)\right) \qquad (11)$$

where *DataRate*, *PER* and *Eff* represent the ad-hoc IEEE 802.11g transmission mode, Packet Error Ratio and channel efficiency, respectively. d is the distance between the transmitter and receiver. IEEE 802.11g defines twelve possible combinations of modulation and coding schemes that result in the set of data rates: {54, 48, 36, 24, 18, 12, 9, 6; 11, 5.5, 2, 1} Mbps. The data rate control algorithm dynamically selects the IEEE 802.11g data rate based on the link quality conditions. The IEEE 802.11g *DataRate* model used in this study has been empirically derived by the authors [16]:

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

(12) indicates that the IEEE 802.11g *DataRate* is set to 54Mbps at short distance. More robust data rates are then used with increasing distances. The IEEE 802.11g *PER* model has also been empirically derived [16]:

$$PER\left(d\right) = \frac{0.75}{1 + \exp\left(-0.019\left(d - 115.15\right)\right)} \qquad (13)$$

(13) indicates that the PER augments with the distance (d) between transmitter and receiver (despite using more robust modulation and coding schemes), although an upper PER limit (0.75) is reached. The IEEE 802.11g channel efficiency (*Eff*) represents the effective time that the 802.11g channel is used to transmit information data, and depends on the transmission time of data packets (t_d) and ACK packets (t_{ack}), the contention period (t_{cont}), and the inter-frame guard times (DIFS and SIFS) [15]:

$$Eff = \frac{t_d}{DIFS + t_{cont} + t_d + SIFS + t_{ack}} \qquad (14)$$

The energy consumption values for the DRAM and NAND flash storage units have been obtained from [17] and [18] respectively. The energy consumption per bit in the transmitter and receiver electronics (e_t and e_r), and the energy consumed for transmitting under LOS and MP conditions, have been obtained from [8]. The file that the static SN needs to upload to the BS has a nominal size of 10Mb, and the time available to complete the transmission has been set to 40s [4]. The scenario considers that the MRs are in line with the SN, and moving towards the BS with a speed of 2m/s. Different spatial densities of MRs within a cell have been simulated. The evaluation of the proposed schemes is conducted for all possible distances between SN and BS.

6. PERFORMANCE EVALUATION

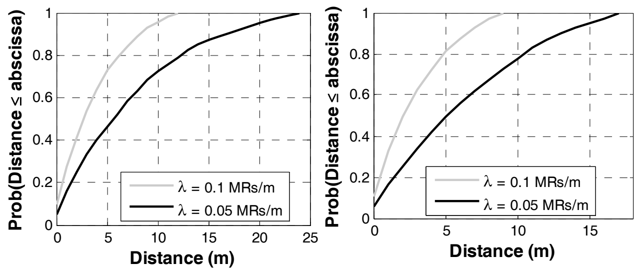
Tables 2 and 3 compare the average energy consumption of traditional single-hop cellular transmissions and the optimum configuration (Section 3), with that obtained with the proposed context-based opportunistic forwarding scheme (Section 4). The results depicted in Tables 2 and 3 correspond to average values obtained for all possible locations of SN within a cell. The obtained results clearly demonstrate that the proposed context-based opportunistic forwarding scheme significantly reduces the energy consumption compared to single-hop cellular communications. In fact, Table 2 shows that, on average, single-hop cellular communications increase by more than 200% the energy consumption with respect to context-based opportunistic forwarding. The significant energy-savings of the context-based opportunistic proposal are achieved without sacrificing the end-to-end transmission deadline. When compared to the optimum configuration (Table 3), only a slight degradation of the energy performance is observed with the context-based opportunistic forwarding scheme (designed for a practical implementation). In fact, optimum configurations only reduce the energy consumption of the context-based proposal by approximately 5 to 12%.

Table 2. Increase in average energy consumption of single-hop cellular communications with respect to opportunistic schemes

Technique	λ=0.1 MRs/m		λ=0.05 MRs/m	
	δ=0.9	δ=0.8	δ=0.9	δ=0.8
Context Opp.	228.1%	214.4%	215%	199.6%
MR close BS	61.1%		87.0%	
MR close SN	49.9%		49.7%	
Full Knowledge	244.2%		236.1%	

Table 3. Reduction in average energy consumption of the optimum configuration with respect to opportunistic schemes

Technique	λ=0.1 MRs/m		λ=0.05 MRs/m	
	δ=0.9	δ=0.8	δ=0.9	δ=0.8
Context Opp.	5.3%	8.7%	8.5%	12.4%
MR close BS	53.1%		46.7%	
MR close SN	52%		51.9%	
Full Knowledge	1.5%		3.5%	



a) $\delta = 0.9$ b) $\delta = 0.8$

Figure 4. CDF of the distance between the MR selected by the context-based opportunistic scheme and the optimum location of an MR to minimize the total energy consumption.

To understand the differences observed between the optimum configuration and the context-based opportunistic scheme, it is interesting to analyze the operation of the context-based approach. Figure 4 shows the distance between the MR selected by the context-based approach, and what would be the optimum location of an MR to minimize the total energy consumption following the optimization process presented in Section 3. Such distance is represented in Figure 4 by means of a Cumulative Distribution Function (CDF). The results depicted in Figure 4 show that, in the case of δ=0.9, the probability that it is not possible to find a potential MR at the exact optimum location (distance equal to 0 in the figure) can be higher than 95% (90% in the case of δ=0.8). The fact that it is generally not possible to find a MR at the exact optimum location explains why the context-based opportunistic scheme cannot reach the exact same energy consumption levels as those obtained for the optimum configurations. In any case, the results reported in Table 3 show that the differences are not high, and this is due to the fact that large distances between the selected MR and optimum locations are less probable (Figure 4)[3].

The results depicted in Table 3 show that the differences in energy consumption levels between the context-based opportunistic and the optimum configurations are dependent on the density of mobile nodes within the cell and the probability with which the presence of a MR is guaranteed within the search area. In particular, the results reported in Table 3 show that the difference increases when the density decreases as a result of the higher distance between the selected MR and the optimum location (Figure 4). Table 3 also shows that the differences observed between the context-based proposal and the optimum configuration reduces as the probability of guaranteeing the presence of at least one MR in the search area increases. This is due to the fact that as this probability increases, a higher percentage of 2-hop opportunistic MCN-MR connections are established (Table 4). This trend is observed in Table 3 even if δ=0.9 is characterized by higher limits of the search area (Figure 4). This is due to the fact that the results reported in Table 3 show the average performance of the context-based opportunistic scheme independently of whether the file transmission between the SN and the BS was done using an opportunistic MCN-MR connection or a traditional single-hop cellular link. As explained in Section 4, if it is not possible to find a MR in the search area that satisfies the identified constraint (9), the context-based opportunistic proposal requests that the SN to BS transmission is done using a single-hop cellular connection. If we analyze the energy consumption differences only for the SN to BS transmissions that were established using a 2-hop opportunistic MCN-MR connection, the effect of the probability δ varies (Tables 5 and 6). In this case, the results depicted in Tables 5 and 6 show that the shorter distances between the selected MR and the optimum location observed for δ=0.8 (Figure 4) results in a lower energy consumption compared to δ=0.9 (Tables 5 and 6).

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[3] The upper limit of the distances shown in Figure 4 coincides with the radius of the search area (9). For δ=0.9, this limit is equal to 12m and 24m when λ is equal to 0.1 and 0.05 MRs/m respectively. The limit is further reduced to 8m and 16m (λ=0.1 and λ=0.05 MRs/m) when δ=0.8.

Table 4. Percentage of SN-BS transmissions established using 2-hop MCN-MR connections (context-based scheme)

δ=0.9		δ=0.8	
λ=0.1	λ=0.05	λ=0.1	λ=0.05
92.63%	88.64%	81%	81.82%

Table 5. Reduction in average energy consumption of the optimum configuration with respect to the 2-hop MCN-MR connections established with the context-based scheme

λ=0.1 MRs/m		λ=0.05 MRs/m	
δ=0.9	δ=0.8	δ=0.9	δ=0.8
1.9%	1.1%	3.1%	2.7%

Table 6. Increase in average energy consumption of single-hop cellular communications with respect to the 2-hop MCN-MR connections established with the context-based scheme

Optimum		Single-hop cellular	
δ=0.9	δ=0.8	δ=0.9	δ=0.8
246.4%	247.9%	236.1%	239.7%

The results shown in Table 2 demonstrate the potential of opportunistic MCN-MR communications to reduce energy consumption for delay tolerant services with respect to traditional single-hop cellular communications. For comparative purposes, Tables 2 and 3 also show the difference in energy consumption obtained with other schemes reported in the literature. For example, Tables 2 and 3 include the performance obtained with the technique presented in [8], and that is here referred to as '*Full Knowledge*'. In this technique, the BS collects location and mobility information from all mobile nodes in the cell. Having complete knowledge of the location and mobility of nodes within a cell, the '*Full Knowledge'* technique can select the MR that minimizes the total energy consumption. The results reported in Table 3 show that the '*Full Knowledge*' technique is the one obtaining the closer energy consumption levels to the optimum configuration. However, it is important noting that the '*Full Knowledge'* technique requires collecting location and mobility information from all MRs in the cell to decide the optimum forwarding path from source to destination. On the other hand, the proposed context-based opportunistic scheme only requires knowing the location of MRs within the defined search area, which significantly reduces the signaling overhead with respect to '*Full Knowledge'*. The signaling overhead is here measured as the number of signaling messages needed to transmit the location of potential MRs. In fact, the conducted experiments have shown that the '*Full Knowledge'* technique increases on average the signaling overhead by a factor of 70 if compared with the proposed context-based opportunistic scheme. This signaling overhead results in additional energy consumption[4], as well as the use of communication resources or transmission bandwidth.

Tables 2 and 3 also include the energy performance obtained with two additional schemes. In the case of the '*MR close BS*' scheme, the SN selects the MR that provides a higher progress towards the BS [19]. On the other hand, the '*MR close SN*' scheme selects the MR that is closer to SN [20]. Once the MR is selected (independently of whether it is closer to the BS or SN), it is possible to compute the energy consumed in the ad-hoc transmission. For a fair comparison, a similar optimization process to that reported in Section 3 is then conducted for both techniques, but considering only the *Store-Carry and Forward* and the *Cellular tx* processes. This optimization process allows determining the location at which the selected MR should forward the information towards the BS in order to minimize the total energy consumption. In the optimization problem, the time available to transmit the information to the BS is reduced by the time needed for the ad-hoc transmission between SN and the selected MR. The results reported in Table 2 show that both schemes can reduce on average the energy consumption with respect to traditional single-hop cellular transmissions. However, these schemes result in a significant lower energy-efficiency performance with respect to the proposed context-based opportunistic scheme as a result of a selection of the MR that does not take into account the optimum configuration.

Finally, it is interesting to analyze how dependent is the energy-efficiency performance and trends as a function of the distance between the source and BS nodes. To this aim, Figures 5 and 6 represent the total energy consumption (in logarithmic scale) as a function of the distance of the SN to the BS for all the compared schemes[5]. The depicted energy consumption corresponds to the energy consumption levels represented in the objective function (1), and that take into account the energy consumed by the P2P transmission, the store-carry and forward process, and the cellular transmission. The results depicted in Figures 5 and 6 show that if the source node is close to the BS, the use of opportunistic MCN-MR communications does not reduce the energy consumption compared to traditional single-hop cellular communications. The reduction is only present for distances higher than 50m. The results depicted in Figures 5 and 6 clearly show that the context-based opportunistic proposal can closely follow the energy consumption levels obtained with the optimum configuration and the '*Full Knowledge'* technique, independently of the location of the source node. On the other hand, the energy consumption levels of opportunistic MCN-MR communications increase if the MR is not adequately selected ('*MR close BS'* and '*MR close SN'* schemes). In the case of the '*MR close BS'* scheme, the results illustrated in Figures 5 and 6 show that selecting the MR as close as possible to the BS can significantly increase the energy consumption levels when the SN is close to the BS. This effect is due to the high energy consumption levels experienced in the ad-hoc transmission between SN and MR.

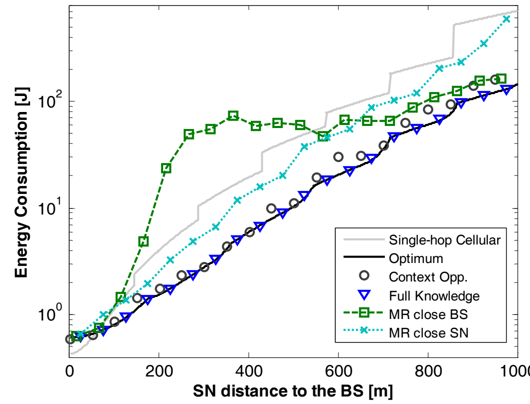

Figure 5. Total energy consumption (λ=0.1 MRs/m, *δ*=0.9)

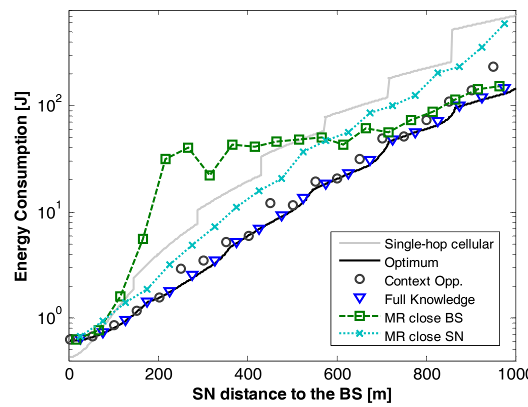

Figure 6. Total energy consumption (λ=0.05 MRs/m, *δ*=0.9)

7. CONCLUSIONS

This paper has investigated the potential of opportunistic store-carry and forward techniques in MCN-MR networks to improve the energy efficiency for delay tolerant services. The study has focused on a two-hop MCN-MR scenario, and has analytically formulated the energy optimization problem that allows identifying the optimum mobile relay location, and the location at which the relay needs to start forwarding the information to the cellular network. Building from these results, the paper has proposed, for practical implementations, a context-based opportunistic forwarding scheme that searches for potential MRs around the identified optimum location of an MR. The proposed scheme exploits information about the spatial density and distribution of nodes within a cell to define the area where to look

[4] These energy consumption levels are not considered in the results reported in Tables 2 and 3 since they were not part of the optimization processes defined in Sections 3 and 4.

[5] Similar trends are observed for *δ*=0.8.

for potential MRs around the optimum location. The conducted study has demonstrated that opportunistic forwarding schemes can significantly reduce the energy consumption compared with traditional single-hop cellular communications. The obtained results also show that the proposed context-based opportunistic forwarding scheme can provide energy consumption levels similar to those experienced with an optimum configuration. Future research in this area should also consider some architectural issues of how this new paradigm can be incorporated in emerging cellular networks.

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