Opportunistic Networking for Improving the Energy Efficiency of Multi-Hop Cellular Networks

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***Abstract*—Relaying technologies can help address the capacity and energy-efficiency challenges faced by cellular networks as a result of the rapid increase in mobile data consumption. A non-negligible portion of such consumption corresponds to delay tolerant services. This delay tolerance offers the possibility for opportunistic networking to exploit contact opportunities between mobile devices in order to reduce the impact of data traffic on the cellular capacity and energy-efficiency without sacrificing the end-user quality of service. In this context, this paper investigates the use of opportunistic forwarding in MCN-MR (Multi-hop Cellular Networks with Mobile Relays) to reduce energy consumption in the case of delay tolerant services. The study proposes to exploit context information provided at a low cost by the cellular infrastructure to efficiently select the forwarding node in a two-hop MCN-MR scenario. The proposed solution results in significant energy savings compared to traditional single-hop cellular communications and other forwarding solutions reported in the literature.**

***Index Terms*—Multi-hop cellular networks, opportunistic networking, mobile relaying, energy efficiency, context-awareness, delay tolerant.**

I. Introduction

The recent evolution of cellular networks is characterized by the rapid increase of data traffic, and the consequent capacity and energy consumption challenges. Several solutions are being investigated to address these challenges. One of them is the integration of relaying techniques into cellular systems that is usually referred to as Multi-hop Cellular Networks (MCN). Initial standardization activities in MCN focused on fixed relaying stations. However, the increasing resources of mobile devices are fostering research on MCN networks with Mobile Relays (MCN-MR). In fact, 3GPP is recently considering direct communications between mobile devices (using both cellular and 802.11 technologies) as well as the future use of Peer to Peer (P2P)-enabled mobile relays between the base station (BS) and the end user [1].

MCN-MR networks substitute long-distance, and generally Non-Line of Sight (NLOS), cellular links with multi-hop transmissions with improved link budgets, which can result in significant benefits in terms of quality of service (QoS), energy-efficiency and capacity [2]. The use of mobile relays also allows introducing opportunistic networking schemes that exploit the store, carry and forward paradigm to establish links between nodes based on connectivity opportunities and the node's inter-contact time. Opportunistic networking is particularly suited for delay tolerant services that represent a non-negligible portion of current mobile data traffic. According to the latest Cisco's global mobile data traffic forecast [3], relevant delay tolerant services include updates to social networking, emails, firmware and software updates, or some cloud services. In this context, this study focuses on the integration of opportunistic networking into MCN-MR, and investigates the capacity of opportunistic schemes to reduce the energy consumption of delay tolerant services in two-hop MCN-MR scenarios. In particular, this paper investigates the possibility to exploit the cellular infrastructure (and its signaling capabilities) to provide at low cost context information useful to improve the search for adequate mobile relays. The study demonstrates that context-aware opportunistic MCN-MR schemes can provide significant energy benefits compared to other forwarding solutions and traditional single-hop cellular communications.

II. Related Work

Several studies have demonstrated that mobile relaying and opportunistic forwarding can help reduce the energy consumption in cellular and wireless networks. For example, [4] shows that simple distance-based mobile relaying schemes can reduce the energy consumption in MCN-MR. Opportunistic schemes where a source node stores and carries the information until favorable communication conditions with the destination node are found, can also reduce the overall energy consumption [5]. Context-aware and infrastructure-assisted solutions can further improve the operation and efficiency of MCN-MR and opportunistic networks. For example, the study reported in [6] proposes a centralized scheme where the cellular BS selects the mobile relay for a 2-hop MCN-MR connection with the longest multi-hop link duration. To do so, the BS collects GPS information about the location of mobile nodes using measurement report messages. The infrastructure-assisted selection of mobile relays is shown to minimize the relay switching rate and increase the system throughput. In [7], the authors propose a mode selection scheme that decides whether to establish a single-hop or multi-hop connection between a mobile user and the BS based on the signal strength of the pilot symbols from the BS. Infrastructure-assisted context-aware schemes can also reduce energy consumption of mobile P2P communications [8]. To this aim, the authors propose in [8] a server-based mechanism to

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determine the state (wake up or sleep) of the P2P interface. Mobile devices periodically transmit their GPS location to a server (using their cellular interface), and the server uses this information to decide whether nodes can establish a P2P communications link. The design of efficient opportunistic networking schemes is generally a challenging task due to the frequent lack of information about the network's topology. To address this challenge in opportunistic MCN-MR networks, the authors propose in [9] that the BS collects information about the location and mobility of mobile nodes. Using this information, the BS can identify end-to-end opportunistic forwarding paths that reduce energy consumption and co-channel interference, increase spatial capacity, balance the load across cells, and switch-off low-utilization base stations.

Previous studies have shown that opportunistic networking and mobile relaying can reduce the energy consumption at the expense of some transmission delay. These solutions are therefore more adequate for delay tolerant services that offer the possibility to manage the tolerable delay for an efficient integration of opportunistic networking into cellular systems. The energy benefits resulting from such integration can be enhanced through the use of context information provided by the cellular infrastructure. However, it is necessary that the context information is generated and transmitted at a low cost. In this context, this paper investigates the design of simple, yet efficient, opportunistic forwarding schemes in MCN-MR that exploit context information already available in cellular networks to reduce the energy consumption in MCN-MR.

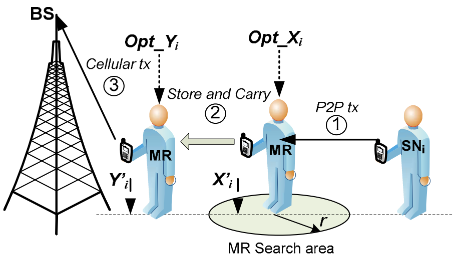


Fig. 1. 2-hop opportunistic MCN-MR scenario.

III. Opportunistic Forwarding in MCN-MR Networks

This study focuses on a 2-hop MCN-MR scenario (Fig. 1) where a Source Node (SN) wants to transmit information to a Base Station (BS) using a Mobile Relay (MR). The study considers a delay tolerant service that requires the information to be transmitted from SN to the BS within a time T. This time has to consider: 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 and Carry*), and 3) the time needed by the MR to transmit the information to the BS (*Cellular tx*). Estimating the time needed for each one of these processes is equivalent to determining the location of the MR when the P2P and cellular transmissions should start. To identify the optimum MR location, and the location at which the relay needs to start forwarding the information to the cellular network in order to reduce the energy consumption, this study defines the following multi-objective function:

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

where ① represents the energy consumed by the *P2P tx* process, ② the energy consumed in the *Store and Carry* process, and ③ the energy consumed by the *Cellular tx* from MR to the BS. The time available to transmit the information from SN to the BS (T) has been discretized in (1) as $\{\tau_0, \tau_1 \ldots \tau_T\}$. $\sum_{\tau=\tau_0}^{\tau_{b-1}} E_{adhoc}\left(d_{SN-MR},\tau\right)$ represents the energy consumed in the P2P ad-hoc transmission between SN and MR within the time interval $\{\tau_0, \tau_1 \ldots \tau_{b-1}\}$, and considering that SN and MR are separated by d_{SN-MR} at τ. $\sum_{\tau=\tau_0}^{\tau_{b-1}} \tau\cdot\left(P_R+P_W\right)$ represents the storage power consumption at the SN while transmitting the information, and the storage power consumption at the MR while receiving the information during the ad-hoc transmission [10]. $\sum_{\tau=\tau_b}^{\tau_{c-1}} \tau\cdot P_{IDLE}$ represents the power consumption at the MR when the node stores and carries the information while moving towards the BS [10]. $\sum_{\tau=\tau_c}^{\tau_{c+m}} E_{cell}(d_{MR-BS},\tau)$ represents the energy consumed in the cellular transmission between MR and the BS within the time interval $\{\tau_c, \tau_{c+1} \ldots \tau_{c+m}\}$, and considering that MR and BS are separated by d_{MR-BS} at τ. $\sum_{\tau=\tau_c}^{\tau_{c+m}} \tau\cdot P_W$ represents the storage energy consumption at MR while transmitting the information to the BS during the time interval $\{\tau_c, \tau_{c+1} \ldots \tau_{c+m}\}$.

The objective function shown in (1) has been defined together with three constraints. The first constraints establish that the message (of size F) must be completely transmitted in the P2P (eq. 2) and cellular (eq. 3) processes. TR_{adhoc} and TR_{cell} represent the P2P and cellular transmission rates respectively. The last constraint (eq. 4) guarantees for the derived solution that the end-to-end transmission is completed before the service-dependent deadline T.

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

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

$$0 \leq \tau_0 < \tau_{b-1} < \tau_b \leq \tau_{c-1} < \tau_c < \tau_{c+m} \leq T \quad (4)$$

For a given location of SN, the defined optimization problem (eq. 1 to 4) allows identifying the optimum 2-hop opportunistic MCN-MR configuration that minimizes the energy consumption. The derived solution is given by the time instances τ_0, τ_{b-1}; τ_b, τ_{c-1}; and τ_c, τ_{c+m} at which the *P2P tx*, *Store and Carry* and *Cellular tx* processes take place. This is in fact equivalent to 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 (Fig. 1).

It is possible that a MR cannot be found when needed at the identified optimum location. To address this scenario, this study proposes to increase, around the optimum MR location, the search area where to look for potential MRs using context information provided by the cellular infrastructure. If there is more than one MR within the search area, the SN selects the one that is closer to the optimum location Opt_X_i. Fig. 1 illustrates an example of the search area around the optimum location Opt_X_i. In Fig. 1, r denotes the radius of the MR search area around Opt_X_i. X'_i represents the location of the identified MR within the search area, and Y'_i the location at which the MR will start the cellular transmission to the BS.

The area where to look for potential MRs around the identified optimum MR location needs to satisfy two conditions. The first one is that it must guarantee with certain probability the presence of al least one MR. To compute this probability, this paper proposes to exploit context information provided by the cellular infrastructure, in particular, statistical information about the spatial density and distribution of mobile nodes within the cell. Obtaining this information does not have a cost in current cellular systems that require mobile devices to register their location with the serving BS. Cellular standards such as HSDPA and LTE allow for a more accurate identification of the mobile devices location without uploading any GPS information. These standards divide cells in concentric rings that identify (based on parameters such as the signal strength or Channel Quality Indicator - CQI) the transmission mode or rate to employ by mobile devices located at each ring. The second condition to define the search area is that it must satisfy the established QoS restriction, i.e. independently of the selected MR within the search area, the BS must still receive the complete data before the deadline T. When it is not possible to define a search area that fulfills the two conditions, SN transmits the information to the BS using traditional single-hop cellular communications.

Without loss of generality, the MR search area is first estimated considering a uniform distribution of mobile devices within the cell (such uniform distribution is considered as a reference scenario in 3GPP TR 25.942 V11.0.0). Assuming an average density of μ/R mobile devices uniformly distributed within a cell, the probability to find at least one MR around an identified optimum location (Opt_X_i) can be computed as [11]:

$$P_{Opt\_X_i} = P\left(x > 0; \frac{\mu}{R}\cdot\phi\right) = 1 - \exp\left(-\frac{\mu}{R}\cdot\phi\right),\ \forall Opt\_X_i \in (1,...,R) \quad (5)$$

where μ is the average number of MRs within the cell of radius R, and $\emptyset$ corresponds to the diameter of the search area. It is important noting that (5) is valid for any Opt_X_i location within the cell. Eq. (5) has been obtained considering the average density of users within a cell. The same expression can be used in scenarios where each cell is divided into rings, the spatial density of users per ring is known, and users are uniformly distributed within each ring. In this case, the spatial density of users in (5), i.e. μ/R, should be replaced by φ/l with φ representing the average number of MRs in the ring, and l the ring length. Following (5), the radius r around Opt_X_i that guarantees with probability δ the presence of at least one MR can be estimated as:

$$r = \frac{R\cdot\ln(1-\delta)}{-2\cdot\mu} \quad iff\ \exists Y'_i = \underset{\forall X'_i \in o(Opt\_X_i, r)}{\arg\min} (\vartheta) \quad (6)$$

with the diameter of the search area ($\emptyset$) being equal to $2r$. The condition defined in (6) requires that for every possible location of the MR (X'_i) within the search area, the optimization problem formulated in eq. 1 to 4 (represented by ϑ in (6)) provides the location (Y'_i) at which the MR should start the cellular transmission to the BS that minimizes the total energy consumption and satisfies that the transmission is completed before T. If this condition is met, it is possible to define the MR search area $o(Opt\_X_i, r)$ centered in Opt_X_i and with radius r. If the condition is not met, the SN will transmit the information directly to the BS through a traditional single-hop cellular link.

This study assumes that cells are divided into concentric rings. In this case, the probability to find at least one MR around the identified optimum MR location can be estimated for any kind of non-uniform distributions of mobile devices within the cell. In particular, the probability can be estimated when each ring has different spatial density of users, but the users are uniformly distributed within each ring. In this scenario, the probability can be estimated as:

$$P_{Opt\_X_i} = 1 - \exp\left(-\frac{\varphi_i}{l_i}\cdot\phi\right) \quad (7)$$

with φ_i representing the spatial density of mobile devices in ring i where the optimum MR is located. Considering that the cell is divided into N rings, the average number of MRs within the cell can be calculated as $\mu = \sum_{i=1}^{i=N} \varphi_i$, and the cell radius as $R = \sum_{i=1}^{i=N} l_i$. Following (7), the radius r around Opt_X_i guaranteeing with probability δ the presence of at least one MR can be estimated for non-uniform distributions within the cell as:

$$r_i = \frac{l_i\cdot\ln(1-\delta)}{-2\cdot\varphi_i} \quad iff\ \exists Y'_i = \underset{\forall X'_i \in o(Opt\_X_i, r_i)}{\arg\min} (\vartheta) \quad (8)$$

with $\emptyset$ being equal to $2r$. In this case, the MR search area radius depends on the ring where Opt_X_i is located. It should be noted that the same condition to that analyzed in (6) must be satisfied in (8) in order to define the MR search area $o(Opt\_X_i, r)$. If the condition is not met, the SN will again transmit the information directly to the BS through a traditional single-hop cellular link.

IV. Evaluation Environment

The performance of the proposed infrastructure-assisted opportunistic forwarding scheme is evaluated considering the parameters reported in Table 1. The evaluation has been conducted considering HSPA at 2.1GHz for the cellular transmissions, and IEEE 802.11g at 2.4GHz for the P2P ad-hoc transmissions[1]. These technologies were selected due to the availability of the necessary models. However, the conclusions here reported are not dependent on the selected radio access technologies. The simulated scenario considers that cellular

[1] 3GPP is considering 802.11 for device-to-device communications as an alternative to cellular (e.g. LTE-Direct) in order to offload cellular traffic [1].

transmissions adapt the modulation and coding schemes based on the experienced channel conditions. Following the model reported in [12], the cellular transmission rate is modeled as:

$$TR_{cell}(d) = k \cdot C \cdot log_2(M(d)) \cdot BW \quad (9)$$

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 (more robust modulation and coding schemes are needed as the distance increases). This study considers 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 [12]. Following [13], the IEEE 802.11g transmission rate is modeled as follows:

$$TR_{adhoc}(d) = DataRate(d) \cdot Eff \cdot (1 - PER(d)) \quad (10)$$

with *DataRate*, *PER* and *Eff* representing the ad-hoc IEEE 802.11g transmission mode[2], Packet Error Ratio and channel efficiency, respectively. *d* is the distance between the transmitter and receiver. The *DataRate* and *PER* models used in this study have been empirically derived and can be found in [14]. The IEEE 802.11g channel efficiency (*Eff*) model presented in [13] is used in this study. This parameter represents the effective time that the 802.11g channel is used to transmit information data (considering the overhead time resulting from ACK packets, contention periods and inter-frame guard times).

The signal power level at the receiver can be computed as $P_{RX}=G_{TX}+G_{RX}+P_{TX}-PL$, where G_{TX} and G_{RX} represent the transmitter and receiver antenna gains (here equal to 1), P_{TX} the transmission power, and *PL* the propagation loss. The transmission energy consumption is here computed considering that P_{TX} is the necessary one to guarantee that P_{RX} is equal to the threshold required for a successful communication between two nodes. The propagation loss is here modeled using the WINNER model for urban scenarios [15]. Using this model, it is possible to estimate P_{TX} under LOS conditions as:

$$P_{TX}^{LOS}(d) = \begin{cases} \dfrac{P_{RX} \cdot 10^{4.1} \cdot (f/5)^2}{G_{TX} \cdot G_{RX}} d^{2.7} & if\ d < d_{bp} \\ \dfrac{P_{RX} \cdot 10^{4.1} \cdot (f/5)^2}{G_{TX} \cdot G_{RX} \cdot d_{bp}^{1.73}} d^{4} & if\ d \geq d_{bp} \end{cases} \quad (11)$$

where *d* is the distance between transmitter and receiver, $d_{bp} = 4\cdot(h_{TX}-1)\cdot(h_{RX}-1)/\Lambda$ is the breakpoint distance (h_{TX} and h_{RX} are the transmitter and receiver antenna heights, and Λ is the carrier wavelength, all of them in m), and *f* is the carrier frequency in GHz. The energy consumed in the ad-hoc (E_{adhoc}) and cellular (E_{cell}) transmissions can then be expressed as:

$$E(d) = (e_{rx} + e_{tx} + e_{LOS}(d)) \cdot TR \quad (12)$$

where e_{tx} and e_{rx} represent the energy consumption per bit in the transmitter and receiver electronics respectively (the values reported in [9] have been used in this evaluation), and *TR* is the transmission rate (TR_{adhoc} or TR_{cell}). e_{LOS} represents the transmission energy consumption per bit under LOS conditions and is equal to P_{TX}^{LOS}/TR. A similar process can be followed to estimate the NLOS transmission energy consumption. The energy consumption values for the process to store and carry the information on mobile devices (P_R, P_W and P_{IDLE}) have been obtained from [16] and [17].

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 60s [9]. The scenario considers that the MRs are in line with the SN, and moving towards the BS with a speed of 2m/s.

TABLE I. EVALUATION PARAMETERS

Parameter	Description	Value
R	Cell radius	1000m
δ	Probability to guarantee the presence of at least one MR in the search area	{0.8, 0.9}
AMC	Adaptive modulation and coding	BPSK(r=1/3) QPSK(r=1/3, 1/2, 2/3) 16QAM(r=1/2, 2/3, 5/6)
BW	Bandwidth	10MHz
e_{tx}, e_{rx}	Energy consumed per bit by the transmitter/receiver	50 x 10-9J/b
P_{TH}	Power reception threshold	-52dBm
h_S, h_{MR}, h_{BS}	Antenna height of SN, MR and BS	1.5m, 1.5m, 10m
P_R, P_W, P_{IDLE}	Storage power consumed for Reading, Writing and in Idle state	252mW, 252mW, 1.35mW

V. PERFORMANCE EVALUATION

The energy consumption of the infrastructure-assisted opportunistic proposal is here compared against that obtained with traditional single-hop (SH) communications, the optimum configuration of opportunistic forwarding (eq. 1 to 4) that will be referred to as 'Opt. config.', and 4 other reference schemes from the literature. In the reference scheme 'MR close BS', the SN selects the MR that provides a higher progress towards the BS [18]. On the other hand, the 'MR close SN' reference scheme selects the MR that is closer to SN [19]. Once the MR is selected (closer to the BS or SN), and for a fair comparison, a similar optimization process to that reported in Section III is then conducted for both techniques, but considering only the *Store and Carry* 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. The 'Full knowledge' reference scheme was proposed in [9]. This scheme assumes that a BS can collect all the information about the location and mobility of mobile nodes in the cell, and use this information to identify the MR that minimizes the total energy consumption. Finally, the performance of the infrastructure-assisted proposal is also compared to Direct-contact schemes [5] ('SH direct contact'). In Direct-contact, the SN is mobile and can store, carry and forward the information to the BS without using a mobile relay. In this case, and for a fair comparison, the objective function in (1) is used to define the optimum location at which the moving SN should start

[2] IEEE 802.11g defines 12 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.

forwarding the information to the BS to minimize the energy consumption.

Table II shows the average energy reduction that can be obtained with the different schemes compared to traditional single-hop cellular communications[3]. The depicted results correspond to average values obtained for all possible distances between SN and BS. Different tables are used for uniform and non-uniform spatial distributions of mobile devices within the cell. Results are shown for different spatial densities of MRs (λ={0.1, 0.07, 0.05} MRs/m) within a cell. In the case of a non-uniform distribution of users within the cell, higher densities are considered for the rings closer to the BS without loss of generality[4]. The infrastructure-assisted proposal requires information about the density of users. When such information is provided per cell, the proposal is referred to as 'Cell density'. When the information is provided per ring, the scheme is referred to as 'Ring density'. To provide the density information per ring, this study considers that a cell is divided into seven rings; a cellular transmission mode (Table I) is assigned to each ring.

TABLE II. AVERAGE ENERGY REDUCTION (IN %) COMPARED TO SINGLE-HOP CELLULAR COMMUNICATIONS

A) UNIFORM SPATIAL DISTRIBUTION OF MRS

Technique	λ=0.1 MRs/m		λ=0.07 MRs/m		λ=0.05 MRs/m	
	δ=0.9	δ=0.8	δ=0.9	δ=0.8	δ=0.9	δ=0.8
Cell density	67.6	64.6	66.5	63.7	65.6	62.8
Ring density	70.4	65.1	69.8	64.1	69.0	63.4
MR close BS	-96.5		-85.7		-83.4	
MR close SN	57.7		57.4		56.7	
Full knowledge	74.4		73.9		73.2	
SH direct contact	62.4					
Opt. config.	75.1					

B) NON-UNIFORM SPATIAL DISTRIBUTION OF MRS

Technique	λ=0.1 MRs/m		λ=0.07 MRs/m		λ=0.05 MRs/m	
	δ=0.9	δ=0.8	δ=0.9	δ=0.8	δ=0.9	δ=0.8
Cell density	55.2	50.7	54.3	49.2	52.8	46.5
Ring density	71.2	66.0	71.5	65.3	68.2	64.8
MR close BS	-127.6		-117.7		-110.4	
MR close SN	58.2		58.8		57.8	
Full knowledge	74.5		74.0		72.7	
SH direct contact	62.4					
Opt. config.	75.1					

The results depicted in Table II show that the infrastructure-assisted proposal significantly reduces the energy consumption compared to single-hop cellular communications without sacrificing the end-user QoS (in this case, the transmission deadline). The reduction ranges from 50 to 70%, and is obtained independently on whether the density information is provided per cell or ring. The obtained results show that in terms of energy reduction levels compared to single-hop cellular communications, the infrastructure-assisted proposal is only outperformed by the optimum configuration of opportunistic forwarding ('Opt. config.') and the 'Full knowledge' scheme. As previously mentioned, it is possible that a MR cannot be found when needed at the identified optimum location. This reduces the feasibility to apply the optimum configuration in practical settings. It is also important noting that extracting the location and mobility information required by the 'Full knowledge' technique has a significant overhead cost. In fact, the conducted experiments have shown that the 'Full knowledge' technique increases on average the signaling overhead by a factor of 70 compared with the infrastructure-assisted opportunistic proposal. The signaling overhead has been measured as the number of signaling messages needed to transmit the location of potential MRs. This signaling overhead results in additional energy consumption[5], as well as the use of communication resources or transmission bandwidth.

Table II shows that under a uniform distribution of users within the cell, there is not a significant performance difference between the 'Cell density' and 'Ring density' proposals. On the other hand, the 'Ring density' variant outperforms the 'Cell density' one when there is a non-uniform distribution of users within the cell. The infrastructure-assisted proposal looks for potential MRs in a search area calculated using density information. When a MR cannot be found in the identified search area, the SN directly communicates with the BS using traditional single-hop cellular communications. The 'Cell density' variant looks for potential MRs in a search area calculated using density information per cell. When the distribution of users is non-uniform within a cell, the density information per cell can result in frequent incorrect estimations of the MR search area compared to the case in which the density information is provided per ring; the density information per ring can provide a better indication of the non-uniform distribution of users, and therefore better adjust the MR search area. This trend is observed when analyzing the hit rate [20] of the infrastructure-assisted proposal (Table III), or percentage of transmissions conducted using 2-hop MCN-MR communications. Table III shows that in the case of non-uniform distribution of users within the cell, the 'Cell density' variant significantly decreases the hit rate as a result of an incorrect definition of the MR search area. The lower percentage of 2-hop MCN-MR connections established with the 'Cell density' variant increases the energy consumption with respect to the 'Ring density' variant for non-uniform distributions (Table II.B). On the other hand, the 'Ring density' variant results in a better definition of the MR search area, and therefore a higher hit rate. This is illustrated in Fig. 2 that shows an example of the hit rate as a function of the distance between SN and the BS[6]. Fig. 2.a shows that for a uniform distribution of users within the cell, the 'Cell density' and 'Ring density' variants achieve similar hit rate levels independently of the location of the SN. In the case of non-uniform distributions within the cell (in this study, higher MR densities close to the BS), the 'Cell density' variant underestimates the MR search area with increasing distances

[3] The 'MR close BS' technique consumes more energy than single-hop cellular communications (negative values in Table II) due to the high energy being consumed during the ad-hoc transmission as a result of selecting the MR as close as possible to the BS.

[4] For λ=0.1 MRs/m, the density (in MRs/m) in the seven rings is (values are shown from closer to more distant to the BS): {0.4, 0.085, 0.071, 0.057, 0.043, 0.029, 0.014}. For λ=0.07 MRs/m, these values are equal to: {0.28, 0.06, 0.05, 0.04, 0.03, 0.02, 0.01}. For λ=0.05 MRs/m, these values are equal to: {0.2, 0.043, 0.036, 0.026, 0.021, 0.014, 0.007}.

[5] These energy consumption levels are not considered in the results reported in Table II since they were not part of the optimization processes defined in Section III.

[6] Similar trends are observed for δ=0.8 and λ={0.07, 0.05}MRs/m.

from SN to the BS, which results in a decrease of the hit rate (Fig. 2.b). On the other hand, the 'Ring density' variant adapts the MR search area to the density of users in the ring around the MR optimum location. In particular, the 'Ring density' variant increases the radius of the MR search area as the distance between SN and BS increases in order to compensate the reduction of density of users. This capacity to adapt the MR search area explains the higher hit rate of 'Ring density', and therefore its better energy performance (Table II.B).

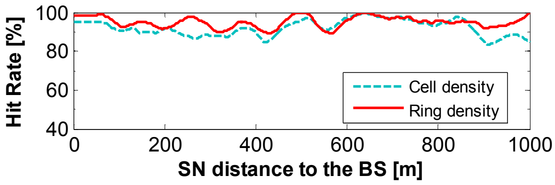
TABLE III. HIT RATE: PERCENTAGE OF SN-BS TRANSMISSIONS ESTABLISHED USING 2-HOP MCN-MR COMMUNICATIONS

A) UNIFORM SPATIAL DISTRIBUTION OF MRS

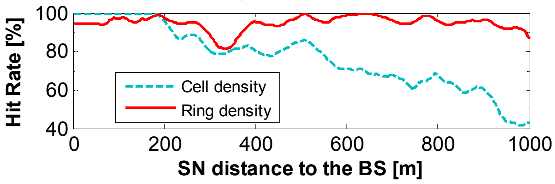
Technique	δ=0.9			δ=0.8		
	λ=0.1	λ=0.07	λ=0.05	λ=0.1	λ=0.07	λ=0.05
Cell density	91.1	89.6	91.8	83.1	79.4	84.3
Ring density	94.8	94.5	95.0	87.0	86.7	88.0

B) NON-UNIFORM SPATIAL DISTRIBUTION OF MRS

Technique	δ=0.9			δ=0.8		
	λ=0.1	λ=0.07	λ=0.05	λ=0.1	λ=0.07	λ=0.05
Cell density	78.0	79.2	75.6	72.8	71.2	68.3
Ring density	96.1	97.0	94.6	89.3	88.7	89.0



a) Uniform spatial distribution of MRs



b) Non-uniform spatial distribution of MRs

Fig. 2. Percentage of transmissions established using 2-hop MCN-MR as a function of the distance from SN to the BS (λ=0.05 MRs/m, δ=0.9).

VI. CONCLUSIONS

This paper has investigated the energy benefits that can be obtained from the integration of opportunistic networking into MCN-MR networks in the case of delay tolerant services. In particular, the study has proposed an opportunistic scheme that exploits context information provided by the cellular infrastructure to improve the search for adequate mobile relays. The context information (spatial density and distribution of mobile nodes) can be obtained in current cellular systems at a low cost. The obtained results have shown that the proposed infrastructure-assisted opportunistic forwarding scheme can significantly reduce (up to 70%) the energy consumption compared to traditional single-hop cellular communications. The obtained results have also shown that the provision of the context information per ring rather than per cell can improve the energy performance of the proposed scheme, in particular when users are non-uniformly distributed within the cell.

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