Store, Carry and Forward for Energy Efficiency in Multi-hop Cellular Networks with Mobile Relays

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***Abstract*— The wide scale adoption of smartphones is boosting cellular data traffic with the consequent capacity constraints of cellular systems and increase in energy consumption. A significant portion of cellular data traffic can be deemed as delay tolerant. Such tolerance offers possibilities for designing novel communications and networking solutions that can accommodate the delay tolerant cellular data traffic while reducing their impact on the overall cellular capacity and energy consumption. In this context, this work studies the use of opportunistic store, carry and forward techniques in Multi-Hop Cellular Networks (MCN) to reduce energy consumption for delay tolerant traffic. The study focuses on two-hop MCN networks using mobile relays (MCN-MR), and identifies 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. The study shows that the use of opportunistic store, carry and forward techniques in MCN-MR can significantly reduce energy consumption compared to other solutions, including traditional single-hop cellular systems or direct contact store, carry and forward solutions.**

Keywords—Store, carry and forward; multi-hop cellular networks; opportunistic networking; energy efficiency

I. INTRODUCTION

Cellular data traffic is continuously growing, and currently represents one of the major challenges for cellular operators. To cope with such growth and increase the spectral efficiency, many efforts have been devoted to the development of new radio access technologies and advanced physical layer schemes, as well as to the deployment of small cells. Multi-hop Cellular Networks (MCN) represent an alternative approach for improving capacity and energy-efficiency, and offload data traffic [1]. MCN systems are based on the integration of relaying technologies with cellular systems. Such integration allows substituting long-distance, and generally Non-Line of Sight (NLOS), cellular links with various multi-hop transmissions with improved link budgets. The introduction of relaying techniques into cellular systems initially focused on the use of fixed relays. However, the use of mobile relays in MCN networks (MCN with Mobile Relays, MCN-MR) can offer additional networking possibilities through a collaborative use of the resources of mobile devices [2]. For example, the use of mobile relays offers the possibility to design and implement opportunistic networking solutions. Opportunistic schemes establish communication links between nodes based on connectivity opportunities and the nodes' inter-contact time. As a result, opportunistic schemes can exploit the mobility of nodes and the store, carry and forward paradigm to establish communication links between mobile relays based on contact opportunities [3]. Opportunistic schemes can introduce an end-to-end transmission delay. However, it is important highlighting that, according to the latest Cisco's global mobile data traffic forecast [4], some of the services and applications that are mainly driven the growth of cellular data traffic can be deemed as delay tolerant services (e.g. updates to social networking, emails, firmware and software updates, or cloud services). In this context, the capacity and energy-efficiency of cellular systems could be improved without sacrificing quality of service, by exploiting opportunistic networking approaches in MCN-MR systems for delay-tolerant services. In this context, this paper studies the energy-efficiency gains that can be obtained through the use of opportunistic store, carry and forward techniques in 2-hops MCN-MR communications. In particular, the paper identifies 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. The obtained results demonstrate that the use of opportunistic store, carry and forward techniques in MCN-MR can significantly reduce energy consumption compared to traditional single-hop cellular systems or direct contact store, carry and forward solutions. In addition, the optimum conditions identified in this paper can be used as a benchmark for the design of novel opportunistic forwarding schemes tailored for MCN-MR systems. It is worth also highlighting that 3GPP is recently considering direct communications between mobile devices (using both cellular and 802.11 technologies) to be introduced in future cellular networks which can be considered as an enabler of the proposed set of ideas discussed hereafter [5]. In addition such operation may be highly relevant for future 5G systems where it is envisioned to utilize the millimeter wave (mm-wave) frequency spectrum for broadband cellular [6]; store, carry and forward can help combat path losses by bringing the transmission closer to the base station.

II. RELATED WORK

The possibilities that mobile relaying offers to reduce energy consumption were first highlighted in [7] where cells were divided into concentric rings. The study showed that the overall energy consumption can be reduced if only mobile

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relays located at the inner-most ring are allowed to directly transmit data to the cellular base station (those in outer rings need to find relays placed at inner rings). Energy consumption can be further reduced using opportunistic networking solutions. For example, simple schemes where a source node stores and carries the information until favorable communication conditions with the destination node are found, can reduce energy consumption [8]. The benefits that can be obtained from the integration of multi-hop opportunistic communications into cellular systems are discussed in [9]. To obtain such benefits, the authors propose the implementation of multi-hop opportunistic routing schemes. The schemes are defined 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 identifies all possible routes for forwarding information towards a cellular base station. Using this network graph and the knowledge of the relays' mobility, multi-hop opportunistic routing schemes can be designed for reducing the energy consumption [10], increasing spatial capacity, reducing co-channel interference [11], balance the load across cells, and switch-off low-utilization base stations [12].

Previous studies have shown that the integration of opportunistic store, carry and forward into cellular systems can reduce energy consumption at the expense of some transmission delays. The design of these schemes should therefore target services that tolerate delays. A key aspect is then how to manage the tolerable delay to reduce energy consumption. In this context, this paper identifies 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 energy consumption in MCN-MR.

III. Energy-Efficient Opportunistic Store, Carry and Forwarding in MCN-MR Networks

Fig. 1 illustrates the two-hop MCN-MR scenario under study in this paper. The scenario considers a static Source Node (SN) that wants to transmit information to a Base Station (BS) using a single Mobile Relay (MR) with store, carry and forward capabilities. To do so, it is first necessary to identify the location of the MR node, and transmit the information from SN to MR (① in Fig. 1). The MR would then store and carry the information (② in Fig. 1) until it reaches a location from where to transmit the information to the BS using its cellular interface (③ in Fig. 1). The study considers that there is a transmission deadline by which the information needs to be received at the BS. Such deadline must be met considering the time needed for the ad-hoc transmission from SN to MR (*P2P tx*), the time that the MR stores and carries the information (*Store and Carry*), and 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 MR at which the P2P transmission starts, and the location from which the MR starts the cellular transmission. In this context, this paper focuses on estimating these two locations with the final objective to reduce the total energy consumption subject to the transmission of the information from SN to BS in the established transmission deadline.

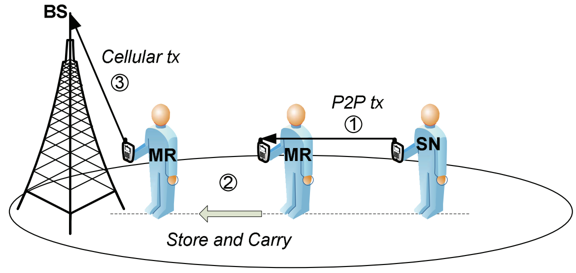

Fig. 1. 2-hop opportunistic MCN-MR scenario.

A. Problem formulation

A multi-objective constrained optimization approach has been adopted to minimize the total energy consumption following the objective function shown in (1). The objective function is defined considering the energy consumed by the processes involved in 2-hop opportunistic MCN-MR communications (see Fig. 1): *P2P tx* ①, the *Store and Carry* process ② and the *Cellular tx* ③. As previously mentioned, the BS has to receive the information before a deadline T (eq. 4) that is discretized in (1) as $\{\tau_0, \tau_1, \ldots, \tau_\Gamma\}$. $\sum_{\tau=\tau_0}^{\tau_{b-1}} E_{adhoc}\left(d_{SN-MR}, \tau\right)$ represents the energy consumed in the P2P ad-hoc transmission between the SN and MR nodes within the time interval $\{\tau_0, \tau_1, \ldots, \tau_{b-1}\}$ considering that the SN and MR nodes are separated by d_{SN-MR} at the time instant 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 explained in Section III.C). $\sum_{\tau=\tau_c}^{\tau_{c+m}} E_{cell}(d_{MR-BS}, \tau)$ represents the energy consumed in the cellular transmission between the MR and the BS within the time interval $\{\tau_c, \tau_{c+1}, \ldots, \tau_{c+m}\}$ considering that the MR and BS nodes are separated by d_{MR-BS} at the time instant 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. $R_{ad\text{-}hoc}$ and R_{cell} represent the P2P ad-hoc and cellular transmission rates respectively. Constraint (4) ensures the communication processes are conducted before the deadline T. Following the previous discussion, identifying the optimum mobile relay location, and the location at which the relay needs to start forwarding the information to the BS in order to minimize the overall energy consumption, is equivalent to finding τ_{b-1}, τ_{c-1} and τ_{c+m} in (1).

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

$st:$

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

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

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

B. Transmission energy consumption

The signal power level at the receiver can be computed as:

$$P_R = G_T + G_R + P_T - PL \quad (5)$$

where G_T and G_R are the transmitter and receiver antenna gain, P_T is the transmission power, and PL is the propagation loss. This study models the propagation losses between SN and MR, and between MR and BS, using the WINNER model for urban scenarios [13]. The transmission energy consumption is here computed considering that the transmission power (P_T) is the necessary one to guarantee that the receiver's signal power level (P_R) is equal to the threshold required for a successful communication between two nodes. In this context, and considering the WINNER propagation losses, it is possible to estimate the transmission power under LOS conditions as:

$$P_T^{LOS}(d)=\begin{cases}\dfrac{P_R\cdot 10^{4.1}\cdot\left(f/5\right)^2}{G_T\cdot G_R}d^{2.7} & if\ d<d_{bp}\\[2ex] \dfrac{P_R\cdot 10^{4.1}\cdot\left(f/5\right)^2}{G_T\cdot G_R\cdot d_{bp}^{1.73}}d^{4} & if\ d\geq d_{bp}\end{cases} \quad (6)$$

where d is the separation distance between the transmitter and receiver, $d_{bp} = 4\cdot(h_T-1)\cdot(h_R-1)/\lambda$ is the breakpoint distance (h_T and h_R 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 under LOS can then be expressed as:

$$E(d) = \left(e_r + e_t + e_{LOS}(d)\right)\cdot R \quad (7)$$

where e_t and e_r represent the energy consumption per bit in the transmitter and receiver electronics respectively, and R is the transmission rate (R_{adhoc} *or* R_{cell}). e_{LOS} represents the transmission energy consumption per bit under LOS conditions and is equal to P_T^{LOS}/R. A similar process can be followed to estimate the NLOS transmission energy consumption.

C. Storage energy consumption

Following the conclusions reported in [14], the total energy is computed taking into account the energy consumed by the *Store and Carry* process. 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 to reduce 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 cellular 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 Fig. 2 [14].

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

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.

The *P2P tx* (①) part of 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 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 while moving towards the BS. This process takes place within the time interval $\{\tau_b, \tau_{b+1}, \ldots, \tau_{c-1}\}$. Part ③ of objective function (1) represents the cellular transmission of the information from the MR to the BS. This part includes then the storage energy consumption for transmitting the informatin (P_W) during the time interval $\{\tau_c, \tau_{c+1}, \ldots, \tau_{c+m}\}$.

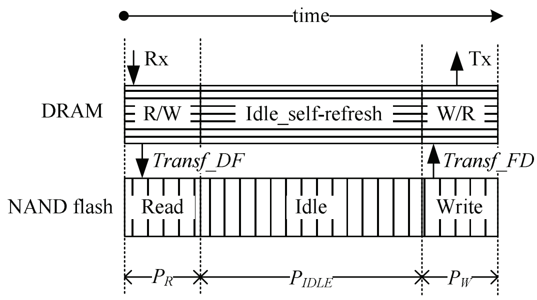

Fig.2. Transition states of the storage units as a function of the time when the data is transferred from DRAM to FLASH, and sent back to DRAM.

IV. EVALUATION SCENARIO

The numerical resolution of objective function (1) is done considering the parameters summarized in Table I. The evaluation considers HSPA at 2.1GHz for the cellular transmissions, and IEEE 802.11g at 2.4GHz for the ad-hoc transmissions[2]. These technologies have been selected based on the availability of the necessary models. In any case, the conclusions here reported are not dependent on the selected radio access technologies. The cellular transmission adapts the modulation and coding schemes based on the experienced channel conditions. Following the model reported in [15], the cellular transmission rate of the communication from MR to BS is modeled as follows:

$$R_{cell}(d) = k\cdot C\cdot log_2\left(M(d)\right)\cdot BW \quad (8)$$

where BW, M and C represent the system 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 received signal strength, and more robust modulation and coding schemes are needed). This study considers seven

[2] It is interesting noting that 3GPP is recently considering 802.11 technologies as an alternative to cellular ones (e.g. LTE-Direct) for device-to-device communications in order to offload cellular traffic [5].

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 [15].

The work in [16] models the IEEE 802.11g transmission rate for the P2P ad-hoc communication between SN and MR as follows:

$$R_{adhoc}(d) = DataRate(d) \cdot Eff \cdot (1 - PER(d)) \quad (9)$$

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 [17]:

$$DataRate(d) = \begin{cases} 54 & d < 78.47m \\ \dfrac{54}{\dfrac{1}{78.47} - \dfrac{1}{270.85}} \cdot \left(\dfrac{1}{d} - \dfrac{1}{270.85}\right) & 78.47m \le d < 270.85m \\ 0 & 270.85m \le d \end{cases} \quad (10)$$

(10) 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 [17]:

$$PER(d) = \frac{0.75}{1 + e^{-0.019 \cdot (d - 115.15)}} \quad (11)$$

(11) 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 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*) [16]:

$$Eff = \frac{t_d}{DIFS + t_{cont} + t_d + SIFS + t_{ack}} \quad (12)$$

The energy consumption values for the DRAM and NAND flash storage units have been obtained from [18] and [19] respectively. The energy consumed per bit in the transmitter and receiver electronics (e_t and e_r), and the power reception threshold (P_r), have been obtained from [10]. The scenario considers the MR is in line with the SN, and moving towards the BS with a speed v of 2m/s. The SN needs to transmit to the BS a 10Mb (F) file before a 40s deadline T [9].

TABLE I. EVALUATION PARAMETERS

Parameter	Description	Value
Cell	Cell radius	1000m
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	System bandwidth	10MHz
G_T, G_R	Transmitter and receiver antenna gain	1
e_t, e_r	Energy consumed per bit by the transmitter/receiver	50 x 10^{-9}J/b
P_r	Power reception threshold	-52dBm
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_EF	Transfer speed from the DRAM to the NAND flash and vice versa	4.85 MiB/s, 927.1 KiB/s

V. RESULTS

The resolution of the objective function results in the optimum MR location to start the P2P transmission depicted in Fig. 3-left. The MR location is represented by means of the distance between SN and MR, and is depicted in Fig. 3-left as a function of the distance between SN and BS. Figure 3-left shows for example that if SN is located 400m away from the BS, the MR should be ideally located 77m away from the SN in the direction of the BS in order to minimize the total energy consumption (practical implementation to know the actual distance between SN and MR is out of the scope of this paper). Fig. 3-left shows that the distance between SN and the optimum MR that minimizes the energy consumption increases with the distance between SN and BS. This is the case because as the distance between SN and MR increases, the MR is closer to the BS, and the cellular transmission energy decreases. On the other hand, the P2P transmission energy increases as MR is closer to the BS. As a result, the distance between SN and the optimum MR location only increases when the energy saving of the *Store and Carry* process can compensate the increase in the P2P transmission energy consumption. The energy consumption levels for the P2P transmission from SN to the optimum MR location are reported in Fig. 3-right in logarithmic scale. The energy consumption levels are shown as a function of the distance between SN and BS, and are labeled '2-hop MCN (Opt MR location)'. The increasing distances between SN and the optimum MR (Fig. 3-left) result in that the *P2P tx* energy consumption levels increase with the distance between SN and BS.

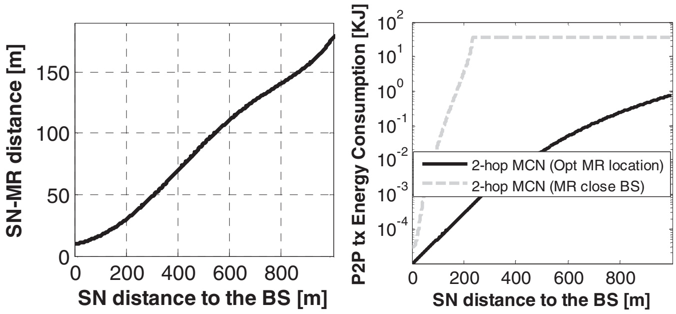

Fig. 3. *P2P tx*: optimum MR location (left) and energy consumption (right).

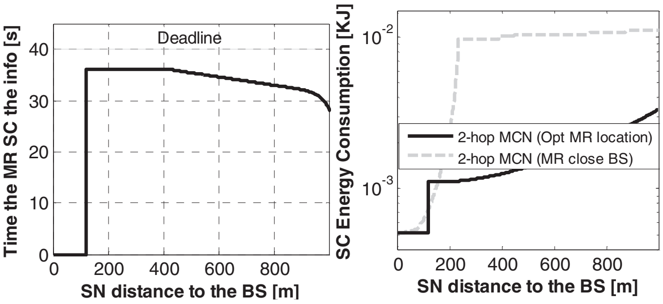

Fig. 4. *Store and Carry* (SC): time the MR stores and carries the information while moving towards the BS (left) and energy consumption (right).

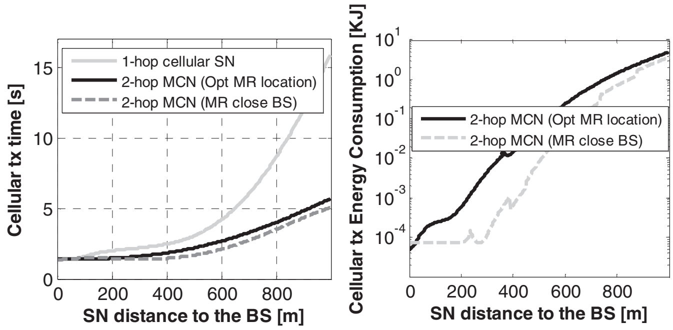

Fig. 5. *Cellular tx*: time the MR requires to transmit the data to the BS (left) and energy consumption (right).

Fig. 4-left shows the time that the MR needs to store and carry the information towards the BS, from the location identified in Fig. 3-left, in order to minimize the total energy consumption. Fig. 3-left showed that if the distance between SN and BS is 400m, the optimum MR that minimizes the total energy consumption is located 77m away from SN. Fig. 4-left shows that this optimum MR needs then to store and carry the information for 36s before transmitting it to the BS using its cellular interface. The obtained results indicate that when the SN is close to the BS, the optimum MR does not need to store and carry the information. The optimum MR should instead forward it to the BS as soon as received from the SN. This is the case because the store and carry energy consumption levels do not compensate the energy savings resulting from forwarding the information at distances closer to the BS. The results depicted in Fig. 4-right show that when the MS is close to the BS, the *Store and Carry* energy consumption level is minimum[3]. As the distance from SN to the BS increases, the optimum MR should store and carry the information so that its cellular transmission starts closer to the BS where higher cellular data rates are possible. However, Fig. 4-left shows that for high distances between SN and BS, the time the MR stores and carries the information to minimize the total energy consumption decreases. On the other hand, the *Store and Carry* energy consumption levels increase with the distance between SN and BS ('2-hop MCN (Opt MR location)' in Fig. 4-right). These two effects are due to the increase in the time needed to complete the P2P (Fig. 3-left) and cellular transmissions ('2-hop MCN (Opt MR location)' in Fig. 5-left). Fig. 5-left shows the time the optimum MR needs to transmit the information to the BS using its cellular radio interface, while Fig. 5-right reports the resulting cellular transmission energy consumption levels.

The optimum configurations[4] illustrated in Figures 3, 4 and 5, result in the total energy consumption levels shown in Fig. 6 ('2-hop MCN (Opt MR location)' in Fig. 6). Fig. 6 also shows the total energy consumption level if the SN directly transmits the information to the BS through traditional single-hop cellular communications ('1-hop cellular SN' in Fig. 6). The obtained results show that when SN is very close to the BS, there are no energy benefits from using opportunistic MCN-MR communications compared to traditional single-hop cellular communications. However, as the distance increases, opportunistic MCN-MR communications can result in significant energy benefits compared to traditional single-hop cellular communications. For example, when the distance between SN and BS is 200m, opportunistic MCN-MR can reduce the energy consumption level by 79.96% compared to traditional single-hop cellular communications. This value increases to 86.08% at the cell edge. On average, an optimum configuration of MCN-MR schemes using opportunistic store, carry and forward can reduce energy consumption levels by over 85% compared to traditional single-hop cellular communications (Table II).

For comparative purposes, this study has also evaluated the energy consumption of other schemes reported in the literature. For example, the results shown in Fig. 6 also consider the scenario in which the SN is mobile, and can store, carry and forward the information to the BS without using a mobile relay ('1-hop Direct-contact' in Fig. 6); this scheme is usually referred to as *Direct-contact* in the literature [8]. In this case, and for a fair comparison, the objective function defines the optimum location at which the moving SN should start forwarding the information to the BS to minimize the energy consumption. Despite reducing the energy consumption with respect to traditional single-hop cellular communications (on average by 41.54%), the sole adoption of store, carry and forward schemes does not reach the energy savings that can be obtained when combining MCN-MR communications with opportunistic store, carry and forward ('2-hop MCN (Opt MR location)' in Fig. 6). The benefits that can be achieved when combining MCN-MR and opportunistic store, carry and forward schemes, depend on an adequate selection of the MR location and the location at which the MR should start forwarding the information to the BS. To demonstrate such dependency, Fig. 6 also reports the total energy consumption levels with a scheme in which the SN selects the MR that provides the higher progress towards the BS [20] ('2-hop MCN (MR close BS)' in Fig. 6). For a fair comparison, a similar optimization process to that reported in section III is conducted for this scheme, but considering the new location of the MR (the closest to the BS). This configuration results in that the MR is able to minimize the time needed to upload the information to the BS (Fig. 5-left), and therefore the cellular transmission energy consumption (Fig. 5-right). However, this is obtained at the expense of a significant increase in the total

[3] Even if the MR does not need to store and carry the information when SN is close to the BS, the *Store and Carry* energy consumption levels are not null since they include the storage power consumption at SN and MR while transmitting and receiving the information (P_W and P_R).

[4] MR location, time the MR should store and carry the information, and location at which the MR should start forwarding the information to the BS.

energy consumption levels compared to an optimum configuration of opportunistic MCN-MR communications (Fig. 6). Fig. 6 also shows 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 P2P ad-hoc transmission between SN and MR (Fig. 3-right), and the *Store and Carry* process (Fig. 4-right). Finally, the results reported in Table II show that an optimum configuration of opportunistic MCN-MR communications can reduce on average the energy consumption by up to 97% compared to selecting the MR that provides a higher progress towards BS.

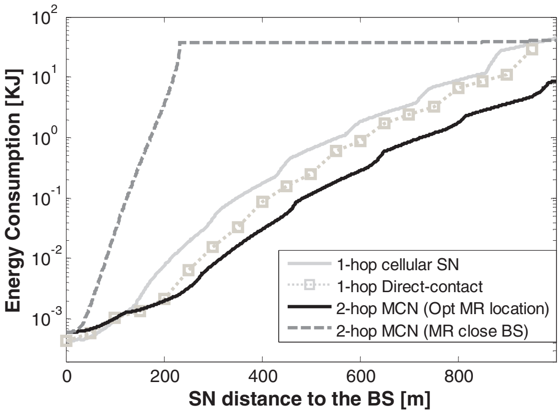

Fig. 6. Total energy consumption.

TABLE II. AVERAGE REDUCTION IN TOTAL ENERGY CONSUMPTION THAT CAN BE ACHIEVED WITH AN OPTIMUM CONFIGURATION OF OPPORTUNISTIC MCN-MR COMMUNICATIONS COMPARED TO OTHER SCHEMES

Opportunistic Schemes	Energy Saving [%]
1-hop cellular SN	85.04
1-hop Direct-contact	74.40
2-hop MCN (MR close BS)	96.51

VI. CONCLUSIONS

This study has investigated the potential of opportunistic store, carry and forward techniques in MCN-MR networks to improve the energy efficiency in the transmission of 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. The obtained results show that significant energy gains can be achieved (on average 85%) compared to traditional single-hop cellular transmissions. The conducted study has focused on deriving optimum configurations that can be used as performance bounds. This is the case because it might happen that a MR cannot be found when needed at the optimum location here identified. The significant achieved gains allows the possibility for sub-optimal heuristics techniques to be used since they will still provide gains in terms of energy consumption. Hence, the optimum locations should then be considered as reference points from where to look for other neighboring MRs. In this context, the presented study can be used as a benchmark (upper bounds in terms of energy gains) for the design of opportunistic forwarding schemes in emerging and future MCN-MR systems. The authors are currently working on the design of practical opportunistic MCN-MR implementations.

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REFERENCES

[1] L. Long and E. Hossain, "Multihop Cellular Networks: Potential Gains, Research Challenges, and a Resource Allocation Framework", *IEEE Communications Magazine, vol.45, no.9, pp.66-73*, Sept. 2007.

[2] J. Gozalvez and B. Coll-Perales, “Experimental Evaluation of Multi-Hop Cellular Networks using Mobile Relays”, *IEEE Communications Magazine*, *vol. 51, no.7, pp. 122-129,* Jul. 2013.

[3] L. Pelusi, A. Passarella and M. Conti, "Opportunistic networking: data forwarding in disconnected mobile ad hoc networks", *IEEE Communications Magazine, vol.44, pp.134-141*, Nov. 2006.

[4] Cisco Visual Networking Index. Globla Media Data Traffic Forecast Update, 2012-2017, *Cisco Whitepaper*, Feb. 2013.

[5] 3GPP TR 22.803. Technical Specification Group Services and System Aspects; Feasibility study for Proximity Services (ProSe). Mar. 2013.

[6] T.S. Rappaport, S. Shu, R. Mayzus, Z. H. Zhao, Y. Azar, K. Wang, G.N. Wong, J.K. Schulz, M. Samimi and F. Gutierrez, “Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!”, *IEEE Access, vol. 1, pp. 335-349*, Dec. 2013.

[7] A. Radwan and H.S. Hassanein, "Does Multi-hop Communication Extend the Battery Life of Mobile Terminals?" *Proceedings of the IEEE GLOBECOM '06, pp. 1-5*, San Francisco, USA, Nov. 2006.

[8] S. Kapadia, B. Krishnamachari and L. Zhang. “Data Delivery in Delay Tolerant Networks: A Survey” in *Mobile Ad-Hoc Networks: Protocol Design* , Prof. Xin Wang, Ed. China: InTech, 2011, pp. 565-578.

[9] P. Kolios, V. Friderikos and K. Papadaki, "Future Wireless Mobile Networks", *IEEE Vehicular Technology Magazine, vol.6, no.1, pp.24-30*, Mar. 2011.

[10] P. Kolios, V. Friderikos and K. Papadaki, "Ultra Low Energy Store-Carry and Forward Relaying within the Cell", *Proceedings of the IEEE VTC 2009-Fall*, pp.1-5, Alaska, USA, Sept. 2009.

[11] P. Kolios, V. Friderikos and K. Papadaki, "Inter-Cell Interference Reduction via Store Carry and Forward Relaying", *Proceedings of the IEEE VTC 2010-Fall*, pp.1-5, Ottawa, Canada, Sept. 2010.

[12] P. Kolios, V. Friderikos and K. Papadaki, "Switching off low utilization base stations via store carry and forward relaying", *Proceedings of the IEEE PIMRC Workshops*, pp. 312-316, Istanbul, Turkey, Sept. 2010.

[13] WINNER consortium, “D1.1.2 V.1.1. WINNER II channel models”, *WINNER European Research project Public Deliverable*, Nov. 2007.

[14] B. Zhao and V. Friderikos, "Optimal stopping for energy efficiency with delay constraints in Cognitive Radio networks", *Proceedings of the IEEEPIMRC, pp.820-825*, Sydney, AUS., Sept. 2012.

[15] R. Schoenen and B.H. Walke, "On PHY and MAC Performance of 3G-LTE in a Multi-Hop Cellular Environment", *Proceedings of the IEEE WiCom, pp.926-929*, Shangai, China, Sept. 2007.

[16] A. Duda, "Understanding the Performance of 802.11 Networks", *Proceedings of the IEEE PIMRC, pp. 1-6*, Cannes, France, Sept. 2008.

[17] B. Coll-Perales, J. Gozalvez and J. Sanchez-Soriano, “Empirical Performance Models for Peer-to-Peer and Two hops Multi-hop Cellular Networks with Mobile Relays”, *ACM PM2HW2N 2013*, in press.

[18] M. Greenberg, “How Much Power Will a Low-Power SDRAM Save you?”, White Paper Denali Software, 2009.

[19] A. Carroll and G. Heiser, “An analysis of power consumption in a smartphone”, *Proceedings USENIX, pp. 21-25*, Boston, USA, Jun 2010.

[20] B. Karp and H. Kung, “Greedy Perimeter Stateless Routing for Wireless Networks”, *Proceedings of the ACM/IEEE International Conference on MobiCom, pp. 243-254,* Boston, USA, Aug., 2000.