Energy Efficiency in Multi-hop Cellular Networks with Mobile Relays

Baldomero Coll-Perales(1), Javier Gozalvez(1), Vasilis Friderikos(2)
bcoll@umh.es, j.gozalvez@umh.es, vasilis.friderikos@kcl.ac.uk
(1) Laboratorio UWICORE, Universidad Miguel Hernández de Elche. Avda. de la Universidad s/n, 03202, Elche (España).
(2) Centre for Telecommunications Research, King's College London, Strand Campus. WC2R 2LS, London (UK).

***Abstract*- The increasing data demand and expected capacity constraints of cellular systems is fostering research on novel communication and networking mechanisms. Multi-hop Cellular Networks using Mobile Relays (MCN-MR) have emerged as a promising technology to tackle these problems through the integration of cellular and ad-hoc networks using Device to Device (D2D) communications. This work considers the use of opportunistic store-carry and forward techniques in MCN-MR networks to increase energy efficiency for delay tolerant traffic. Focusing on a two-hop MCN-MR scenario, the paper 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 derived framework can be used as a benchmark for the development of opportunistic forwarding schemes in MCN-MR systems exploiting D2D communications.**

I. INTRODUCTION

The growth in cellular data traffic represents a significant challenge for network operators. To address it, new radio access technologies and advanced techniques have been developed to increase the spectral efficiency. Despite the significant improvements achieved, infrastructure-centric cellular networks might not be able to handle the foreseen data traffic demand. In this context, the integration of relaying and distributed networking techniques within cellular systems (referred to as Multi-hop Cellular Networks, MCN) has attracted significant research attention due to its potential benefits in terms of capacity, energy-efficiency, and traffic offloading [1]. The use of mobile relays in MCN networks (MCN with Mobile Relays, MCN-MR) can offer novel communications and networking possibilities through an opportunistic and collaborative use of the resources of deployed mobile devices. Mobile relaying can also contribute towards the energy-efficiency of future mobile communication systems through the integration of opportunistic communications and networking schemes. 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 [2].

The benefits of the integration of MCN and opportunistic networks are discussed in [3], where the authors present novel routing policies that make use of mobility information from the relays to reduce energy consumption, increase spatial capacity, reduce co-channel interference, balance the load across cells, and switch-off low-utilization base stations. The authors demonstrate that the higher is the time available to transmit the information towards the destination node, the greater the energy-efficiency benefits of integrating cellular and opportunistic communications. The authors extend their prior study to cognitive cellular networks [4], and highlight the importance of considering the power consumption of storage units in mobile relays for the study of opportunistic networks. In this context, this paper studies the integration of opportunistic store-carry and forward techniques in MCN-MR networks to reduce the energy consumption of 2-hop uplink MCN-MR links. In particular, the paper 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.

II. OPPORTUNISTIC FORWARDING IN MCN-MR NETWORKS

A key aspect in the integration of opportunistic store-carry and forward mechanisms in cellular networks is how to manage the available time to achieve the desired outcome; in the case of this study, reduce the energy consumption. 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 (Fig. 1). 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 (D2D 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 MR location at which the D2D transmission starts, and the MR location at which the cellular transmission starts. In this context, this paper focuses on estimating these two locations with the final objective to reduce the total energy consumption.

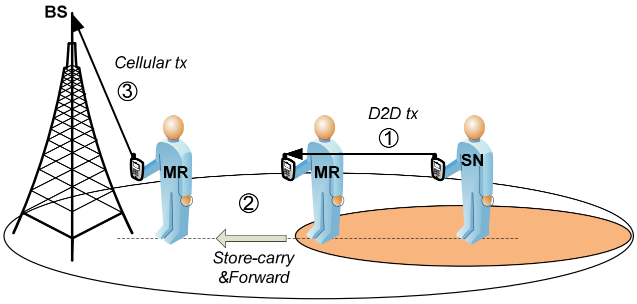

Fig. 1. 2-hop opportunistic MCN-MR scenario.

A. Problem formulation

A multi-objective constrained optimization problem is considered to minimize the total energy consumption. The objective function shown in (1) has been defined together with two constraints and the requirement that the BS receives the information before a deadline *T*. This deadline is discretized in (1) as $\{\tau_0, \tau_1, ..., \tau_T\}$. The objective function is established considering the energy consumed by the D2D tx ①, the Store-carry & Forward process ② and the Cellular tx ③. $E_{ad\text{-}hoc}$ is the energy consumed in the D2D transmission, and is a function of the distance between SN and MR and the time needed for the D2D transmission. P_R, P_W and P_{IDLE} refer to power consumed in the process to store and carry information on mobile devices. These three variables are defined in the following section. E_{cell} represents the energy consumed in the cellular transmission, and is a function of the distance between MR and BS and the time needed for the cellular transmission. The objective function includes two constraints for the message (of size F) to be completely transmitted in the D2D (2) and cellular (3) transmissions. $R_{ad\text{-}hoc}$ and R_{cell} represent the ad-hoc and cellular transmission rates respectively. 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 cellular network in order to minimize the overall energy consumption, is equivalent to finding τ_{b-1}, τ_{c-1} and τ_{c+m} in (1).

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

$$st:$$

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

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

1) D2D tx. The pathloss between the SN and MR nodes is modeled using the deterministic two-ray ground model. In this context, the energy consumed in the ad-hoc transmissions can be expressed as [3]:

$$E_{adhoc}\left(d\right)=\begin{cases}(e_r+e_t+e_{LOS}\cdot d^2)\cdot R_{adhoc} & if\ d<d_{brake}\\ (e_r+e_t+e_{MP}\cdot d^4)\cdot R_{adhoc} & if\ d\geq d_{brake}\end{cases} \tag{4}$$

where e_t and e_r represent the energy consumption per bit in the transmitter and receiver electronics respectively, and R_{adhoc} is the ad-hoc transmission data rate. The distance between the transmitter and receiver is *d*, and $d_{brake} = 4\pi h_T h_R/\lambda$ 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 $d \geq d_{brake}$. This energy model considers that the transmission power (P_{LOS} and P_{MP}) is the necessary one to guarantee that the receiver's signal level is equal to the power threshold required for a successful communication between the two nodes (P_r). P_{LOS} and P_{MP} can then be expressed as [3]:

$$P_{LOS}=\frac{P_r\left(4\pi\right)^2}{\lambda^2}\ ;\quad P_{MP}=\frac{P_r}{h_t^{\,2}h_r^{\,2}} \tag{5}$$

and e_{LOS} and e_{MP} are equal to P_{LOS}/R_{adhoc} and P_{MP}/R_{adhoc}, respectively.

In this paper, we consider that the ad-hoc SN-MR communications is done using IEEE 802.11g at 2.4GHz (the study could be reproduced for other radio access technologies). The IEEE 802.11g transmission rate has been modeled as [5]:

$$R_{adhoc}\left(d\right)=DataRate(d)\cdot Eff\cdot\left(1-PER\left(d\right)\right) \tag{6}$$

where *DataRate* represents the ad-hoc IEEE 802.11g transmission mode:

$$DataRate\left(d\right)=\begin{cases}54 & d<78.47m\\ \dfrac{54}{\dfrac{1}{78.47}-\dfrac{1}{270.85}}\cdot\left(\dfrac{1}{d}-\dfrac{1}{270.85}\right) & 78.47m\leq d<270.85m\\ 0 & 270.85\leq d\end{cases} \tag{7}$$

PER is the experienced IEEE 802.11g *Packet Error Ratio*[1]:

$$PER\left(d\right)=\frac{0.75}{1+e^{-0.019\cdot\left(d-115.15\right)}} \tag{8}$$

and *Eff* is the IEEE 802.11g channel efficiency that 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*) [5]:

$$Eff=\frac{t_d}{DIFS+t_{cont}+t_d+SIFS+t_{ack}} \tag{9}$$

2) Store-Carry & Forward. As suggested in [4], this work considers 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 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[2]. In this context, 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] The IEEE 802.11g ad-hoc DataRate and PER models have been derived by the authors following an extensive field test campaign.

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

3) Cellular tx. The cellular pathloss has also been modeled using the two-ray ground model. The communications energy consumption between the MR and BS is modeled using (4), but replacing $R_{ad\text{-}hoc}$ by R_{cell}. Also, the antenna heights and wavelength should be updated in (4). This study considers HSPA at 2.1GHz for the cellular transmission between MR and BS (the study could be reproduced for other radio access technologies). The cellular data rate has been modeled assuming that the cellular system adapts its operation to the reported radio channel conditions using Adaptive Modulation and Coding (AMC) and Automatic Repeat Request (ARQ) schemes. Without loss of generality, the cellular transmission data rate can be modeled considering concentric rings [6]:

$$R_{cell}(d) = k \cdot C \cdot log_2(M(d)) \cdot BW \qquad (10)$$

where BW, M and C represent the system bandwidth, the modulation constellation size and the 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 measured at the mobile device, and the lower the modulation/coding scheme). k represents an attenuation factor that limits the cellular data rate, and includes, among others, the effect of transmission failures, retransmissions, and interference [6].

III. NUMERICAL INVESTIGATIONS

The numerical resolution of objective function (1) is done considering the parameters reported in Table I. The study considers a cell with a radius of 800m. The cell is divided into seven equally spaced and concentric rings defined by the AMC schemes shown in Table 1. The cellular data rate is considered to decrease with increasing distances between MR and BS. The first ring (closer to BS) considers a maximum uplink HSUPA cellular data rate of 7Mbps. The energy consumption values for the DRAM and NAND flash storage units have been obtained from [7] and [4] respectively, and the values of e_t, e_r and P_r from [3]. The message that the static SN needs to upload to the BS has a nominal size of 50Mb, and the time available to complete the transmission has been set to 60s. The scenario considers the MR is in line with the SN, and moving towards the BS with a speed of 1m/s.

Table 1. Scenario parameters

Parameter	Value	Parameter	Value
F	50Mb	T	60s
R	800m	v	1m/s
h_{SN}, h_{MR}, h_{BS}	1.5m, 1.5m, 5m	*Max UL Thr*	7Mbps
e_t, e_r	50 x 10^{-9}J/b	P_r	-52dBm
DRAM P_R, P_W, $P_{Idle\_self\text{-}refresh}$	252mW, 252mW, 1.35mW	*AMC*	BPSK (r=1/3) QPSK (r=1/3, 1/2, 2/3) 16QAM (r=1/2, 2/3, 5/6)
NAND Eff_{Read}, Eff_{Write}, P_{Idle}	1.83nJ/b, 11.92nJ/b,	*Transf_DF*, *Transf_EF*	4.85 MiB/s, 927.1 KiB/s

Fig. 2 shows the optimum mobile relay location as a function of the distance of the SN to the BS. The location is represented by means of the distance between the SN and MR. For example, when the SN is located 400m away from the BS, the defined objective function determines that in order to minimize the energy consumption the MR should be ideally located 125m away from the SN in the direction of the BS. Fig. 2 shows that the distance from the SN to 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 the SN and MR increases, the MR is closer to the BS, and the energy being consumed as part of the cellular transmission decreases. On the other hand, the energy consumed in the D2D transmission increases as the MR is closer to the BS. In this context, the distance between SN and the optimum MR only increases when the energy saving of the *Store-carry & Forward* process compensates the increase in the D2D energy consumption. The peaks shown in Fig. 2 correspond to the case when the MR moves towards the BS and approaches a ring with higher cellular data rate; the use of higher data rates reduces the energy consumption.

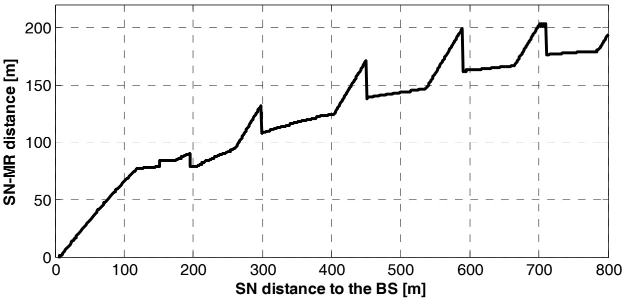

Fig. 2. *D2D tx*: optimum mobile relay location.

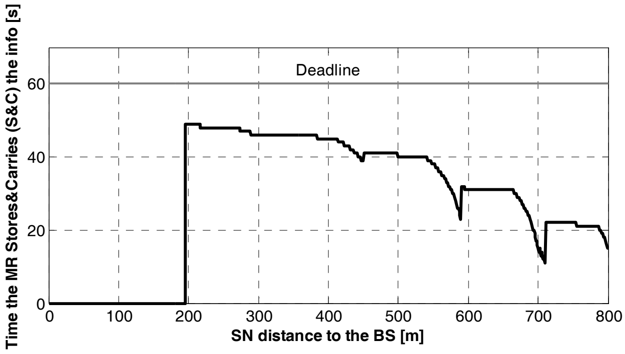

Fig. 3. *Store-carry & Forward*: time the MR stores and carries the information while moving towards the BS.

Fig. 3 shows the time that the MR needs to store and carry the information towards the BS from the location identified in Fig. 2. Considering the previous example, the optimum MR located 125m away from the SN (the distance between the SN and BS is 400m) needs to store and carry the information for 45s before forwarding it to the BS. The obtained results indicate that when the SN is close to the BS (in the cellular ring with highest cellular data rate), the selected/optimum MR does not need to store and carry the information. It should instead forward it to the BS as soon as received from the SN. This is because the energy consumed at these locations by the storage and carrying processes does not compensate the energy savings resulting from transmitting closer to the BS. As the distance from the SN to the BS increases, the optimum MR should store and carry the information so that it launches the cellular communication with the BS at a ring with a higher cellular data rate than the one where the MR was initially located. The results depicted in Fig. 3 show that as the SN is further away from the BS, the time the MR is allowed to store and carry the information decreases since the time needed to complete the D2D (Fig. 2) and cellular transmissions increase (Fig. 4). Fig. 4 shows the time the selected/optimum MR needs to transmit the information to the BS using the cellular radio interface ('2-hop MCN (Opt MR location)').

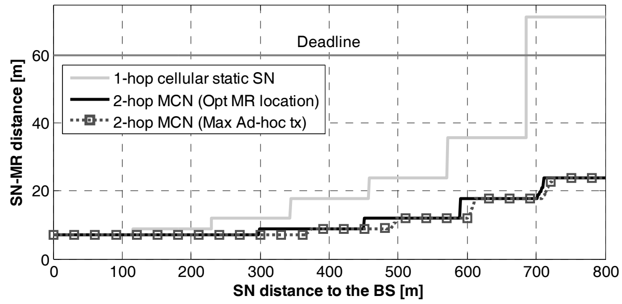

Fig. 4. *Cellular tx*: time the MR requires to tx the information to the BS.

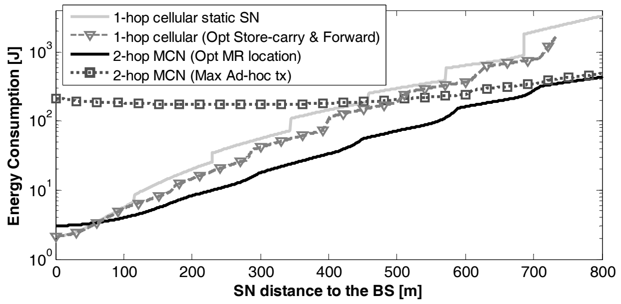

Fig. 5. Total energy consumption.

The optimum configurations[3] illustrated in Figures 2, 3 and 4 result in the total energy consumption levels shown in Fig. 5 ('2-hop MCN (Opt MR location)'). Fig. 5 also shows the energy consumption levels measured at the static SN if the SN would directly communicate with the BS through the cellular radio interface ('1-hop cellular static SN')[4]. The obtained results demonstrate that the optimum configuration derived for the 2-hop opportunistic MCN-MR results in significant energy benefits compared to direct cellular transmissions from SN to BS. The energy savings increases with the distance between SN and BS: from 60% at 200m distance to 85% at the cell edge[5]. Fig. 5 also shows that when SN is close to the BS it is not energy efficient to transmit through a 2-hop opportunistic MCN-MR link. The results shown in Fig. 5 also consider the scenario in which the SN is mobile and can store, carry and forward the information to the BS without using a MR ('1-hop cellular (Opt Store-carry & Forward)'). In this case, the objective function defines the optimum location at which the moving SN should start forwarding the information to the BS. The energy benefits of the store-carry and forward process in the 1-hop cellular communication are demonstrated in Fig. 5 if compared to the '1-hop cellular static SN' (on average 27% energy reduction)[6]. However, these benefits are outperformed by the 2-hop opportunistic MCN-MR communications, except for very short distances between the SN and BS. The obtained results clearly demonstrate the potential of 2-hop opportunistic MCN-MR communications to reduce energy consumption for delay tolerant services. However, this potential strongly depends on the correct selection of the optimum MR location and optimum location at which the MR should start forwarding the information to the BS. To demonstrate such dependency, this study has also evaluated the energy consumed in the case of a 2-hop opportunistic MCN-MR communications where the MR is selected as closer as possible to the BS ('2-hop MCN (Max Ad-hoc tx)'). This configuration results in that the MR is able to minimize the time needed to upload the information to the BS (Fig. 4), but at the expense of a significant increase in the total energy consumption levels shown in Fig. 5.

IV. CONCLUSIONS

This study 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. The obtained results show that significant energy gains can be achieved (up to 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 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 for the design of opportunistic forwarding schemes in MCN-MR systems.

ACKNOWLEDGEMENTS

This work is supported in part by the Spanish Ministry of Economy and Competitiveness and FEDER funds (TEC2011-26109), and the Local Government of Valencia with reference ACIF/2010/161 and BEFPI/2012/065.

REFERENCIAS

[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] 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*, November 2006.

[3] P. Kolios, V. Friderikos and K. Papadaki, "Future Wireless Mobile Networks", *IEEE Vehicular Technology Magazine, vol.6, no.1, pp.24-30*, Mar. 2011. doi: 10.1109/MVT.2010.939905.

[4] B. Zhao and V. Friderikos, "Optimal stopping for energy efficiency with delay constraints in Cognitive Radio networks", *Proceedings of the IEEE International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC), pp.820-825*, Sydney, Australia, 9-12 Sept. 2012.

[5] A. Duda, "Understanding the Performance of 802.11 Networks", *Proceedings of the IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), pp. 1-6*, Cannes, France, 15-18 Sept. 2008.

[6] R. Schoenen and B.H. Walke, "On PHY and MAC Performance of 3G-LTE in a Multi-Hop Cellular Environment", *Proceedings of the IEEE International Conference on Wireless Communications, Networking and Mobile Computing (WiCom), pp.926-929*, Shangai, China, 21-25 Sept. 2007.

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

---

[3] MR mobile location and location at which the MR should start forwarding the information to the BS.

[4] Note that the static SN located at the cell edge is not able to transmit the information to the BS before the deadline (Fig. 4).

[5] From d_{brake} distance (660m for the scenario parameters) to the cell edge the energy benefits increase because of the higher energy consumption at the direct cellular link.

[6] The area where the mobile SN is not able to transmit the information to the BS before the deadline has not been depicted (shorter than for the static SN).