Mode Selection for Mobile Opportunistic Multi-hop Cellular Networks

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***Abstract* — Multi-hop Cellular Networks using Mobile Relays (MCN-MRs) are being investigated to help address certain limitations of traditional single-hop cellular communications. The MCN-MR benefits depend on the probability to find adequate mobile relays, and on the design of mode selection schemes capable to identify the optimum connection mode. The probability to find adequate mobile relays can be significantly enhanced for delay tolerant services through the adoption of mobile opportunistic networking that exploits the store, carry and forward paradigm. In this context, this paper proposes and evaluates the first mode selection scheme that integrates opportunistic networking into MCN-MR. The obtained results demonstrate that the proposed scheme helps achieve the expected QoS and energy benefits that opportunistic networking can bring to multi-hop cellular networks.**

Keywords— Mobile opportunistic, mobile relays, multi-hop cellular networks, mode selection, energy efficiency.

I. INTRODUCTION

Single-hop cellular networks require a direct link between Base Stations (BSs) and end users. The quality of such links varies as a result of the effect of distance and attenuation caused by surrounding obstacles which difficult guaranteeing homogeneous Quality of Service (QoS) levels across a cell. This limitation can be partly overcome through the integration of relaying techniques in cellular systems, referred to as Multi-hop Cellular Networks (MCNs). MCN systems can substitute long-distance, and generally Non-Line of Sight (NLOS), cellular links with various multi-hop transmissions with improved link budgets. MCN networks offer significant benefits in terms of capacity, energy-efficiency and traffic offloading among others [1]. Although MCN will initially use fixed relays, recent experimental studies have also demonstrated significant benefits from the use of mobile relays (MCN with Mobile Relays, MCN-MR) [2]. However, such benefits can only be achieved when a Multi-Hop connection (MH mode) between source and destination guarantees improved link budgets compared to a direct Single Hop cellular one (SH mode). As result, mode selection schemes capable to indentify the optimum connection mode are critical to realize the expected MCN-MR benefits [3].

The performance of MH transmissions is conditioned by whether Relay Nodes (RNs) offering improved link budgets compared to SH can be found [4]. Real-time services would only benefit from MH transmissions if such RNs can be found at the time the service is requested. However, delay-tolerant services can benefit from opportunistic networking principles, and establish MH connections when their quality exceeds that of SH. In fact, opportunistic schemes can exploit the mobility of nodes and the store, carry and forward paradigm to establish communication links between RNs based on contact opportunities and improved link quality budgets [5]. Opportunistic networking can introduce an end-to-end transmission delay not acceptable for real-time services. However, some of the services and applications that are mainly driven the growth of cellular data traffic (according to the latest Cisco's global mobile data traffic forecast [6]) can be deemed as delay tolerant services, e.g. updates to social networking, emails, firmware and software updates, or cloud services. Such delay tolerance can then be exploited by opportunistic schemes to search for RNs that improve the QoS and/or energy efficiency of MH connections in MCN-MR. The integration of opportunistic networking into MCN-MR requires the design of novel mode selection schemes that consider the possibility to find adequate RNs for MH connections within the time deadline established by the requested service. In this context, this paper proposes and evaluates the first mode selection scheme that integrates opportunistic networking into MCN-MR. The proposed scheme is based on a mode selection scheme previously defined by authors [7] for a MCN-MR system where only real-time MH connections were allowed (i.e., no opportunistic transmissions). The new mobile opportunistic scenario incorporates new time restrictions and potential benefits and risks that must be evaluated. The obtained results demonstrate that the proposed scheme helps achieve the expected QoS and energy consumption benefits that opportunistic networking can bring to multi-hop cellular networks.

II. MODE SELECTION PROPOSAL

The study reported in [8] indicates that most MCN-MR benefits can be obtained with just 2 hops between source and destination. This study focuses then on the 2 hop scenario illustrated in Fig. 1. In this scenario, a BS has to decide for downlink transmissions whether to establish a direct SH link

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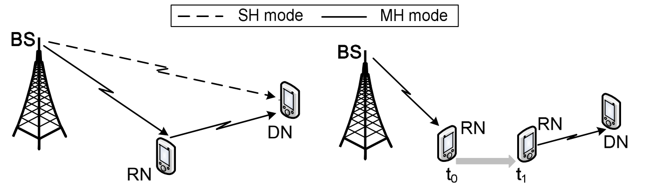
with the destination node (DN) or a MH connection using RN as a relay node. MH connections can be real-time (Fig. 1.a) or opportunistic (Fig. 1.b). Real-time MH connections refer to the scenarios where the RN is selected at the time the service is requested, and the MH transmission starts as soon as RN is selected. On the other hand, opportunistic MH connections can delay the transmission from RN to DN until link quality conditions improving the MH performance and energy efficiency can be found. The study considers that there is a maximum end-to-end transmission time by which the information needs to be received at the DN. Such time needs to take into account the cellular and ad-hoc transmissions, as well as the store and carry process in the case of opportunistic MH connections.



a) SH and real-time MH connections b) Opportunistic MH connection

Fig. 1. SH and MH modes in 2 hop MCN-MR scenarios.

A. Mode selection criterion

This paper integrates opportunistic networking into the BRISK (mode selection scheme based on Benefits and RISKs) scheme proposed by the authors in [7]. BRISK was designed to select the connection mode that provides the higher expected performance (SH or real-time MH). The expected performance is evaluated considering the potential risks and benefits of each connection mode. This is done so that the mode selection scheme does not only consider the potential performance levels that can be obtained by a given connection mode, but also the possible risks that could prevent operating under the conditions necessary to achieve such performance levels.

The benefit that can be obtained with each possible connection mode is represented by the performance (e.g. throughput) that such mode could achieve if the connection is established under the adequate conditions (e.g. if MH can find an RN improving the performance at DN). The benefit is here denoted by $Benefit_m$, with m representing the connection mode (SH or MH). The risk taken when selecting a given connection mode comes from the probability that the transmission cannot be conducted under the conditions required to achieve the expected benefit (e.g. if MH cannot find an RN improving the performance at DN). The risks resulting from trying to establish an m connection is denoted by $Risk_m$. The performance P_m^i that a node DN i could expect from the use of mode m can then be expressed as:

$$P_m^i = Benefit_m^i \cdot (1 - Risk_m^i) \quad (1)$$

For each transmission between BS and a DN i, BRISK selects the connection mode m_i^* that provides a better compromise between benefits and risks, and therefore the higher expected performance:

$$m_i^* = \arg \max_{m \in \{\mathrm{SH},\mathrm{MH}\}} P_m^i \quad (2)$$

The original BRISK scheme only considered SH and real-time MH connection modes. On the other hand, this study evolves BRISK to consider SH, real-time and opportunistic MH connection modes. This requires redefining the MH benefits and risks to account for opportunistic MH connections. In this paper, we refer to 'Opportunistic scenario (*Opp*)' when applying the new BRISK scheme that enables opportunistic MH connections. On the other hand, we refer to 'Non opportunistic scenario (*No-Opp*)' when applying the original BRISK scheme that does not enable the establishment of opportunistic MH connections.

B. Benefits and risks in mobile opportunistic scenarios

This study considers a cellular system (e.g. HSDPA or LTE) with QoS rings (Fig. 2) characterized by varying cellular link quality levels and optimal transmission modes (modulation and coding scheme). A QoS ring R can be defined as the coverage area of a BS where a given transmission mode is optimum. R_i represents the QoS ring where node i is located. Rings closer to the BS are generally characterized by better link quality levels, and therefore the use of transmission modes with higher data rates. $R' \succ R$ indicates that a node located at R' has higher data rates than a node located at R. It is reasonable to assume that all users within the same QoS ring R experience on average the same performance when assigned an equal number of radio resources s, which is represented as $p(s,R)$. The performance that a user will experience needs to reflect the user satisfaction level. This is a challenging task since user satisfaction is a subjective concept that heavily depends on user perceptions. In this study, $p(s,R)$ is represented as a function of the cellular throughput experienced at the RN (MH mode) or DN (SH mode). This throughput depends on the RN or DN location (and therefore R) and the number of assigned cellular radio resources s. In particular, this study assumes that $p(s,R)$ is equal to zero for throughput values below a minimum threshold th_{min}, and then grows linearly with the cellular throughput until a maximum level from which it asymptotically tends to 1. Other criterion could have been considered to establish the $p(s,R)$ function. However, the impact of a different criterion would be limited for this study that is aimed at comparing mode selections, and not at establishing absolute performance values.

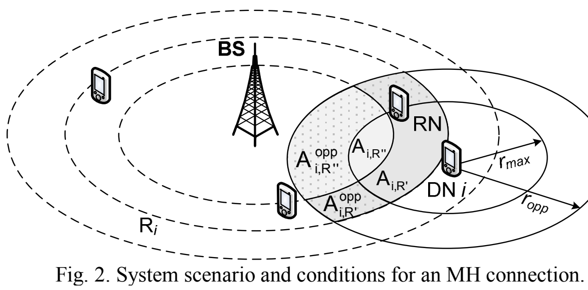


Fig. 2. System scenario and conditions for an MH connection.

1) SH benefits and risks

The benefit of using a SH link for a communication between BS and DN i depends on the QoS ring R_i where DN i is located and the number of assigned cellular radio resources. The ring R_i where DN i is located is determined by the distance d_i between DN i and its serving BS. The SH benefit can then be expressed as a function of d_i and the number of cellular radio resources s_i assigned to DN i:

$$Benefit^i_{SH}(s_i, d_i) \equiv p(s_i, d_i) \quad (3)$$

The BS can establish a direct SH link with a user located in its coverage area as long as cellular radio resources are available. The risk that cellular radio resources are unavailable is present for all connection modes. As a result, such risk can be omitted in the estimation of the risk factor for each mode. The risk resulting from selecting the SH mode for a transmission between BS and DN i is then $Risk^i_{SH}(d_i) = 0$, and the expected SH performance can be expressed as follows:

$$P^i_{SH}(s_i, d_i) = Benefit^{\,i}_{SH}(s_i, d_i) \equiv p(s_i, R_i) \quad (4)$$

2) MH benefits

MH can improve the performance at DN i over SH if two conditions are met. The first condition is that the BS can find a RN located in a cellular ring R with higher data rates than R_i ($R \succ R_i$). Real-time MH connections also require that the distance between RN and DN i is shorter than a maximum distance r_{max} that allows transferring the RN performance to DN i [9] (Fig. 2). RN has then to be located within an area A_i defined as the union of the intersection areas $A_{i,R}$ (Fig. 2) between a circle $C(i,r_{max})$ centred in DN i with radius r_{max} and the rings R that satisfy $R \succ R_i$:

$$A_i = \bigcup_{R|R\succ R_i} A_{i,R}\ \text{, with } A_{i,R} = R \cap C(i, r_{\max}) \quad (5)$$

Opportunistic MH connections can also provide better performance than SH if an RN is found within A_i. If such RN cannot be found, opportunistic MH connections can still outperform SH if an RN can be found at a distance from DN i higher than r_{max}, but smaller than a distance r_{opp} that guarantees that a mobile RN moving towards DN reaches A_i before a store and carry deadline $t_{s\&c}$. The store and carry deadline must be such that the end-to-end transmission to DN finishes before the service-dependent deadline $t_{deadline}$:

$$t_{s\&c} = t_{deadline} - t_{adhoc} - t_{cell} \quad (6)$$

where t_{adhoc} represents the time required to complete the ad-hoc transmission between RN and DN, and t_{cell} the time required to complete the cellular transmission between BS and RN. t_{adhoc} is computed following the transmission model reported in [10], and assuming that the ad-hoc transmission starts as soon as RN is at distance r_{max} from DN. t_{cell} is estimated considering that only the radio resources necessary to guarantee the minimum throughput threshold (th_{min}) are assigned to the cellular link. While this approach is conservative, it is independent of the position of RN or DN, and represents a worst case scenario. In this context, the r_{opp} distance can be expressed as:

$$r_{opp} = r_{\max} + t_{s\&c} \cdot v_{mean} \quad (7)$$

where v_{mean} represents the average mobility speed of RN towards DN[1]. An opportunistic MH connection can then also provide better performance than SH if RN is located within an area A^{opp}_i defined as the union of the intersection areas $A^{opp}_{i,R}$ between a circle $C(i,r_{opp})$ centred in DN i with radius r_{opp} and the rings R that satisfy $R \succ R_i$, excluding the A_i area:

$$A^{opp}_i = \bigcup_{R|R\succ R_i} A^{opp}_{i,R} \ \text{ with } A^{opp}_{i,R} = R \cap C(i, r_{opp}) - A_{i,R} \quad (8)$$

The MH benefit (including real-time and opportunistic connections) can then be expressed as:

$$Benefit^i_{MH}(s_i, d_i) = \frac{\sum_{R,R\succ R_i} \sum_{A,A\subset\{A_{i,R},A^{opp}_{i,R}\}} p(s_i,R)\cdot \text{prob}^{\text{RN}}(A)}{\sum_{R,R\succ R_i} \sum_{A,A\subset\{A_{i,R},A^{opp}_{i,R}\}} \text{prob}^{\text{RN}}(A)} \quad (9)$$

where $\text{prob}^{\text{RN}}(\cdot)$ represents the probability to find at least one RN within the related area. It is important highlighting that d_i influences the intersection areas $A_{i,R}$ and $A^{opp}_{i,R}$, and consequently $\text{prob}^{\text{RN}}(A_{i,R})$ and $\text{prob}^{\text{RN}}(A^{opp}_{i,R})$.

3) MH risks

Trying to establish a MH connection has non negligible risks. First, there is the risk that the BS cannot find a RN with higher cellular performance than a SH connection to DN. Second, even if such RN can be found, it is possible that the RN is not located within the adequate area to establish a real-time or opportunistic MH link that outperforms SH. In this study, MH connections first try to establish a real-time MH link. If no RN can be found within A_i, then an opportunistic MH link is sought searching for an RN within A^{opp}_i. The risk $Risk^i_{MH}$ to establish a MH connection comes then from the probability of not being able to find RN within A_i or A^{opp}_i:

$$\begin{aligned} Risk^{\,i}_{MH}(d_i) &= 1 - [\text{prob}^{\text{RN}}(A_i) + \\ &+ \left(1 - \text{prob}^{\text{RN}}(A_i)\right)\cdot \text{prob}^{\text{RN}}(A^{opp}_i)\cdot \text{prob}^{\text{RNtoDN}}] \end{aligned} \quad (10)$$

where $\text{prob}^{\text{RNtoDN}}$ represents the probability that RN moves in the direction towards DN. $Risk^i_{MH}$ is defined as a function of d_i since this distance influences the intersection area A_i and $A^{opp}_{i,R}$, and consequently $\text{prob}^{\text{RN}}(A_i)$ and $\text{prob}^{\text{RN}}(A^{opp}_i)$. The expected performance of a MH connection $P^i_{MH}(s_i, d_i)$ can then be computed using expressions (1), (9) and (10).

C. Interaction between mode selection and RRM

The SH and MH performance is a function of the number of assigned cellular radio resources s_i, and depends then on the RRM (Radio Resource Management) policy and the interaction between the mode selection and RRM schemes. The interaction operates as follows. First of all, the mode selection scheme identifies the optimum connection mode for all possible radio resource assignments. In particular, and following (2), the scheme determines $m^*_i(s)$ for all possible values of $s \in [1,S]$, with S representing the maximum number of available cellular radio resources in the cell. The expected performance for each possible radio resource assignment s can then be expressed as:

$$P^i(s, d_i) = \max\left\{P^i_{SH}(s, d_i), P^i_{MH}(s, d_i)\right\} \quad (11)$$

The RRM scheme analyses then, for all possible radio resource assignments, the $P^i(s,d_i)$ level achieved for the

[1] We assume that such speed can be estimated by the cellular network.

optimum connection mode identified by the mode selection scheme. Following this analysis, the RRM scheme decides the allocation of cellular radio resources for each link between the BS and DNs. The RRM scheme implemented in this study is the MAXIHU technique aimed at providing the highest possible homogeneous performance to all users. Readers are referred to [7] for additional details on the MAXIHU technique and its interaction with the mode selection scheme.

III. Performance Analysis

A. Evaluation Environment

The performance of the proposed mode selection scheme is evaluated using a C++ software simulating a single cell with a 1000m radius. DN users request downloading a 20Mb file. The deadline to finish the download ($t_{deadline}$) is 60s following the indications in [11]. Users are initially distributed across the cell following an homogeneous Poisson distribution with average density ρ. Node densities equal to 7.5, 12.5 and 25 nodes/km (S1, S2 and S3 scenarios) have been evaluated. Nodes move with a constant speed equal to 3 m/s and select their movement direction randomly. This mobility pattern results in a uniform distribution of nodes within the cell. The probability to find at least a RN within an area A is then computed following a Poisson distribution as $\text{prob}^{\text{RN}}(A) = 1 - \exp(-\rho A)$. If a real-time MH connection is to be established and there are several candidate RNs within A_i, the RN closer to the BS is selected. If no RNs are present within A_i, an opportunistic MH connection is established selecting the RN closer to DN and at a shorter distance to the BS than DN.

BRISK can be applied to any cellular technology. In this study, HSDPA (High Speed Downlink Packet Access) has been selected for SH transmissions, and the cellular link between BS and RN in the case of MH connections. In particular, this study considers the HSDPA transmission modes associated to the 30 CQI values defined for category 10 terminals (3GPP TS 25.214). HSDPA data rates are selected based on the distance of users to the BS, and therefore the ring where users are located (rings are related to the CQI). IEEE 802.11g is considered for the ad-hoc link of MH connections using the model reported in [10]. HSDPA and IEEE802.11g were chosen for this study due to the availability of an empirical 2-hops MH throughput model in [9] that is here used to model the MH throughput. Based on the model reported in [9], r_{max} has been set equal to 150m.

The simulation platform also models the energy consumption based on [10]. The energy consumed in ad-hoc and cellular transmissions can be estimated as:

$$E(d) = (p_r + p_t + P_T(d)) \cdot t_{Tx} \qquad (12)$$

where p_t and p_r represent the power consumption in the transmitter and receiver electronics respectively, and t_{Tx} is the transmission time. P_T represents the transmission power, and is computed considering that the transmission power is the necessary one to guarantee that the receiver's signal power level is equal to the threshold required for a successful communication between two nodes. The energy consumed in the store and carry process is also modeled as in [10].

B. Performance results

This section is aimed at demonstrating the effectiveness of the proposed mode selection scheme, and the benefits that can be obtained from exploiting opportunistic networking in MCN-MR. To this aim, the performance achieved when integrating opportunistic networking into BRISK (*Opp* scenario) is compared against that obtained when operating traditional SH cellular communications (SH) and when employing BRISK without enabling opportunistic MH connections (*No-Opp* scenario). When opportunistic MH connections are not allowed, $Benefit_{MH}$ and $Risk_{MH}$ are estimated considering r_{opp} equal to r_{max}. In the *No-Opp* scenario, if BRISK selects the MH mode and no RNs are present within A_i, the real-time MH connection is established with the RN closer to DN and at a shorter distance to the BS than DN. In this case, the MH connection might not provide higher performance than SH. A final implementation could then require changing connection modes. However, such changes are here disabled to focus the study on the impact of the mode selection decisions.

Fig. 3 shows the average energy consumption of each end-to-end connection as a function of the distance between BS and DN. The energy consumed in an opportunistic MH connection is computed taking into account the energy consumed in the BS-RN cellular link, the energy consumed in the store and carry process, and the energy consumed in the RN-DN ad-hoc link. From the obtained results, it is first important to highlight that MCN-MR communications reduce the energy consumption compared to traditional SH cellular communications. The SH and MCN-MR performance is close only when opportunistic MH connections are not allowed and the RNs density is small. When the density increases, MCN-MR communications can significantly reduce the energy consumption compared to SH. For example, the reduction is higher than 40% for distances larger than 500m in the *No-Opp* scenario. The energy savings are further increased in the *Opp* scenario. In this case, opportunistic MCN-MR communications can reduce the energy consumption compared to SH by more than 45% for distances between BS and DN larger than 600m, even with the lower density of RNs (S1). The lower energy consumption measured in the *Opp* scenario is due to the fact that opportunistic networking results in that more BS-DN links are established using MH connections. Such connections result in lower energy consumption levels, in particular for larger distances between BS and DN. In the *Opp* scenario, BRISK selects more frequently the MH mode since the possibility to establish opportunistic MH connections increases the RN search area (A_i+ A_i^{opp}), and therefore reduces the MH risk. This results in that BRISK selects the MH mode for 80 to 100% of the BS-DN connections when the distance between BS and DN

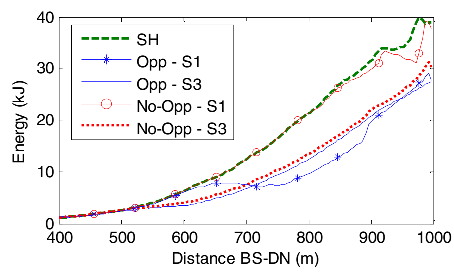


Fig. 3. Average total energy consumption (per BS-DN transmission) as a function of the distance between DN and BS.

is larger than 700m (S1 and *Opp* scenario); 20 to 40% of these transmissions are done using opportunistic MH connections. When the RNs density increases, the difference between the *Opp* and *No-Opp* scenarios decreases. This is due to the fact that as the density of RNs increases, the probability to find an RN within A_i increases, and therefore the need for opportunistic MH connections decreases in the current BRISK configuration.

Opportunistic MCN-MR communications reduces the energy consumption without degrading the QoS. Table I shows the percentage of end-to-end transmissions that ended before the 60s deadline. The depicted results show that MCN-MR communications increase such percentage with respect to SH, with the increment being higher (over 6% for S3) when opportunistic MH connections are allowed (*Opp* scenario). The integration of opportunistic networking into MCN-MR also improves the cellular performance and capacity. Fig. 4 shows the average cellular throughput experienced for all connection modes when enabling (*Opp*) or disabling (*No-Opp*) opportunistic MH connections for the S1 scenario. Fig. 5 shows the reduction in average cellular channel occupancy that can be achieved when enabling opportunistic MH connections (*Opp*) compared to when disabling them (*No-Opp*) for all 3 scenarios. The obtained results clearly show that the integration of opportunistic networking in MCN-MR can improve the cellular performance and capacity when employing BRISK. The cellular performance gains can range from 20% close to the BS to 600% close to the cell edge.

TABLE I. PERCENTAGE OF END-TO-END TRANSMISSIONS ENDING BEFORE THE 60 SECONDS DEADLINE

	S1		S2		S3	
SH	**Opp**	**No-Opp**	**Opp**	**No-Opp**	**Opp**	**No-Opp**
83.32	85.01	83.77	85.02	83.78	88.63	88.5

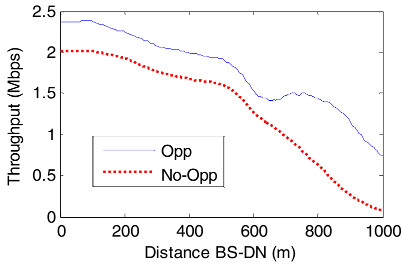


Fig. 4. Average cellular throughput when enabling (*Opp*) and disabling (*No-Opp*) opportunistic MCN-MR communications.

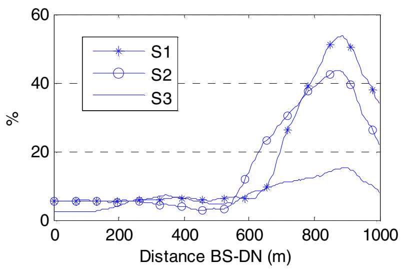


Fig. 5. Reduction in average cellular channel occupancy comparing *Opp* with *No-Opp*.

IV. CONCLUSIONS

This paper has proposed and evaluated the first mode selection scheme for mobile opportunistic multi-hop cellular networks using mobile relays. The proposed scheme estimates the possible benefits and risks for different connection modes, and selects the one providing the best trade-off. The proposed scheme has been evaluated considering the possibility to establish traditional single-hop cellular links, or MCN-MR connections enabling or disabling opportunistic networking. The obtained results show that the BRISK mode selection scheme can enable the integration of opportunistic networking in MCN-MR, and reduce the energy consumption while improving QoS and cellular capacity. These achievements can be obtained even in scenarios with low densities of potential relay nodes where non-opportunistic MCN-MR communications generally fail to achieve significant performance benefits compared to traditional single-hop cellular communications. In this study, the proposed mode selection scheme has been configured so that MCN-MR connections do not consider opportunistic networking if it is possible to establish a real-time MH connection that improves the end-to-end performance compared to single-hop cellular communications. Future studies could then evaluate the additional performance and energy benefits that could be obtained if opportunistic networking was exploited even if real-time MH connections outperforming SH could be established at the start of a connection.

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. 1, pp. 122-129, July 2013.

[3] G. Fodor, et al., "Design Aspects of Network Assisted Device-to-Device Communications", IEEE Communications Magazine, vol. 50, no. 3, pp. 170-177, March 2012.

[4] H. Zhang, P. Hong, K. Xue, "Mobile-based Relay Selection Schemes for Multi-hop Cellular Networks", Journal of Communications and Networks, vol. 15, no. 1, Feb. 2013.

[5] 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.

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

[7] M.C. Lucas-Estañ and J. Gozalvez, "Mode Selection for Multi-Hop Cellular Networks with Mobile Relays", Proc. IEEE/IFIP Wireless Days Conference 2013 (WD 2013), 13-15 November 2013, Valencia (Spain).

[8] S. Mukherjee, D. Avidor, K. Hartman, "Connectivity, Power, and Energy in a Multihop Cellular-Packet System", IEEE Trans. on Vehicular Technology, vol. 56, no. 2, pp. 818-836, March 2007.

[9] B. Coll-Perales, J. Gozalvez, J. Sanchez-Soriano, "Empirical Performance Models for P2P and Two Hops Multi-hop Cellular Networks with Mobile Relays", Proc. 8th ACM Performance Monitoring, Measurement and Evaluation of Heterogeneous Wireless and Wired Networks Workshop (PM2HW2N'13), Nov. 2013, Barcelona (Spain).

[10] B. Coll-Perales, J. Gozalvez, V. Friderikos, "Store, Carry and Forward for Energy Efficiency in Multi-hop Cellular Networks with Mobile Relays", Proc. IEEE/IFIP Wireless Days Conference 2013 (WD 2013), 13-15 November 2013, Valencia (Spain).

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