Energy Efficient Routing Protocols for Multi-Hop Cellular Networks

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***Abstract*—Multi-hop Cellular Networks using mobile relays require efficient multi-hop networking protocols that provide a high end-to-end performance and reduce the terminal's energy consumption. In this context, this paper proposes a set of novel multi-hop routing protocols that exploit the location of the destination node to reduce their network signalling and overall energy consumption. These two aspects are crucial factors to progress towards the future implementation of Multi-hop Cellular Networks based on mobile relays.**

***Keywords*—Multi-hop Cellular Networks, routing protocols, cost function, energy efficiency.**

I. Introduction

Future 4G cellular systems are required to provide high and homogeneous bit rates over the complete cell coverage area. Traditional cellular architectures, where each Mobile Station (MS) directly communicates with the Base Station (BS), are not capable to provide such homogeneous high bit rates due to the signal attenuation with the increasing distance. Achieving the defined 4G objectives requires installing a higher number of base stations, or integrating cellular and ad-hoc networking technologies. Increasing the number of base stations has an economical and social cost due to the growing social reaction against base stations. The integration of cellular and ad-hoc technologies, also referred as Multi-hop Cellular Network (MCN) [1], has gained significant research attention given its capacity to achieve the 4G objectives by substituting a direct MS-BS link by multi-hop links using intermediate nodes to retransmit the information from source to destination. In this case, MCN networks offer the potential to increase the overall multi-hop transmission rate by reducing the communications distance and signal loss in each hop. MCN networks can either use fixed (MCN-Fixed Relay, MCN-FR) or mobile relays (MCN-Mobile Relay, MCN-MR). MCN-MR networks are characterised by a lower implementation cost than MCN-FR networks, but a higher management complexity due to the participation of mobile terminals. However, exploiting the mobile terminals communications capabilities in a decentralized and distributed manner, also increases the potential and future perspectives of MCN-MR networks. To reach such potential, it is necessary to overcome important technological challenges, such as the design and optimization of robust, adaptive, context-aware and energy-efficient multi-hop routing protocols.

Different multi-hop routing protocols and cost functions have been proposed in the literature for wireless mesh networks. The first proposals were mainly based on the number of hops between the source and destination nodes [2]-[3]. This parameter has a direct impact on the multi-hop latency and stability, and has since then been generally taken into account in multi-hop routing protocols and cost functions. Other cost functions have proposed to consider diverse parameters that are relevant to the network and system performance and operation. For example, parameters such as the energy [4], network congestion [5], Packet Error Rate (PER) [6] and throughput [7] have been shown to impact the multi-hop wireless mesh networking performance. An interesting multi-hop routing protocol combining some of these parameters, and referred to as Multiple-Metric (MM), has been reported in [8]. In particular, the MM cost function combines the energy, channel congestion and number of hops from source to destination for its multi-hop routing decisions. Despite these important contributions, novel reliable multi-hop networking protocols minimising energy consumption or signalling load are still needed to improve the feasibility of mesh networking systems, and in particular of MCN-MR networks that heavily rely on the collaboration from mobile nodes.

In MCN-MR networks, the communications between a mobile station and a base station is established through mobile relaying nodes. Considering the perspective future implementation of MCN-MR systems, it would be reasonable to assume that, in the uplink direction, the source node (MS) knows the location of the destination node (BS). In fact, many countries currently release online the location of all their base stations nationwide. Knowing the location of the destination node for downlink communications would require the use of location technologies, which is not unrealistic given the continuous increase of devices with embedded GPS capabilities. The long range signalling capabilities offered by cellular architectures would then make possible to feedback this information to the source node (BS). This work focuses on uplink communications and proposes several location-based routing protocols that exploit the location of the destination and intermediate nodes to efficiently reach the addressed node.

Most location-based routing protocols (e.g. LAR [9]), extensively studied in the literature, need to assume that the destination node's locations is known and accordingly limit the search area in the discovery route process. Contrary to existing routing techniques, this work proposes to exploit the knowledge of the BS's location to design a set of efficient multi-hop routing protocol capable to reduce the energy consumption. The proposed techniques, besides reducing the signalling load and network congestion in the route search process, outperform the related previous work using a cost function to select the route that best fit to the MCN-MR communications requirements. Relevant results have been mainly achieved with one of the novel proposal, which allows the existence of a limited number of relaying nodes that are not in the direction towards the destination. The goal of the proposed work has been focused on compromises techniques that adequately balance performance and energy consumption.

II. 802.11S STANDARD

The IEEE 802.11s standard [10] could represent a suitable candidate for the multi-hop ad-hoc operation of MCN-MR networks since it incorporates all networking functions necessary for the establishment and management of wireless mesh networks. In particular, it defines new networking functions such as the mesh discovery process, mesh route establishment, channel selection, mesh links management, congestion control, authentication and security. In this context, this work is based on IEEE802.11s, although the contributions here presented could perfectly be implemented in other wireless mesh networking standards.

The mesh network discovery process is enabled through the periodic broadcast exchange of beaconing messages among neighboring nodes. The routing protocol proposed in the 802.11s standard is the Hybrid Wireless Mesh Protocol (HWMP), which includes both a reactive and proactive operational mode. In this paper, we focus on the reactive modified version of the AODV (Ad-Hoc On-Demand Distance Vector) protocol that is part of HWMP. AODV [2] is a reactive routing protocol that only searches and establishes a route when the source has information to transmit and does not know the route to reach the destination node; therefore overall network information is not required unlike proactive protocols. In this case, the source node sends a broadcast Route REQuest (RREQ) message that is retransmitted by neighboring nodes. When the destination node receives the RREQ message, it replies with a unicast Route REPly (RREP) message to confirm the route establishment. The reception of RREQ and RREP messages allow intermediate nodes to know their neighboring nodes in the route towards the source and destination nodes.

In the original AODV protocol, the route selected between the source and destination nodes is that with the lower latency, which generally coincides with the route with the lowest number of hops from source to destination. This is the case because an intermediate node only retransmits the first RREQ message it receives from a neighboring node in the quest for a multi-hop route from source to destination. Such RREQ message, and therefore the particular multi-hop route we are looking to establish, is identified by a given sequence number. If the intermediate node receives the same RREQ message (i.e. with the same sequence number as the first one) from a different neighboring node, the original AODV protocol would discard it. On the other hand, the modified AODV protocol, and in particular the on-demand routing mechanism included in the 802.11s standard [10] and implemented in this work, allows for other routes to be considered and analysed, and therefore does not discard the second received RREQ message. In this case, the modified AODV protocol evaluates whether the cost of the new route is lower or higher than the previously identified route, with the cost computed following a cost function. To compute the cost of each peer link, the 802.11s proposes the *Airtime Link* metric but allows for other metrics and cost functions to be implemented.

III. SIMULATION ENVIRONMENT

To investigate the performance of the proposed multi-hop routing protocols, this study is based on a 2250m x 2250m Manhattan type scenario emulated with the ns2 software platform. The base station is located at the centre of the scenario, and nodes move following the '*Random Walk Obstacle*' model [11]. Nodes communicate using the 5.8GHz 802.11a technology. The propagation loss is modelled through the deterministic pathloss model implemented in the WINNER project for the urban micro-cellular scenario. Despite not considering equal transmitting and receiving antenna heights, to the author's knowledge this model is one of the most complete ones for urban environments with low BS antenna heights. In addition, the WINNER model differentiates between Line of Sight (LOS) and Non LOS (NLOS) conditions [12].

The implemented traffic model follows the on-off bursty pattern characteristic of data transmissions but does not try to exactly characterise any specific traffic source. In particular, the model simulates 200 seconds traffic sessions where *on* and *off* periods last 5 and 15 seconds respectively. The defined *off* period ensures that the nodes routing tables validity has expired at the start of the following *on* period. During the *on* period, the source nodes transmit 50 packets to the BS. The remaining simulation platform parameters are summarised in Table I.

TABLE I. NS2 SIMULATION PARAMETERS

Parameter	Value
Number of nodes	500
Buildings width (m)	225
Street width (m)	25
Transmission power (W)	0.2
Transmission rate (Mbps)	12
Node's speed (m/s)	1.5
Data packet size (bytes)	500
Beacon's period (s)	5
Simulation time (s)	10000

IV. MULTIPLE-METRICS ROUTING PROTOCOL

The Multiple-Metrics (MM) proposal [8] has been selected as the reference technique over which to compare the energy efficient MCN-MR multi-hop routing protocols proposed in this work. This is the case because of its high performance, and the fact that its cost function is based on some of the most relevant parameters (energy, channel congestion and number of hops from source to destination) for the performance and operation of MCN-MR networks.

A. MM Implementation

MM defines different possible routes from source to destination, and characterises their cost using a lineal cost function dependent on the number of hops, the channel congestion and the node's energy. The objective is then to select the multi-hop route that minimises the cost function, with the possibility to differently weight each parameter based on the operating conditions or the specific network topology. The MM cost function is defined as follows:

$$cost = \alpha_1 \cdot hops + \alpha_2 \cdot load + \alpha_3 \cdot energy \tag{1}$$

where *hops* represents the number of hops from source to destination, *load* the channel congestion, and *energy* the node's energy consumption. The α variables are defined to weight the importance of the three parameters in the MM cost function. In our implementation, all parameters have been equally weighted.

The MM implementation reported in [8] considers CBR traffic and estimates the channel congestion using the time interval between two data packets. Since this approach is not feasible for bursty data traffic, the channel congestion is here estimated using the beacon messages that are regularly transmitted in the IEEE 802.11s standard. In the absence of channel congestion, a node would be periodically receiving the beacon messages from a neighboring node. As the channel congestion increases, the reception of the beacon message can be delayed, with the delay increasing with the channel congestion. Given that the beacon's periodicity is known by all nodes, this work estimates the channel congestion using the beacon's message reception delay. In this case, the time interval between beaconing messages (*intvl*) is estimated as:

$$\text{intvl} = \frac{t_{now} - t_{last\_beacon} - t_{beacon}}{t_{beacon}};\ 0 \le \text{intvl} \le 1 \tag{2}$$

with t_{now}, t_{last_beacon} and t_{beacon} representing the current time, the time at which the last beacon was received and the beacon's periodicity, respectively. The *load* is then estimated considering the previous *load* estimate as follows:

$$load = (1-\beta) \cdot load_{previous} + \beta \cdot \text{intvl} \tag{3}$$

with the β parameter offering the possibility to differently weight the importance of the last *load* and *intvl* estimates.

The MM implementation reported in [8] looked at minimizing energy consumption through a power control mechanism. On the other hand, this work does not implement a power control mechanism, and the *energy* represents the energy consumed by a node. In this case, the energy inclusion in the MM cost function is focused at maximizing the node's lifetime battery by trying to distribute the energy consumption over all the nodes of the network.

B. MM Performance

The MM cost function is here evaluated using the modified AODV protocol defined in the 802.11s standard, and that is referred in [8] as MMRP-I (Multiple Metric Routing Protocol-Improvement). For simplicity, this implementation is further noted as MM. Figure 1 depicts the packet delivery ratio to the destination node with regards to the packets generated at the application level (rate_app), and the routed packets (rate_net). As it can be observed from Figure 1, MM achieves high delivery ratios. This high performance is due to its cost function and routing protocol that broadcasts its route discovery process in all directions, and finally selects the route offering the lower cost. This broadcast process is enabled by the modified AODV protocol that allows intermediate nodes to retransmit a previously received RREQ message if it exhibits a lower route cost. However, the achieved high MM performance comes at the expense of a significant signalling load, represented in Figure 2 as the ratio between the number of retransmitted RREQ messages by intermediate nodes and the number of RREQ messages generated by the source node per route selection. Such signalling load can increase the channel congestion and significantly reduce the node's energy, which will in turn impact the MCN-MR operation. To reduce this constraint, this work proposes and evaluates a set of energy efficient MCN-MR multi-hop routing protocols, aimed at maintaining MM's performance while reducing its signalling load and energy cost.

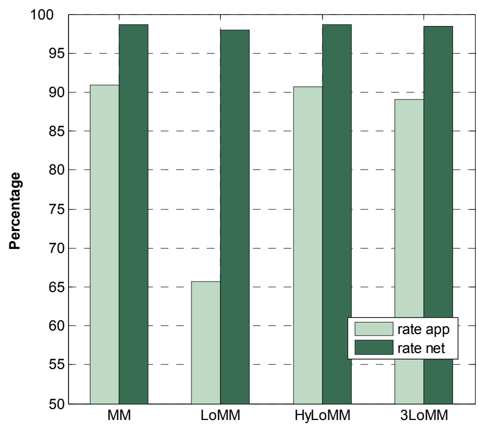

Figure 1. Application and routing Packet Delivery Ratios (in %).

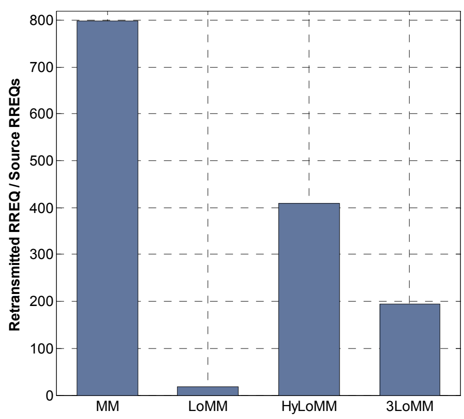

Figure 2. Ratio between the number of retransmitted RREQ messages by intermediate nodes and the number of RREQ messages generated by the source node per route selection

V. Energy Efficient MCN-MR Multi-hop Routing Protocols

To overcome the potential signalling and energy inefficiencies of multi-hop networking protocols, this work proposes a set of protocols tailored for MCN-MR networks, and that base their operation on the knowledge of the destination node's location. All the proposed techniques are based on the MM cost function, but modify the protocol to select the relaying nodes.

A. *Location based-Multiple Metrics*

The first proposal, referred to as Location based-Multiple Metrics (LoMM), is based on the MM cost function, but modifies the 802.11s multi-hop route search. In particular, LoMM does not allow intermediate nodes that are further away from the destination node (i.e. the base station) than the previous relaying node to retransmit RREQ messages. This change reduces network flooding by ensuring that each hop progresses towards the destination node. After all viable routes have been identified, LoMM selects the route with the lower cost following the MM cost function.

The results depicted in Figure 2 clearly show that limiting the relaying nodes to only those in the direction towards the destination significantly reduces the signalling load and the potential multi-hop routing channel congestion. In particular, LoMM reduces by 97% the signalling load compared to the original MM proposal. However, this significant signalling load reduction comes at the expense of decreasing the application packet delivery ratio due to the reduced number of candidate relaying nodes (Figure 1). In fact, 95% of the application packets discarded by the LoMM proposal are discarded by the source node due to its inability to find a route from source to destination. On the other hand, when such route is established, the LoMM proposal achieves a high packet delivery ratio with respect to the routed packets (Figure 1), and increases the application throughput by 18% with respect to the original MM proposal (Figure 3). This improvement is due to the fact that exploiting the destination node's location in the routing process reduces the number of hops to reach the destination and the distance from source to destination (Table II).

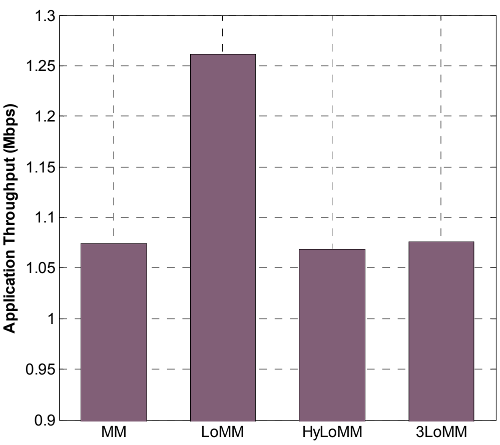

Figure 3. Application throughput for established routes

B. *Hybrid Location and Multiple Metrics*

The Hybrid Location and Multiple Metrics (HyLoMM) proposal has been designed to find a compromise between the MM performance and the LoMM efficiency. HyLoMM technique follows the same philosophy in the route discovery process as LAR-2 [9], but using MM cost function to select the best route instead of the first arrival route. In the modified on-demand AODV protocol, the source node is allowed to launch several route requests if it does not receive a RREP message from the destination node before a timer expires. In this context, the hybrid HyLoMM proposal performs its first route search using the LoMM mechanism, and if it is not capable to find a route between the source and destination, it performs the following route searches using the original MM technique in order to maximize the probability to establish a route from source to destination.

Figure 1 shows that HyLoMM is capable to increase the application packet delivery ratio and achieve the same performance as the original MM proposal. This performance improvement with respect to LoMM comes at the expense of reducing the application throughput for the established routes (Figure 3) due to a higher route distance and number of hops from source to destination (Table II). In addition, it is important to note that HyLoMM reduces the signalling load (Figure 2) with respect to the original MM by 48%, highlighting its capacity to offer a compromise between performance and efficiency.

TABLE II. Multi-hop routing operation

Technique	MM	LoMM	HyLoMM	3LoMM
Number of hops	7.16	5.63	7.11	7.07
Route distance (m)	1191.9	980.8	1192.8	1178.2

C. *x-hops Location permissive-Multiple Metrics*

As it has been observed from the previous proposals, limiting the candidate relaying nodes by using the knowledge of the destination node's location, can help reduce the signalling load of multi-hop networking protocols, and therefore increase their future implementation perspectives. However, the results obtained have also shown that in a context of continuous mobility and challenging propagation conditions, a certain compromise in the selection of relaying nodes must be reached to guarantee a satisfactory multi-hop end-to-end performance. To this aim, and after analysing the performance and operation of LoMM and HyLoMM, the authors finally propose the x-hops Location permissive-Multiple Metrics (xLoMM) technique. In LoMM, only nodes in the direction towards the destination node could be selected as relaying nodes. xLoMM follows the LoMM operating principle, except that it allows for a maximum of x relaying nodes that are not in the direction towards the destination node as estimated by LoMM. With this approach, xLoMM aims to exploit, whenever possible, the knowledge of the destination's location to improve its implementation efficiency. However, xLoMM does not sacrifice performance to efficiency, and still allows selecting a maximum of x relaying nodes that do not progress towards the destination. In this paper, the allowed maximum number of relaying nodes that do not progress towards the destination has been set to three.

The results depicted in Figures 1 and 3 highlight that 3LoMM achieves nearly the same application packet delivery ratio than MM, while slightly increasing its application throughput. However, despite exhibiting a similar operating performance to MM (Table II), 3LoMM significantly reduces the signalling load with respect to MM (Figure 2). The conducted study has also shown that varying the allowed maximum number of relaying nodes that do not progress towards the destination offers a trade-off between signalling/congestion load and end-to-end performance.

The technical proposals reported in this paper have shown that exploiting the knowledge of the destination's location in the design of multi-hop networking protocols can improve the implementation feasibility of MCN-MR systems by reducing their signalling and congestion load. Improving such signalling load is crucial to tackle one of the key challenges in the design and implementation of MCN-MR networks, that is, the energy consumption of mobile nodes. Figure 4 compares the energy consumption related with the signalling functions of multi-hop routing protocols with respect to the total energy consumed by mobile nodes. The obtained results show that 55% of the total energy consumed by mobile nodes implementing the original MM proposal was due to signalling functions of the MM multi-hop networking protocol. This percentage is greatly reduced by the protocols proposed in this paper. In particular, it is important to emphasize the results achieve with the 3LoMM proposal that reduce by half the multi-hop networking energy consumption while exhibiting the same end-to-end performance as the original MM technique.

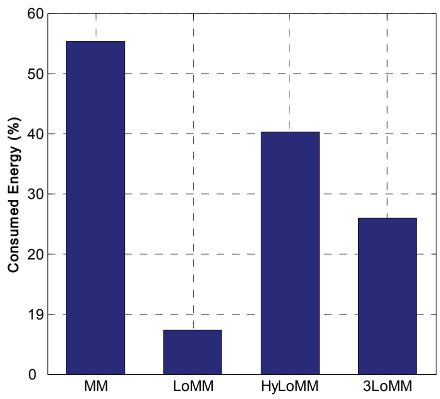

Figure 4. Energy consumed by the routing protocol with respect to the total energy consumed by the mobile terminals (in %).

To conclude, Table III depicts the total average energy consumed by mobile nodes for each of the simulated multi-hop routing protocols. Table III emphasizes the energy efficiency of the proposed multi-hop routing protocols. The obtained results demonstrate that reducing the multi-hop networking energy consumption helps increasing the terminals battery lifetime. This energetic contribution is believed to represent a key aspect to progress towards the future implementation of MCN-MR networks.

TABLE III. AVERAGED TOTAL ENERGY CONSUMPTION

Technique	MM	LoMM	HyLoMM	3LoMM
Consumed energy (J)	0.33	0.15	0.26	0.21

VI. CONCLUSION

This paper has proposed a set of multi-hop routing protocols for MCN-MR systems that base their networking operation on the knowledge of the location of the destination node. The achieved results demonstrate that the proposed protocols are capable to provide a high end-to-end performance, while reducing the signalling load of multi-hop networking protocols, and consequently their risk of network congestion. In addition, the proposed protocols reduce the energy consumption due to multi-hop networking functions, and increase the battery life of mobile terminals, which is a crucial aspect to improve the potential future deployment of MCN-MR networks.

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