Multi-Hop Cellular Networks based on Mobile Relays: Capabilities and Enabling Technologies

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1. Introduction

Beyond 3G or 4G wireless networks will be based on the seamless coexistence and cooperation of heterogeneous radio access technologies with complementary technical characteristics. Despite continuous technical advances, traditional cellular architectures fail to offer homogeneous Quality of Service (QoS) levels throughout the coverage area as requested by the ITU recommendations for future 4G systems [1]. This is the case because of the strong signal attenuation with the distance, and the highly variable propagation conditions caused by the presence of obstacles. Although reducing the cell size or augmenting the number of base stations can help increasing the user-perceived QoS levels, it also has a high economic and social cost. A different alternative for achieving the 4G objective is the introduction of relaying techniques, or the integration of cellular and ad-hoc networking technologies into what is usually referred as Multi-hop Cellular Networks (MCN) [2]. MCN networks are capable of increasing and providing more homogenous QoS levels by substituting a direct Mobile Station (MS)-Base Station (BS) link by multiple hops using either fixed relays (MCN-Fixed Relay, MCN-FR) or mobile relays (MCN-Mobile Relay, MCN-MR). Most research and standardization efforts have focused to date on FR solutions due to their lower management and deployment complexity. However, the possibility to exploit the mobile terminals communication capabilities in a decentralized and distributed manner increases the potential and future perspectives of MCN-MR, but also its management complexity. To further advance the development of viable and efficient MCN-MR systems, the mHOP project at the University Miguel Hernandez of Elche is investigating three key aspects: the experimental MCN-MR connectivity and QoS levels that can be achieved, and under which conditions they can be achieved; mechanisms to foster and control the user terminal's cooperation in relaying other users' data; and the development of advanced resource management schemes to efficiently integrate MCN-MR systems into the Beyond 3G heterogeneous framework.

2. MCN-MR Connectivity

Previous studies have already reported the multiple advantages that MCN networks can provide over traditional cellular architectures in terms of capacity improvement, radio cell extension, power consumption, throughput, etc [3-4]. However, these studies have been based exclusively on theoretical and simulation studies, and there is yet the need to validate the potential of MCN-MR through field trials. In this context, the mHOP project has implemented the first MCN-MR testbed available in the scientific community to investigate the performance improvements that can be achieved through MCN-MR over traditional cellular links, and the operating conditions under which such improvements can be achieved [5].

The implemented platform incorporates two cellular links, one of these links will be part of a MCN-MR connection, while the other one will represent a conventional single-hop cellular link with which to compare the performance of MCN-MR. The cellular link is implemented using a Nokia 6720c handset that incorporates the Nemo Handy application, which provides the terminal with a powerful radio monitoring capability offering a valuable set of KPIs (Key Performance Indicators), such as the throughput, BLER (Block Error Rate), or RSSI (Received Signal Strength Indicator). The ad-hoc mobile relaying nodes have currently been implemented using conventional laptops under Linux using the Ubuntu 9.10 distribution that includes the Linux kernel 2.6.31 (a migration to handheld terminals is foreseen). The nodes have several wireless interfaces to be capable to transmit, receive, and capture the transmitted and received packets for monitoring the quality of ad-hoc links using the Kismet and Wireshark tools. One of the ad-hoc relaying nodes acts as a bridge between the cellular and ad-hoc technologies without downgrading the overall end-to-end-performance.

Figure 1 illustrates an example of the performance improvements that can be obtained with MCN-MR compared to a traditional cellular link when operating under NLOS (Non Light of Sight) conditions. To this aim, the performance of a traditional HSDPA cellular link with NLOS

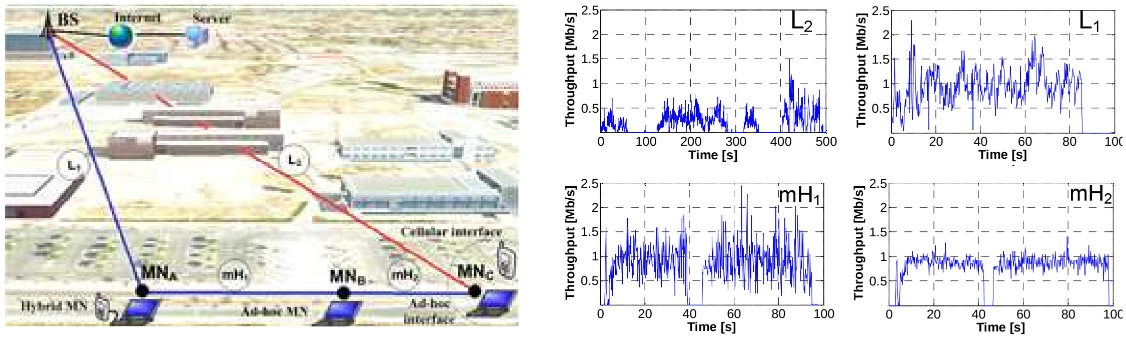

Figure 1. Field test and MCN-MR vs cellular throughput comparison

conditions with its serving BS is compared to that achieved with a MCN-MR link (integrating HSDPA and 802.11g at 2.4GHz) operating under LOS conditions through various hops. The field tests have been conducted at the campus of the University Miguel Hernandez of Elche. As it can be observed from Figure 1, the MCN-MR link (L1–mH1–mH2) can significantly increase the performance compared to the traditional cellular link (L2). The authors are currently conducting a large field testing campaign, including outdoor, indoor and outdoor/indoor scenarios, to investigate the performance benefits of MCN-MR. The resulting field traces, such as those reported in Figure 1, will be openly distributed to the community once all the processing and formatting has been done (the traces will be available at: http://www.uwicore.umh.es/mhop.html).

3. MCN-MR Networking

To achieve the expected benefits of MCN-MR systems, advanced multi-hop communications and networking protocols will be necessary. In particular, robust and energy-efficient multi-hop routing protocols will play an important role considering the challenging peer-to-peer propagation conditions and the constrained terminal's energy. Different multi-hop routing protocols have been proposed in the literature for MANETs (Mobile Ad-hoc NETworks) and mesh networks. Such proposals define cost functions considering parameters such as the number of hops between the source and destination nodes, energy, network congestion, Packet Error Rate (PER) or throughput [6-7]. MCN-MR systems are characterised by the presence of an ubiquitous signalling capability through the cellular network, and a fixed and known location of the BS (which represents either the destination or source node). Such knowledge can be further exploited to optimise the reliability and energy-efficiency of MCN-MR multi-hop routing protocols. With this philosophy, the authors have designed a set of energy-efficient routing and neighbour selection mechanisms [8-9] that reduce the energy consumption, signalling load and network congestion in the route search process, and provide alternatives to adequately balance performance and energy consumption. After extensive simulation studies, the mHOP project is now working to validate some of the implemented networking techniques through experimental SDR (Software Defined Radio)-based hardware testbeds using the USRP2 platform. To this aim, an 802.11 real-time fully programmable node has been implemented. The platform incorporates the transmitter's physical layer implementation done by FTW [10], and a complete MAC implementation developed at UMH [11]. The MAC code will be openly distributed to the community (http://www.uwicore.umh.es/mhop.html).

4. Reputation Techniques

MCN-MR systems will require the cooperation of terminal's in relaying other user's data. However, certain users might exhibit a selfish behavior motivated by aspects such as battery exhaustion, traffic overload, technological distrust, or intrinsic selfishness. To incentive nodes to cooperate in network functions, and prevent intentional attacks from malicious nodes, Selfishness Prevention Protocols (SPPs) are being investigated, in particular in the domain of MANETs [12]. Three main SPP categories can be identified: reputation-based, credit-based, and those based on game theory. Credit-based schemes use a virtual or real currency to pay for self originated data retransmitted by other nodes. Credit is then used to compensate for the utilization of resources in the relaying process, and it can be obtained by retransmitting other nodes packets or just by exchanging real money. Credit-based solutions are characterised by the need for a complex signalling solution and a tamper-proof hardware that compromise their scalability. Game theory models simulate a game where each mobile node can choose either to retransmit other nodes data or not. Equilibrium stability of different strategies can be studied analytically, but game theory models usually fail to reproduce important parameters of real systems. In this context, a more viable solution for future MCN-MR systems might be reputation techniques that base their operation on the observation of the behaviour of other nodes in order to fill a reputation table where the willingness to cooperate of the neighbor nodes is quantified. The reputation table is then used to identify selfish nodes and establish reliable multi-hop routes.

Despite their applicability perspective, current reputation techniques, which in general use the watchdog mechanisms to observe the behavior of other nodes [13], exhibit certain inefficiencies since they can mistake packet collisions or packet errors with intentional packet drops. To overcome these inefficiencies, the mHOP project has proposed new techniques that enhance the ability of the SPP to detect the real selfish nodes and reduce the number of incorrect accusations [14]. The proposed mechanisms are intended to be run in parallel with any reputation based SPP using the watchdog mechanism to detect nodes acting selfishly.

The majority of reputation-based SPP mechanisms proposed to date consider fully distributed systems, with the consequent difficulty to trace the reputation of mobile nodes. To integrate reputation-based SPP mechanisms into MCN-MR systems, the mHOP project is currently investigating how to exploit the ubiquitous cellular signalling capability of MCN-MR systems to develop robust and efficient (in terms of signalling, bandwidth and energy consumption) reputation-based SPP mechanism capable to adequately trace the users' reputation under mobile environments.

4. Conclusions

MCN-MR systems can offer significant benefits over the traditional infrastructure-centric cellular systems. The integration of cellular and ad-hoc technologies, and the participation of mobile terminals in the relaying of data, creates new communication paradigms, but requires advanced mechanisms to efficiently manage the communications and computing resources of mobile terminals. In this context, the mHOP project is investigating some of the key technological components in MCN-MR systems, in addition to analyzing the experimental potential of this emerging technology through field testing and prototyping. The following project's target will be to investigate how MCN-MR solutions can be fully integrated and efficiently managed in an heterogeneous wireless framework.

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