Research Testbed for Field Testing of Multi-Hop Cellular Networks using Mobile Relays

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***Abstract*— Multi-hop Cellular Networks have recently emerged as a promising technology to overcome the current limitations of cellular systems through the integration of cellular and ad-hoc networking technologies. Several studies have addressed the challenges of Multi-hop Cellular Networks based on Mobile Relays, and demonstrated their performance and potential to improve the user-perceived Quality of Service. However, most of these studies are based on analytical and simulation techniques, and there is yet the need for field tests that confirm their performance. In this context, this paper introduces a novel testbed to investigate Multi-hop Cellular Networks using Mobile Relays through field testing. In addition, this paper also presents the first field test results that demonstrate the performance improvements that can be achieved with Multi-Hop Cellular Networks over traditional cellular systems.**

Keywords: Multi-hop Cellular Networks; Mobile Relaying; Field Trials; Hardware Testbed

I. Introduction

Beyond 3G or 4G wireless networking research is being driven by the need to provide high and homogeneous Quality of Service (QoS) levels throughout the coverage area [1]. Traditional cellular architectures fail to offer such homogeneous QoS levels mainly due to the strong signal attenuation with the distance, and the highly variable propagation conditions caused by the presence of obstacles. Although 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 to increasing such QoS levels has recently emerged through 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). 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, the possibility to exploit the mobile terminals communication capabilities in a decentralized and distributed manner also increases the potential and future perspectives of MCN-MR.

Using multiple hops from source to destination reduces the communications distance and signal loss in each hop, and thereby offers the potential to increase the overall multi-hop transmission rate compared to long-distance and single-hop communication links. In addition, the use of relaying nodes can help improve the signal quality by replacing Non-Line-of-Sight (NLOS) links by multiple hops with LOS propagation conditions. Previous publications have already reported the multiple advantages that MCN networks provide over traditional cellular architectures in terms of capacity improvement, radio cell extension, lower infrastructure deployment cost, power saving and energy efficiency [3 - 5]. However, these studies have been based exclusively on theoretical and simulation studies, and there is yet the need to validate the potential of multi-hop cellular networking through hardware testbed platforms and field trials. In this context, and to the authors' knowledge, this work introduces the first MCN-MR testbed developed to investigate the performance improvements that can be achieved through MCN networks using mobile relays, and the operating conditions under which such improvements can be achieved. In addition, this paper presents the first field test results that verify the performance benefits of MCN networks.

II. MCN-MR Research Testbed

There is a growing interest in the research community to design and develop hardware platforms to investigate the potential, performance and operation of multi-hop communication systems. Most of the activities focus around 802.11 networks and the study of cooperative mechanism in multi-hop ad-hoc communications. A practical demonstration of the potential of cooperative networks is shown in [6], where the authors propose a cross-layer mechanism for 802.11 along with a Medium Access Control (MAC) protocol that allows selecting neighboring helper stations for MAC layer forwarding. Despite initially concentrating on fixed relaying solutions, it is important to highlight the recent activities conducted to develop LTE-Advanced hardware testing platforms. These activities are highly relevant since LTE-Advanced will be the first cellular standard to consider an MCN architecture. In this context, the work reported in [7] presents a prototype implemented to demonstrate that relaying techniques have a high impact on the coverage and capacity of cellular systems. The LTE-Advanced platform corroborates the benefits that MCN-FR can achieve at the expense of an infrastructure deployment cost, and the need to strategically locate the relay nodes at the cell edge in LOS conditions to the BS in order to achieve the maximum capacity and end-user QoS. In this context, the work presented in this paper represents a step beyond the current state of the art by introducing, what is, to the authors' knowledge, the first MCN-MR research platform.

A. Testbed architecture

The design and implementation of a research hardware testbed for the study of MCN-MR communications had to be done considering certain design criteria to guarantee its functionality and capacity to further evolve as the research progresses. As it has been previously explained, one of the objectives of the testbed is to investigate the performance benefits of MCN-MR over traditional cellular systems, and the conditions under which such benefits can be obtained. As a result, the platform requires two cellular links with the tools necessary to monitor and evaluate their performance. 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 ad-hoc relaying nodes should also have the capability to continuously monitor their radio performance, and their design should guarantee the platform's scalability and capacity to integrate an increasing number of mobile nodes. Their configuration should also ensure the flexibility to investigate various communications settings, such as advanced multi-hop routing protocols, different 802.11 standards, frequencies, etc. In addition, one of the ad-hoc relaying nodes should act as a bridge between cellular and ad-hoc technologies in the MCN-MR communications link. This node should be capable of forwarding in real-time the transmitted data between the radio technologies without downgrading the overall network performance. With all these design criteria in mind, Fig. 1 illustrates the MCN-MR testbed architecture. The testbed initially concentrates in downlink transmissions from a local server placed at the University Miguel Hernández of Elche. The data is downloaded to a destination mobile node through either a conventional single-hop cellular link (L_2), or a MCN-MR link ($L_1 – mH_1 – mH_2$).

B. Mobile Nodes

The implemented MCN-MR testbed integrates three different types of Mobile Nodes (MN) with different communication capabilities: ad-hoc MN (802.11a/b/g in ad-hoc mode), cellular MS (HSDPA, High Speed Downlink Packet Access), and hybrid MN (HSDPA and 802.11a/b/g in ad-hoc mode).

1) Cellular mobile station

The cellular mobile station is a Nokia 6720c handset that supports the radio access technologies GSM/EDGE and UMTS/HSDPA. The Symbian-base terminal also incorporates the Nemo Handy application, which provides the terminal with a powerful radio monitoring capability. Nemo Handy provides extensive network parameters and measurement data captured over voice and video calls, FTP/HTTP data transfers, HTML/WAP browsing and video streaming. The processing of the logged measured data has been done using the professional Nemo Outdoor tool. This tool offers a valuable set of Key Performance Indicators (KPIs), such as the throughput, BLER (Block Error Rate) or RSSI (Received Signal Strength Indication) that have been very valuable to analyze the cellular links QoS in the MCN-MR testbed. The Nemo Handy application also provides spatial and time synchronization through an external GPS connected via Bluetooth. The GPS data also allows tracking the MS position and geo-referencing all the performance measurements.

2) Ad-hoc mobile node

The ad-hoc mobile nodes have currently been implemented using conventional laptops. Built-in wireless interfaces in laptops are not generally capable of operating in ad-hoc mode under Linux. As a result, the laptops used as ad-hoc mobile nodes had to be equipped with an additional wireless interface and a USB GPS receiver. The USB GPS receivers are necessary to time synchronize all the devices present in the testbed. In addition, the use of a GPS at each node allows them to continuously trace their position and geo-reference all the logged radio measurements. The added wireless interface is in charge of the ad-hoc and multi-hop transmission and reception of packets. On the other hand, the laptop built-in wireless interface is in charge of capturing the transmitted and received packets by the added external wireless interface. This capturing capability allows continuously monitoring the performance of the ad-hoc 802.11 links. The chosen additional wireless interface is a wireless ExpressCard with Atheros chipset. This solution was chosen due to its outdoor range, date rate, reliability and capacity to operate under ad-hoc mode using IEEE 802.11a/b/g/n.

The ad-hoc nodes work under Linux using the Ubuntu 9.10 distribution that includes the Linux kernel 2.6.31. This configuration was chosen due to the need to configure parameters of the physical layer interface, and the availability of tools for such configuration under the Linux operating system. The testbed uses the Linux Ath9k driver [8]. Ath9k is a Free and OpenSource Software (FOSS) originally developed by Atheros, and that expands the technical features of the Madwifi WLAN driver to support all the available 802.11n chipsets from Atheros. It is important to note that the hardware platform is ready to support 802.11n transmissions. However this option was not considered since the Ath9k driver still does not support the 802.11n ad-hoc mode. To have access to the Ath9k driver, it is important to use at least the 2.6.27 kernel or a newer one. In this work, the Ath9k release included in the compat-wireless 2.6.32.11 package [8] has been used. To modify the physical layer parameters through the Ath9k driver, the testbed uses the *wireless tools* package, a generic Linux API. Using this package, the user can select the operation channel (channel) or the transmission power (txpower), to name a few. The *wireless tool* package is also used to configure the wireless ExpressCard interface in the ad-hoc mode, while the laptop built-in wireless units are configured in monitor mode to capture the data exchanged through the wireless ExpressCard.

The ad-hoc nodes also include packet sniffer software to capture 802.11 traffic[1] through the laptop built-in wireless interface operating in monitor mode. In particular, the ad-hoc nodes incorporate the Kismet and Wireshark tools. Kismet is an 802.11 layer 2 wireless network detector and sniffer, while Wireshark, formerly known as Ethereal, is a network packet analyzer. In addition, Wireshark can also capture traffic and filter it. The MCN-MR testbed uses both software tools due to their distinctive features. Kismet is capable of time and geo-referencing all the transmitted packets using the GPS data into a single log file. However, it does not provide a graphical user

[1] The sniffer software adds a header to the captured packets that includes useful information such as the RSSI, data rate, frequency channel, packet size, or frame check sequence (FCS), to name a few.

interface. This interface is provided by Wireshark that also offers powerful tools to organize and filter the captured network traffic. These capabilities are highly desirable for the post-processing of the MCN-MR communications performance. As a result, the Kismet tool is used to capture network traffic, time- and geo-reference it, and store into a file using a pcap (packet capture) interface. Wireshark is then used to filter the captured packets, and transform the processed data into a text file for its further processing when analyzing the QoS provided by MCN-MR networks.

3) Hybrid mobile node

The hybrid nodes are those in charge of acting as a gateway between the cellular and 802.11 multi-hop ad-hoc networks. In order to later incorporate the highest performance 802.11 technologies, e.g. 802.11n, the hybrid node is implemented in a standard laptop. The node uses a Nokia 6720c terminal as modem to provide an HSDPA cellular link, and uses the wireless interfaces of the ad-hoc node to enable its 802.11 multi-hop connectivity. The real-time data forwarding from the cellular link to the 802.11 ad-hoc link has been enabled by modifying the laptop routing tables of the established ad-hoc network[2]. Finally, the hybrid nodes include the software monitoring tools described for the cellular MS and ad-hoc mobile nodes.

III. FIELD TRIALS

In addition to presenting the first research testbed to investigate MCN-MR networks, this paper also presents the first field trials that demonstrate the performance and potential of this emerging technology.

A. Testing Environment

The field trials have been conducted at the campus of the University Miguel Hernández of Elche. Fig. 1 illustrates the location of the base station (BS) and the position of the mobiles nodes (MN). The field measurement campaign described in this section has been conducted to investigate the potential of MCN-MR networks to improve the cellular link quality, and thereby the end-user QoS, when operating under NLOS conditions. To this aim, the performance of a traditional cellular link with NLOS conditions with its serving BS will be compared to that achieved with a MCN-MR link operating under LOS conditions through various hops. In this context, a data file is transferred by the BS to the mobile MN_C, located at a distance of 760 meters through a single-hop cellular link (L_2), and through a MCN-MR link (L_1 – mH_1 – mH_2) using MN_A and MN_B as mobile relaying nodes. MN_A is located at a distance of 740 meters to the BS, while MN_B and MN_C are placed at a distance of 60 meters and 100 meters respectively from MN_A. The L_1, mH_1, and mH_2 links are all operated under LOS conditions. The field trials have been conducted with the cellular links (L_1 and L_2) operating under HSDPA standard given its higher data rates. To control the cellular transmission, the Nemo Handy software tool has been used. In particular, the Nemo capabilities have been employed to force the carrier, using the UARFCN (UTRA[3] Absolute Radio Frequency Channel Number) parameter, and the scrambling code of the cellular link. Fixing these two parameters prevents the instantaneous re-selection of overlapping cells, and enables a stable testing environment over which to compare the cellular and MCN-MR transmissions. It is important to emphasize that the testing base station has not been barred, and therefore other users might be active to obtain realistic operating conditions.

[2] The hybrid node also incorporates two GPS receivers for the cellular and wireless interfaces.

[3] UTRA stands for UMTS Terrestrial Radio Access

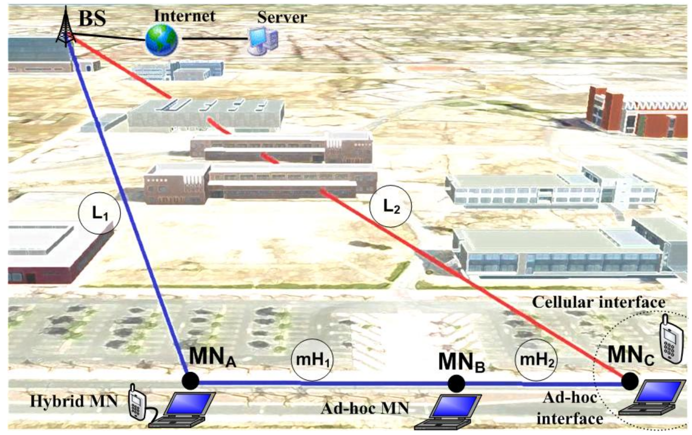

Figure 1. MCN-MR testbed and trial environment

The mobile nodes communicate with each other using the IEEE 802.11g technology at 2.4GHz, which provides a theoretical maximum bit rate of 54Mbits/s. However, the data rate at which the nodes operate is managed by the Ath9k driver through an adaptive rate control algorithm [8]. The transmission power of the mobile nodes for the 802.11 ad-hoc communications has been fixed at 27dBm.

The field trials have been conducted downloading large-size files from a HTTP server located and managed at the Uwicore laboratory. A script launched by the mobile node MN_C executes the simultaneous file download using the single hop cellular link (L_2), and the MCN-MR link (L_1 – mH_1 – mH_2). This has been done to ensure the same cellular traffic load in both transmissions. The MCN-MR link requires that the hybrid mobile node (MN_A) transforms the transport blocks received through the cellular link L_1 to 802.11 packet data units (MAC PDU). The MAC PDU size has been set to 1564 bytes. As a result, the node MN_A stores the cellular transport blocks in a buffer until an 802.11 MAC PDU is filled. Once the 802.11 packet is formed, the node MN_A transmits the MAC PDU to MN_B through an ad-hoc 802.11 link. MN_B acts as a relay and forwards the packet to the destination node MN_C through another ad-hoc 802.11 link.

B. Field Test Results

This section describes the results obtained in the first trials conducted to investigate the communications performance of MCN-MR networks, and compare it to that achieved with conventional cellular systems. In particular, the results shown in this section illustrate the potential of MCN-MR networks to improve the communications link quality, and thereby the user-perceived QoS, by avoiding NLOS conditions. Fig. 2.a shows the throughput measured at the MAC layer of MN_C during the download of a file using an HSDPA single-hop cellular link. As depicted in Fig. 1, the single-hop cellular link (L_2) experiences NLOS propagation conditions. Although the HSDPA standard allows a maximum of 15 simultaneous channelization codes, and the use of the 16QAM modulation to achieve a theoretical maximum data rate of 10.1Mbits/s for MS of category 9, the

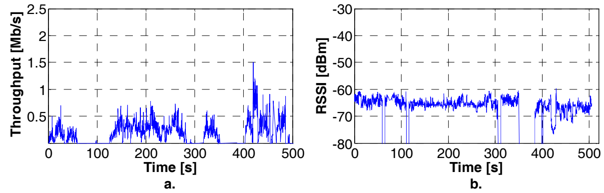

Figure 3. Measured throughput and RSSI for the HSDPA cellular link (L_2)

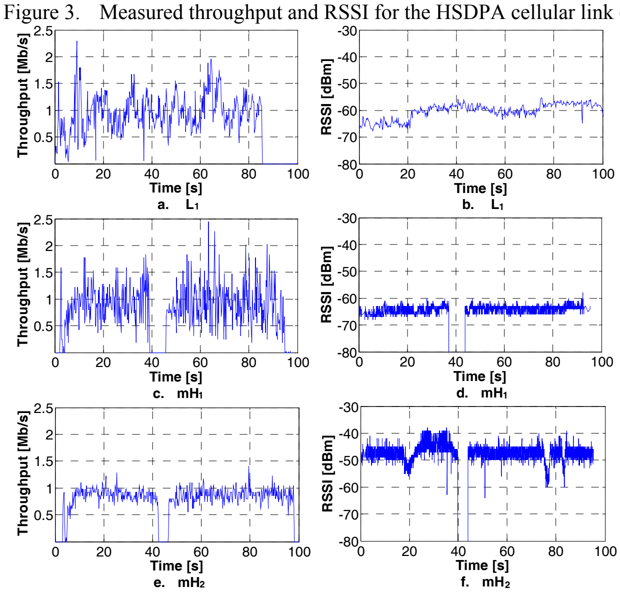

Figure 3. Measured throughput and RSSI for the MCN-MR link

NLOS conditions resulted in the use of the more robust QPSK modulation. This modulation mode, together with the low number of used channelization codes (on average 2.5) during the field trials, are at the origin of the throughput measurements reported in Fig. 2.a. The time intervals over which the measured throughput is equal to zero are due to a sudden decrease of the RSSI (see Fig. 2.b) that results in a link outage[4]. Although the RSSI recovers after a short time (Fig. 2.b), MN_C requires certain time to get access to the system and obtain the necessary radio resources, which explains the larger duration of the time intervals over which the measured throughput is equal to zero.

Figures 3.a, 3.c and 3.e show the throughput measured for each of the links that are part of the whole MCN-MR network. It is important to note that to adequately compare the cellular and MCN-MR performance, the file download was simultaneously launched in both links using a script. This procedure ensures that the results reported for both technologies are time-synchronized. As observed in Fig. 3.a, the LOS conditions significantly increase the throughput measured at the cellular link L_1 compared to that measured over the link L_2 (Fig. 2.a). LOS conditions improve the link quality, as reported in the measured RSSI (Fig. 3.b; no link outage was observed during the file download through the L_1 link), and resulted in the use of a high level modulation mode compared to L_2, and an average of 5 channelization codes during the file download. These improvements are at the origin of the higher throughput measured in L_1, and the fact that the file was downloaded in just 90 seconds compared to the 500 seconds necessary through the single-hop cellular link L_2.

[4] A link outage is defined as the time during which a link is temporarily lost due to a decrease of the received signal level or RSSI.

The throughput measured at the MAC layer in each of the 802.11 ad-hoc wireless links is shown in Figures 3.c and 3.e. Although the 802.11 links are characterized by a higher theoretical throughput than the cellular links, the results illustrated in Figures 3.c and 3.e show similar throughput levels to those measured in L_1. This is due to the real-time forwarding of the data by all the nodes participating in the MCN-MR link. Such real-time operation results in that the cellular link L_1 represents the overall bottleneck of the MCN-MR connection. The throughput results obtained for the ad-hoc links show that mH_2 offers a more stable performance compared to mH_1. The length of each link influences the signal level, measured in terms of RSSI (see Figures 3.d and 3f), and therefore the throughput results. The measured average end-to-end throughput also highlights significant performance differences between the single-hop NLOS cellular link (229kbit/s), and the MCN-MR connection avoiding NLOS conditions through multiple LOS hops (816kbit/s).

IV. CONCLUSIONS

This paper has introduced a first research platform to investigate the performance benefits of MCN-MR networks, and to analyze the conditions under which such benefits can be obtained. In addition, the paper has also presented the first field trial results that validate the potential of MCN-MR networks, and demonstrate the important end-user QoS improvements that can be achieved with this emerging technology compared to traditional cellular systems. The authors are currently working on a large field trial campaign that will investigate the performance of MCN-MR networks under a large set of operating conditions and environments.

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