On the Capability of Multi-hop Cellular Networks with Mobile Relays to Improve Handover Performance

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Abstract—**Traditional single-hop cellular architectures fail to provision high and homogeneous quality of service (QoS) levels throughout a cell area. In addition, the performance and optimization of handover mechanisms poses significant challenges due to degraded channel conditions at the cell boundaries. In this context, multi-hop cellular networking technologies have been identified as an attractive solution to overcome traditional cellular limitations and improve the performance in handover areas. This paper discusses a novel handover process using multi-hop cellular networks with mobile relays (MCN-MR), and illustrates the benefits of this approach over traditional cellular handovers through field tests.**

Keywords-Multi-hop Cellular Networks; Mobile Relaying; Handover Management; Field Tests

I. INTRODUCTION

Cellular systems have significantly evolved over the past decades with the emergence of new and efficient radio access technologies, and the implementation of advanced techniques to support the increased network capacity and the high data rates demanded by novel applications. Despite considerable efforts made in the research community, the traditional single-hop cellular architecture fails offering high and homogeneous quality of service (QoS) levels throughout the cell area, mainly due to the strong signal attenuation with the increasing distance and the highly variable propagations conditions caused by the presence of obstacles and interferers. Such signal degradations result in that mobile users located at the cell boundaries, shadow regions or cell-overlaid areas, experience poor QoS levels. This problem could be partially overcome by augmenting the number of base stations (BSs), although economic and social deployment costs must be taken into account. A different alternative is offered by the integration of cellular and ad-hoc networking technologies into what is usually referred as multi-hop cellular networks (MCNs). MCN networks are capable of increasing and providing more homogeneous QoS levels by substituting a direct mobile station (MS)-BS link by multiple hops using either fixed relays (MCN-FR) or mobile relays (MCN-MR). MCN-MR networks are characterized 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' communications capabilities in a decentralized and distributed manner also increases the potential and future perspectives of MCN-MR networks.

Previous publications have already reported the multiple benefits and advantages that MCN-MR networks provide over traditional cellular architectures in terms of capacity enhancement, radio cell extension, lower infrastructure deployment cost, power saving and energy efficiency [1]. However, these studies have been based exclusively on analytical and simulation studies, and it is still necessary to validate the potential of multi-hop cellular networking through hardware testbed platforms and field trials. The first experimental demonstration of the MCN-MR potential to improve the end-user QoS and link quality when operating under NLOS conditions was presented by the authors in [2]. This paper extends this previous study by analyzing how MCN-MR networks can help address the challenging operational framework of cell-overlaid or handover areas. In this context, this paper introduces a novel handover process exploiting the capabilities offered through the ad-hoc and cellular integration in MCN-MR networks. In addition, the paper presents field test results that highlight the potential of MCN-MR networks to overcome the performance limitations of traditional cellular networks in handover areas.

II. HANDOVER MANAGEMENT IN CELLULAR NETWORKS

Handovers are generally executed to maintain link quality above a certain threshold, and enable active connections as mobile nodes move across neighboring BSs. To this aim, mobile terminals perform continuous measurements of the serving cell and the neighboring cells' signal quality, and report the results to the Radio Network Controller (RNC). Using the reported measurements, the RNC will then decide whether a handover is executed based on pre-established network policies. UMTS (Universal Mobile Telecommunications System) allows for both hard handover (HHO) and soft handover (SHO) mechanisms. In HHO, the connection with the serving BS is released before establishing a new connection with the target BS. On the other hand, SHO allows for mobile terminals to be simultaneously connected to the serving and target BSs.

High Speed Downlink Packet access (HSDPA) was introduced as an extension of UMTS to improve downlink throughput and QoS. HSDPA includes a number of enhancements, such as link adaptation or adaptive modulation and coding (AMC) and new physical layer retransmission mechanisms (Hybrid-ARQ). In addition, HSDPA locates its MAC layer (MAC-high speed, MAC-hs) in the BS rather than in the RNC as it is the case in UMTS. This enables faster packet scheduling and retransmission operation as the data to be transferred is buffered in the BS. However, locating the packet scheduler in the BS implies that multiple BSs cannot transmit simultaneously to a mobile terminal, and thereby HSDPA does not support SHO.

The first release of HSDPA (3GPP Release 5) only allows performing a handover between cells belonging to the mobile user's active set as shown in Figure 1. In the illustrated example, a mobile station (MS) is conducting a HSDPA file download through BS_1 (identified with scrambling code SCR_1). During the file download, the MS executes a number of measurements of the active cell (SCR_1) and the monitored cells (Figure 1 assumes that the monitored set only includes BS_2

identified with SCR_2). When BS_2's signal level increases, the MS sends a measurement report to the RNC through its serving BS indicating that BS_2 fulfills the criteria for being added to the active set (event 1A). Once this process is completed, the RNC sends the ACTIVE_SET_UPDATE message including BS_2 in the active set, and the MS acknowledges the receipt of this message by replying with the ACTIVE_SET_UPDATE_COMPLETE message. The active set process is completed with the establishment of the physical channel (PHY_CHANNEL_RECONF). Although BS_2 belongs now to the MS's active set, the file download is still conducted through BS_1. When the criteria to perform a handover are fulfilled, the RNC sends the RADIO_BEARER_RECONF message that contains the new configuration parameters for the radio bearer and the lower layers. The reconfiguration procedure, including the change of serving cell, is completed when the MS acknowledges the receipt of this message.

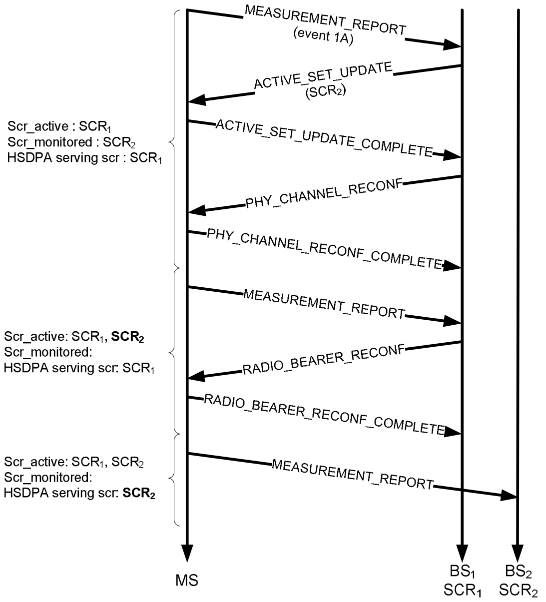

Figure 1. Messages exchanged in the HSDPA-release 5 handover process.

In 3GPP Release 6, the active set update procedure also allows carrying out a HSDPA serving cell change. However, to increase reliability, 3GPP Release 8 introduces the Enhanced Serving Cell Changed (ESCC) procedure [3]. In ESCC, mobile terminals receive the signaling message to change the HSDPA serving cell through the target cell. This has been done in order to exploit the stronger signal strength of the target cell, and thereby increase the reliability with which key signaling messages are exchanged. The communications between the mobile terminal and the target cell is possible thanks to the configuration information received by the mobile terminal during the active set update procedure.

Independently of which 3GPP release is being considered, the RNC decides whether a handover should be triggered or not based on the measurement reports sent by the mobile terminals; these reports contain the pilot channel (CPICH) strength of the active and monitored cells. It is important to note that handover algorithms are not specified in the standards, and are proprietary to each operator. However, a possible method to decide whether a handover procedure should be triggered is by comparing the CPICH strength of the active and monitored cells. In order to avoid frequent changes of serving cell, handover algorithms use a *hysteresis* (H) parameter that identifies the required CPICH power difference between the target cell and the serving cell that must be experienced in order to trigger a handover. In addition, the reliability of the handover procedure is enhanced through the *Time To Trigger* (TTT) parameter, which defines the uninterrupted period of time during which the target cell's CPICH strength has to fulfill the hysteresis condition to trigger the handover. The H and TTT parameters are critical factors to guarantee high performance and avoid frequent connection outages during the serving cell change procedure. If these parameters are not adequately optimized, the HSDPA throughput and user-perceived QoS may significantly decrease. In fact, previous studies have analyzed how to optimize HSDPA performance in cell overlaid areas. The work reported in [4] studies two different handover methodologies. The first one simply changes the HSDPA serving cell when entering the handover area (i.e. hard handover). On the other hand, the second method implies switching from HSDPA to UMTS when the mobile user moves into the handover area (active set size is larger than one), and then switching back again to HSDPA when the mobile user leaves the handover area. This method was proposed to exploit UMTS macro diversity capability during the handover procedure (i.e. soft handover). The results obtained in [4] indicate that switching to UMTS is not an optimum solution, whereas minimizing the handover area (using small H and TTT parameters) results in a higher data rate and a lower connection outage probability. However, the results reported in [5] show that very low values for H and TTT decrease the user-perceived QoS because of frequent handovers in the cell overlaid area. The studies conducted in [5] also demonstrate that the optimization of handover parameters is not easy, and that a trade-off exists between the H and TTT parameters based on the mobile user's speed.

III. HANDOVER MANAGEMENT IN MCN NETWORKS

The benefits of using MCN technology to enhance the handover procedure have been previously highlighted in the literature [6]. Multi-hop handover conditions and the necessary signaling messages are being defined in the baseline documents for standards such as 802.16j and LTE-Advanced [7]. The efforts focus initially on fixed relay solutions, and only a few studies have slightly addressed the handover issues from the mobile relay point of view [8-9]. In this context, this paper discusses a proposal on how to conduct handovers exploiting MCN-MR features. The proposal discussed in this paper concentrates on downlink transmissions, and thereby will be compared with the HSDPA handover management.

A. Handover Management using MCN-MR Networks

In a traditional HSDPA single-hop cellular network, the handover triggering decisions can be based on the measurement reports sent by the mobile user to the RNC. These reports contain the CPICH signal strength of the monitored and active cells. Based on these measurements, the RNC can dynamically compare the signal strength of the serving HSDPA BS and the potential BS candidates. Figure 2 shows an example of the monitored CPICH Ec/NO (energy per chip over the noise) parameter for an HSDPA serving BS (source cell), and the target BS (target cell) over which a handover is to be conducted. This example has been obtained during some field tests conducted using Orange's HSDPA network (implements 3GPP Release 5) at the city of Elche in Spain. The testbed and testing environments are described in Sections IV and V respectively. The pre-established network polices to decide the H and TTT values that trigger the handover process are not standardized, and the operator fixes them according to the characteristics of the cellular environment. In this case, the specific algorithm used by Orange to decide and execute handovers was not public. However, using the testing equipment described in Section IV, it has been possible to determine the moment at which Orange's handover algorithm decides to transfer the active connection from the HSDPA source cell to the target cell (depicted in Figure 2 with the vertical arrow ①). The employed network monitoring tool has also allowed measuring the time between the moments at which the target cell's CPICH Ec/NO is better than the one measured at the source cell and the handover is executed (TTT), and the CPICH Ec/NO difference (H) between the source cell and the target cell.

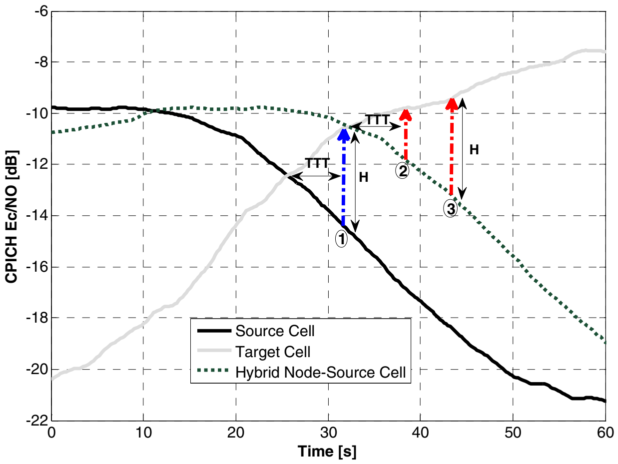

Figure 2. CPICH Ec/NO example.

Although the destination node is the end-point of the MCN-MR link, it is important to note that the cellular transmission in a MCN-MR connection is actually conducted through the hybrid node and not the destination node. In addition, taking into account that the cellular link represents the QoS bottleneck in a MCN-MR connection [2], the quality experienced at the hybrid node can be extended to the destination node through the MCN-MR link. In this context, an unresolved question is how and when to launch a cellular handover process in MCN-MR transmissions. If such process was to be launched based on the (single-hop) cellular link quality experienced at the destination node, the handover of the MCN-MR connection will take place at the same distance to the BS as the handover in traditional single-hop cellular networks. On the other hand, this paper proposes to execute MCN-MR handovers (that is changing the serving cellular BS in a MCN-MR link) at the RNC based on the comparison of the destination node's cellular signal quality with the target BS, and the hybrid node's cellular signal quality with the serving BS. Although the cellular transmission in a MCN-MR connection is conducted through the hybrid node, the destination node also sends periodically its measurements reports to the BS. As a result, the RNC can execute the proposed MCN-MR handover process by comparing the signal quality for the link destination node/target BS and the link hybrid node/source BS. Using the example reported in Figure 2, where the dotted line represents the hybrid node's CPICH Ec/NO cellular quality with the serving/source BS, and the inferred H and TTT parameters from the traditional cellular handover between the source and target cells, it is then possible to identify the times at which the MCN-MR handover process would be executed following this paper's proposal. The vertical arrow ② represents the time at which the MCN-MR handover would be conducted if the handover was based on the TTT parameter. If the handover was based on the measured H parameter, vertical arrow ③ would represent the time at which the MCN-MR handover would be executed. It is important to note that in both cases, the MCN-MR handover will significantly improve the end-user QoS, since the destination node not only leaves the source cell with a higher signal strength than in a traditional single-hop cellular architecture, but it also perceives a stronger signal when it connects to the target cell. The impact of this MCN-MR handover process in the user QoS (estimated by means of the throughput) will be illustrated in Section V through field test measurements.

IV. MCN-MR TESTBED

The field tests have been carried out using the unique MCN-MR research platform developed at the Uwicore laboratory of the University Miguel Hernandez of Elche. The potential of this platform to carry out advanced MCN-MR field test studies has been already reported in [2], where the capability of MCN-MR networks to improve the direct cellular link performance when operating under NLOS conditions was demonstrated. The MCN-MR research testbed integrates three different types of mobile nodes (MN) with different communication capabilities: cellular MS (HSDPA), ad-hoc MN (802.11 a/b/g/n) and hybrid MN (HSDPA and 802.11 a/b/g/n).

1) Cellular Mobile Station

The cellular MS is a Nokia 6720 handset that supports UMTS/HSDPA. The terminal incorporates the Nemo Handy application, which is designed for conducting thorough and advanced measurements on the wireless interface. To this end, Nemo Handy provides extensive network parameters and measurement data captured over voice and video calls, FTP/HTTP data transfers, etc. 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 QoS in the MCN-MR testbed. In addition to its real-time monitoring capabilities, Nemo Handy also offers the possibility to store all the network parameters monitored by the mobile handset for post-processing. Another important feature of Nemo Handy is the possibility to lock the cellular MS to a specific radio access technology and BS. This feature has been important to provide a stable testing environment to compare cellular and MCN-MR transmissions. The Nemo Handy application also allows tracking the MS position and geo-referencing all the performance measurements through an external GPS connected via Bluetooth.

2) Ad-hoc Mobile Node

The ad-hoc MNs can act as relay or final destination nodes in MCN-MR links. These nodes have currently been implemented using conventional laptops under Linux in order to be able to configure parameters of the physical and MAC layers. Built-in wireless interfaces in laptops are not generally capable of operating in ad-hoc mode under Linux. To overcome this limitation, the ad-hoc MNs have been equipped with an additional wireless interface (Ubiquiti SR71X).

The implemented MCN-MR testbed uses the Compat-Wireless and iw packages to configure the wireless devices (channel, transmission power, rate, etc.). The iw package is used to configure the added wireless interface in ad-hoc mode, and to create virtual wireless interfaces. On the other hand, the built-in wireless interface is configured in monitor mode. Linux also provides open source libraries such as libpcap and libgps that have been used to develop a sniffing and a GPS application, respectively. The implemented sniffing application allows to continuously monitor the performance of the ad-hoc 802.11 links (timestamp, RSSI, packet size, data rate, channel, sequence number, etc), whereas the GPS application collects the time, latitude and longitude with a refresh periodicity of 1Hz that allows continuously tracing the position of the MNs and geo-referencing all the logged radio measurements.

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. The hybrid node is implemented in a standard laptop using the Nokia 6720c terminal as modem to provide an HSDPA cellular link, while using 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. The hybrid nodes incorporate two GPS receivers for the cellular and wireless interfaces. Finally, the hybrid nodes also include the software monitoring tools described for the cellular MS and ad-hoc MN.

V. Field Tests

Based on the proposed MCN-MR handover process, this section illustrates through field test measurements the potential of MCN-MR networks to improve the QoS in handover areas compared to traditional single-hop cellular networks.

A. Testing Environment

The field tests have been conducted in the city of Elche (Spain) using Orange's live network. Figure 3 illustrates the location of the serving BS and the target BS, and the initial position of the hybrid MN (H-MN) and the destination MN (D-MN). The field tests described in this section have been conducted to investigate the potential of MCN-MR networks to improve the cellular link quality, and thereby the end-user QoS, when operating in a handover (HO) area. To this aim, the performance of a traditional HSDPA cellular link in the HO area will be compared to that achieved with a MCN-MR link.

The performance of the HSDPA cellular and MCN-MR links has been measured downloading long-size files from a FTP server managed and located at the Uwicore Laboratory. The FTP server configuration allows an unlimited number of users, and has no limit in the download speed. The file download through the MCN-MR link requires that the H-MN and the D-MN execute a script that enable the HSDPA connection from the H-MN to the serving BS (L_1 in Figure 3), and the establishment of the ad-hoc network between the H-MN and the D-MN (mH_1 in Figure 3). The script launched by the D-MN also initializes the file download. The MCN-MR link requires that the H-MN transforms the transport blocks received through the HSDPA cellular link to 802.11 packet data units (MAC PDU). The MAC PDU size has been set to 1564 bytes. As a result, the H-MN stores the cellular transport blocks in a buffer until an 802.11 MAC PDU is filled. This is due to the fact that HSDPA implements adaptive modulation and coding (AMC) techniques that dynamically modify the transmission mode, and therefore the transport block size based on the experienced channel quality conditions. As a result, several HSDPA transport blocks might be needed to fill an 802.11 MAC PDU. Once the 802.11 packet is formed, the H-MN transmits the MAC PDU to the D-MN through an ad-hoc 802.11 link. The MNs communicate with each other using the IEEE 802.11g technology at 2.4 GHz, which provides a theoretical maximum bit rate of 54 Mbps and a maximum transmit power of 27 dBm. The data rate and the transmission power at which the nodes operate are controlled by the network driver (Ath9k) through adaptive mechanisms. In these tests, the transmission power of the MNs has been limited to a maximum of 19 dBm.

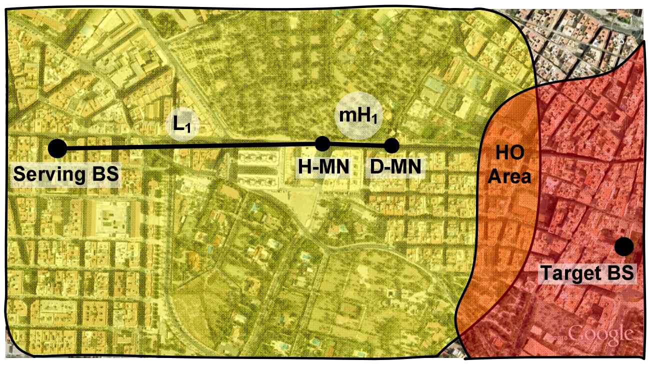

Figure 3. Field testing environment.

B. Field Test Results

The HSDPA performance strongly depends on the implemented radio resource management algorithms. HSDPA adapts its operation to the link quality through the use of mechanisms such as AMC and Hybrid-ARQ. These mechanisms require the mobile terminal to transmit estimates of the experienced channel quality conditions in the uplink direction; the channel quality is measured in HSDPA through the CQI (Channel Quality Indicator) parameter. Based on such estimates, the BS will modify its transmission parameters to ensure a certain QoS target. In this context, it is important to note that the lower the channel quality, the higher the number of resources needed to achieve a QoS target.

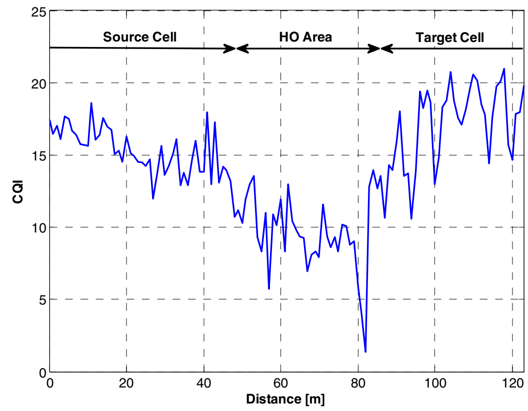

Figure 4. Measured CQI for the HSDPA cellular link.

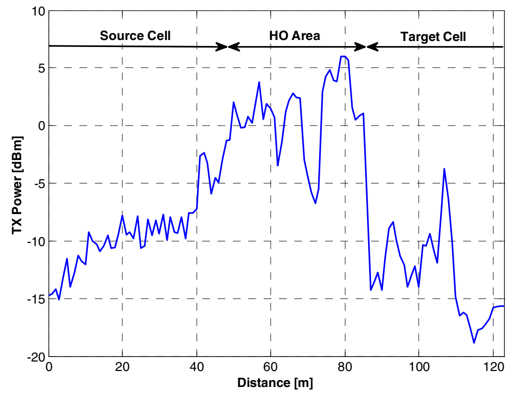

Figure 5. MS transmission power for the HSDPA cellular link.

Figure 4 represents the CQI measurements obtained in the testing environment represented in Figure 3. As expected, the channel quality significantly degrades in the HO area, which thereby requires a significant increase of the mobile terminal's transmission power (*TX Power*) in order to communicate with the BS and send its CQI reports (Figure 5). HSDPA's link adaptation mechanisms aim at maintaining a Block Error Rate between 10% and 20% [10]. Based on the uplink CQI reports (Figure 4), the HSDPA BS adjusts the transmission power and transmission mode (modulation, transport block size and number of parallel codes) to guarantee that the downlink performance is within the target limits. Figure 6 shows that the link adaptation algorithm implemented in Orange's network is able to achieve the BLER target outside the HO area. On the other hand, the worse propagation conditions and higher interference levels experienced in the HO area difficult the adaptation of the transmission parameters and results in higher BLER values. As a consequence of the low channel quality conditions (Figure 4) and the resulting high BLER (Figure 6), the HSDPA throughput significantly degrades in the HO area (Figure 7).

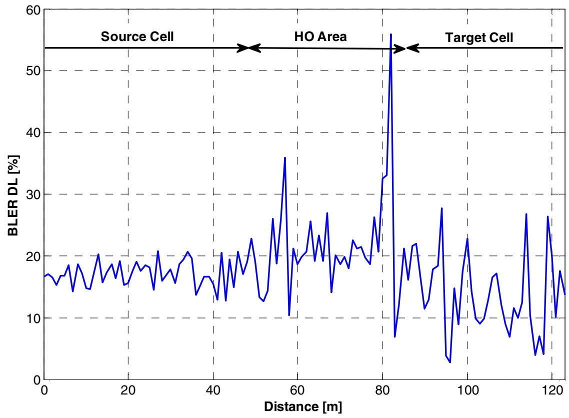

Figure 6. BLER for the HSDPA cellular link.

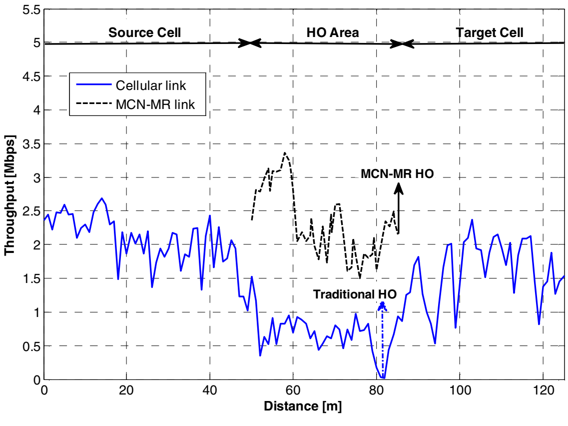

Figure 7. Throughput for the HSDPA cellular link and the MCN-MR link.

Figure 7 also shows the measured MCN-MR throughput at the D-MN when the D-MN traverses the HO area. It is important to note that the D-MN is connected to the serving BS through the H-MN, and that the distance between the D-MN and H-MN was selected so that the H-MN does not enter the HO area during the test. This results in that the MCN-MR connection is capable of guaranteeing to the D-MN the same quality in the HO area as experienced by the H-MN outside the HO. Based on the throughput measurements reported in Figure 7, the adoption of the MCN-MR handover strategy discussed in Section 3.A would then result in that the MCN-MR user is capable of guaranteeing a high throughput performance even in the HO area (MCN-MR link). In fact, the MCN-MR handover will not be triggered until the H-MN node reaches the HO area. If the distance between the H-MN and D-MN is adequately selected, the MCN-MR handover would then be triggered when the D-MN has left the HO area and entered the target cell area, which would again guarantee a high throughput level when the handover is executed. Figure 7 also depicts the moments at which handovers would be executed in a traditional single-hop cellular system, and the deployed MCN-MR solution. The results show that the destination node in the MCN-MR link connects to the target BS at a closer distance, and therefore with higher signal strength as previously illustrated in Figure 2.

VI. CONCLUSIONS

Multi-hop cellular networking has been proposed to overcome certain limitations of traditional cellular architectures by integrating and combining the benefits of cellular and ad-hoc technologies. In particular, MCN technologies have been identified as a potential solution to overcome the traditional cellular performance degradation in handover areas. In this context, this paper has proposed a novel handover mechanism for MCN-MR networks, and has illustrated through field tests, the end-user QoS benefits of MCN-MR systems over traditional single-hop cellular technologies in handover areas.

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REFERENCES

[1] R. Pabst, et al., "Relay-based Deployment Concepts for Wireless and Mobile Broadband Radio", *IEEE Communications Magazine, vol.42, no.9, pp. 80- 89*, September 2004.

[2] J. Muñoz, B. Coll-Perales and J.Gozalvez, "Research Testbed for Field Testing of Multi-Hop Cellular Networks using Mobile Relays", *Proceedings of the 35th IEEE Conference on Local Computer Networks (LCN)*, October 2010.

[3] S. Mohan, R. Kapoor and B. Mohanty, "Enhanced HSDPA Mobility Performance: Quality and Robustness for Voice over HSPA Service", *Proceedings of the 71st IEEE Vehicular Technology Conference (VTC 2010-Spring)*, May 2010.

[4] K. Pedersen, A. Toskala, and P. Mogensen, "Mobility Management and Capacity Analysis for High Speed Downlink Packet Access in WCDMA", *Proceedings of the 60th IEEE Vehicular Technology Conference (VTC2004-Fall)*, September 2004.

[5] L. Seunghyun, et al., "Optimization of the HSDPA Network in the Cell-Overlaid Area", *Proceedings of the 10th IEEE International Conference on Communication Systems (ICCS)*, October 2006.

[6] C. Sunghyun, et al., "Handover in Multihop Cellular Networks", *IEEE Communications Magazine, vol.47, no.7, pp.64-73*, July 2009.

[7] K. Ronny, J. Inuk, Y. Xiangying and C. Chao-Chin, "Advanced Handover Schemes in IMT-Advanced Systems [WiMAX/LTE Update]", *IEEE Communications Magazine, vol.48, no.8, pp.78-85*, August 2010.

[8] M. Ghassemian, V. Friderikos and H. Aghvami, ,"Hybrid Handover in Multihop Radio Access Networks", *Proceedings of the 61st IEEE Vehicular Technology Conference (VTC 2005-Spring)*, May 2005.

[9] H. Nourizadeh, S. Nourizadeh and R. Tafazolli, "Impact of the Inter-Relay Handoff on the Relaying System Performance", *Proceedings of the 64th IEEE Vehicular Technology Conference (VTC-2006 Fall)*, September 2006.

[10] H. Holma and A. Toskala, "WCDMA for UMTS: HSPA Evolution and LTE", *Ed. John Wiley and Sons*, 2010.