

An Integrated Multi-layer Approach for Seamless Soft Handoff in Mobile Ad Hoc Networks

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Abstract—The handoff problem in ad hoc networks needs to be treated through an integrated multi-layer approach, due to its major differences with respect to the counterpart in infrastructure-based networks. In this paper, an integrated framework through the cross layer approach is presented to deal with the handoff problem in heterogeneous wireless networks with multiple interfaces. Further, extensive study has been conducted to evaluate our proposed handoff solution through simulation, emulation with real wireless hardware in the loop, and hardware tests using commercial-off-the-shelf Android phones and GSM base station systems. It has been shown through our study that transparent user application can be achieved using our handoff approach with low latency, minimum packet losses and only necessary control overhead.

Index Terms—seamless handoff; MANET; cross layer design; wireless heterogeneity; cellular network

I INTRODUCTION

The last decade witnessed the proliferation of new wireless technologies providing global information access to users on the move. With such wireless diversity, the fundamental goal of network solutions is to make the existence of heterogeneous networks transparent: users should perceive the system as an integrated connectivity rather than a collection of separate links. This implies handling the dynamics (common in most wireless environments) seamlessly, and continuously offering the best service without disruptions. Thus, an efficient handoff¹ solution with low latency and low packet loss is needed for mobile users.

¹ In this paper, we use the terms handoff and handover interchangeably.

Traditionally, the handoff problem is considered only for the infrastructure based networks where the decision process largely depends on the one-hop performance between the end-host and the infrastructure (e.g., signal strength between the base stations and the mobile device). However, in infrastructure-less wireless environment, where packets travel multiple hops to reach destination, the handoff process should be carefully revisited.

First, the overall connectivity of a mobile ad hoc network (MANET) depends strictly on the set of active wireless interfaces throughout network at any given time. Hence, in an ad hoc setting, link activation decisions taken in an isolated way can result in adverse affects on the overall network connectivity, such as causing network to be disconnected for an extended period of time. Moreover, from a higher layer perspective what matters the most is the end-to-end performance (e.g., available bandwidth, latency, reliability, etc.). All the above imply that the handoff problem in MANETs is fundamentally different than the traditional handoff problem. It is possible to address these key differences successfully through a multi-layer solution that adds the higher-layers of the protocol stack (with the end-to-end view) into the handoff equation.

In [1], we first proposed an integrated multi-layer architecture that captures all the necessary tasks at different layers, and then showed that our handoff scheme can provide practically the equivalent results as the benchmark with no handoff. In [2], we extended our visions in two aspects. First, we distinguished the actual link handovers with session handovers. A topology control scheme is used for multi-interface networks to ensure network connectivity, while an independent session handover process is provided to effectively manage the ongoing connections over the available set of active interfaces. Second, we provided a mobility

management process that maintains ongoing connections before and after a handoff event. This process effectively distinguishes the “identities” of nodes from their addresses and ensures that each node is continuously reachable and discoverable throughout a connection.

In this paper, we continue our work for detailed design and extensive study of our handoff solution in several network setups/scenarios. We first refine the architecture design of our multi-layer handoff solution. We then conduct extensive simulation study in a single-interface ad hoc WiFi network to showcase how to leverage the IEEE 802.21 Media Independent Handover (MIH) framework [3] in our handoff solution.

Moreover, to further evaluate the integrated handoff solution, we establish a network setup that consists of both ad hoc WiFi and infrastructure-based cellular networks (mobile WiMAX [4] or GSM technologies) to demonstrate the validity of our solution in a dual-interface heterogeneous wireless environment. Our integrated handoff solution is extensively investigated through simulation, emulation with real Wireless Hardware (i.e., real WiFi cards) In the Loop (WHIL), as well as pure hardware experiments using Android phones and cellular base station systems. It has been shown that transparent user application can be achieved using our handoff approach with low latency, minimum packet losses and only necessary control overhead.

The rest of this paper is organized as follows. Section II provides a brief overview of our handoff solution [1][2]. Section III presents simulation study of our solution in a single-interface WiFi MANET. Section IV and V show our study in the WiFi-cellular networks, through simulation, WHIL emulation and pure hardware experiments. Finally Section VI concludes the paper.

II MULTI-LAYER APPROACH FOR SEAMLESS HANDOFF

Figure 1 shows the proposed multi-layer architecture, which allows a mobile user to roam among multiple homogeneous and heterogeneous wireless networks in a manner that is completely transparent to applications and that disrupts connectivity as little as possible. The key innovations of this architecture lie in the introduction of various managers that reside at different layers, which collectively and cooperatively render consistent solutions to the seamless handoff problem.

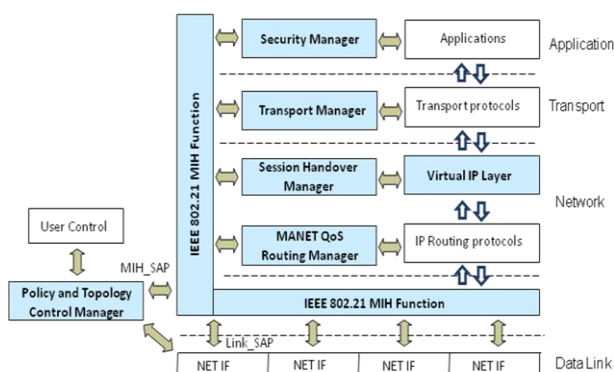


Figure 1. A multi-layer architecture for seamless handoff.

The architecture leverages the IEEE 802.21 MIH standard to facilitate handover related decisions on multiple layers of the protocol stack by providing information and event services. The IEEE 802.21 standard is originally designed for infrastructure based networks and does not consider MANETs. In this effort we have provided several enhancements to the original standard that allows it to support soft handoff in ad hoc networks.

The virtual IP layer introduced between the transport and network layers provides another indirection that allows mapping between a unique node identity that is used to create connections at the transport layer and the multiple IP addresses that the node may have over time. It is the source and destination nodes that are responsible for updating the information at their virtual IP layer. This indirection allows us to keep connections alive while allowing the node to change IP addresses as needed.

The Policy and Topology Control manager is responsible for the actual link handover events. By taking into account active mission policies and the information regarding the status of the wireless interfaces provided by the MIH function (MIHF), the topology control manager dynamically activates/deactivates the wireless interfaces to ensure the network is well connected.

The addressing scheme is based on IP addressing, while the packet forwarding strategy is based on ad hoc routing. Such IP-centric architecture can accommodate essentially any ad hoc routing protocols, once the session handover manager chooses the appropriate interface for each ongoing flow. In addition, the MANET Quality-of-Service (QoS) routing manager addresses the QoS issues.

While our scheme provides link transparency from viewpoint of connection management, after the handoff, traffic senders need to be aware of the handoff events and adapt their service rate based on the new network conditions. These adaptations, handled by Transport Manager, will enable better services, and will lead to more efficient network resource utilization.

Finally, security is a critical design aspect for our multi-layer protocol that provides cryptographic security services, including message encryption for data privacy, message authentication for data integrity, and identity authentication for network membership verification.

A. Link vs. Session Handover

The handoff process generally involves three steps: (i) turning on a new interface and association/authentication with the new network, (ii) switching the active flows from the old interface over the newly activated interface, and (iii) turning off the old interface. While the link activation/deactivation decisions (i.e., steps (i) and (iii)) are called as *link handover*, selection of the appropriate interface for each ongoing flow based on the flow requirements and the current end-to-end performances of the active interfaces (i.e. step (ii)) is called as *session handover*. In infrastructure-based networks, all of the aforementioned steps can be successfully performed by wireless devices separately based only on the local observations. However, this is not the case for MANETs.

First of all, in infrastructure networks activating a new interface immediately provides new connectivity as long as an access point (AP) or base station (BS) is within the communication range. On the other hand, in MANETs, a node activating a new interface does not necessarily obtain an alternative connectivity unless there are other nodes that are also currently using this interface in the vicinity. Therefore, interface activation decisions cannot be taken individually but rather requires nodes' cooperation and coordination. This can be illustrated by a simple example.

In Figure 2, we present a MANET network, where each node in the network has dual ad hoc interfaces. Each node is represented with either a blue circle or a red square indicating the active interface on the node. For example, node N5 is having only the "red" interface active, while node N4 have both red and blue interfaces active simultaneously. It can be observed that node N4 serves as the "bridge" between the "red MANET" and the "blue MANET" in this example. Let us assume that node N4 was initially having two connections: one to node N7 in the red-network and another to node N9 on the blue network. Assuming handoff decisions are taken locally in a selfish manner, node N4 would prefer to turn off one of the active interfaces to preserve energy as soon as one of the ongoing connections is terminated. However, this will clearly lead to two isolated MANET networks, because N4 is currently the only gateway between the two MANETs. Hence, unless MANET nodes collaborate and take decisions in a joint manner, a local handoff decision can potentially lead to significant adverse effects on several other nodes in the domain.

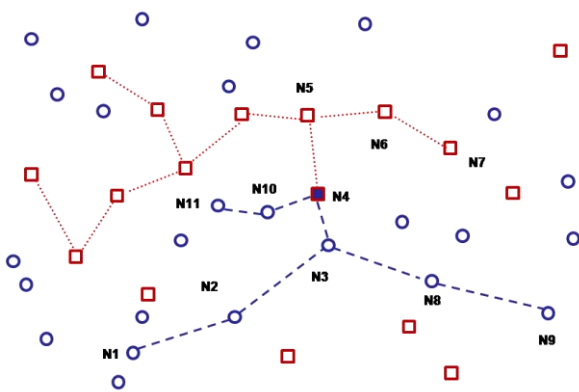


Figure 2. MANET with dual interfaces.

Further, consider another scenario where node N4 is moving southward. As N4 moves further away from node N5, the red connection between these two nodes may eventually break as N4 gets out of range of N5. After this point, N4 may naturally turn-off its red interface to preserve energy as it cannot find any red neighbor to connect to. Again, as in the previous scenario, the two networks become disconnected and any connection between them will fail unless a new node takes over the gateway responsibility (e.g., node N11). It is clear from this example that in ad hoc networks handoff decisions cannot be made locally in a selfish manner and are intricately related with topology control process.

Moreover, in infrastructure networks most of the decision parameters related to session handover are about the quality of the one hop link between the node and the infrastructure. This is validated by the assumption that access points have ample connectivity. However, in mobile ad hoc networks since there are no such privileged nodes, the decision of session handover will have to be given based on the overall multi-hop path quality as opposed to the quality of single hop links.

In summary, it is clear that an effective handover process in mobile ad-hoc networks should consist of two parallel processes: (a) Topology control, and (b) Session Handover. A network-wide topology control process should manage the activation of interfaces throughout the network to maintain the overall network connectivity, while the session handover process make decisions regarding how to forward traffic flows on currently active interfaces. Further the session handover process interacts with the topology control process in the case that the currently active interfaces do not support the traffic load. Taking these requests into account, the topology control process may decide to activate not only an interface of the requesting node but also on several other nodes as needed to match the QoS requirements of the ongoing traffic. It is worth noting that the session handoff decisions do not involve activating or deactivating interfaces but rather select on which interface to send traffic. This guarantees that the local session handover decisions do not cause adverse effects on the connectivity of other nodes in the domain.

B. Session Handover Process

Session handover is responsible for selecting the appropriate interface for each ongoing flow and does not involve link activation decisions. The cause of session handover can be due to local link changes or changes elsewhere in the network. The decisions are guided by the information provided by IEEE 802.21 MIHF. Note that the session handover is a local decision on whether to change the interface where a flow is sent or received.

When switching flows from one interface to another it is critical to ensure that the actual packet delivery can achieve soft handoff with minimum latency and packet losses, since one of the goals in our handoff system is to support multimedia communication across multiple network interfaces. It is well-known that packet losses during handoff have detrimental effects on reliable transport protocols such as TCP. With this in mind, as an option, provisional handoff may be supported for some period of time during which session handover manager simultaneously monitors the quality of both the original and the newly selected wireless interfaces, before leaving the original interface and sending packets via the newly selected interface. In this optional provisional handoff, as shown in Figure 3, duplicate packets are filtered out at the network layer of the receiving node by keeping a small cache of received IP headers and filtering out received packets for which identical packets are already in the cache. The difference in arrival time between the packets from two interfaces must be treated to ensure the QoS. To end provisional handoff, the receiving node can signal the

upstream node that it receives stable packet flows from the new interface.

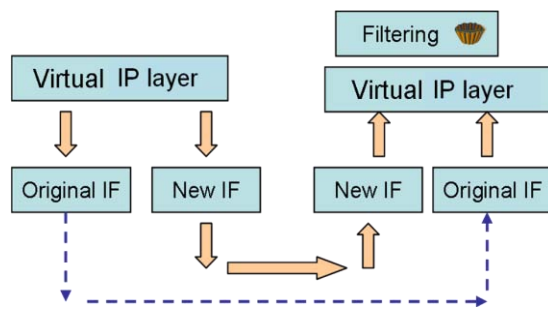


Figure 3. Provisional handoff (optional mode).

Finally we would like to remark on the implications of the session handover process over routing decisions. First of all, conceptually, routing algorithms are responsible for forwarding decisions which in turn decide the interfaces on which packets are sent through. From this perspective, routing and session handover decisions are tightly related. On a high level, one can argue that a QoS based routing scheme can make the session handover decisions obsolete. However, on the practical side, in many existing networks the routing algorithms are predefined and fixed. For instance, it is possible that the network is running the AODV algorithm on one interface and OLSR on the other. In this case, there is still a decision to be made on a node that has multiple interfaces active: which routing algorithm (and hence link interface) should each session use? This is in fact exactly the decision made by the session handover manager. Hence, in scenarios where routing algorithm is given and is not a part of the decision process, the overall handover process can be seen as topology control at the slowest timescale, session handoff process and routing at a faster timescale.

C. Virtual IP Layer

The transport layer connections are established using the source IP address, source port, destination IP address and destination port. As a result, when either the source or destination goes through an IP address change after a handoff process, the connections break and are aborted. In traditional infrastructure based networks, Mobile IP based solutions try to deal with this problem via foreign address/home address combinations. However, in our work there is not always infrastructure available to guide mobile nodes about address changes. Therefore, a new approach is needed to tackle the addressing problem in order to keep the ongoing connections alive. That is where the virtual IP layer solution comes into the picture. In this approach every node has a uniquely assigned virtual IP address that is used by the upper layer protocols (e.g. Transport layer). The virtual IP addresses are fixed; there is a static one-to-one mapping from domain names and virtual IP addresses. Through this way, the upper layer protocols are kept transparent from any IP address change due to handoff decisions or any other reasons that might cause an IP address update. This approach has similarities with the Host Identity Protocol [5].

Below the IP layer there is no indirection; wireless interfaces obtain actual IP addresses, IP tables are created accordingly, and routing is performed as usual based on actual IP addresses. Hence the routing is not done based on virtual IP addresses. Further, at any intermediate node, i.e., for packets that are not destined to the node receiving the packet, packets do not reach the virtual IP layer; these packets are forwarded in the traditional way at the default IP layer. Hence, since routing is performed based on actual IP addresses, any intermediate node en route will not need an update regarding an ongoing handoff. It is the source and destination nodes of a connection that are responsible for updating the information at their virtual IP layer to reach each other by learning the new actual IP addresses that they can be reached.

To achieve successful and efficient mapping of current and virtual IP addresses, the following approach is used. Any upper layer protocol trying to access another node in the network consults a local or remote static table for domain name-to-virtual IP translation. This is a table that can either be loaded in the nodes or can be located at DNS-like servers. However, due to the fact that the mapping is static, nodes can learn and store the name-to-virtual IP mappings and eventually would not need to consult the servers for this mapping.

The TCP/UDP sockets are established with virtual IP addresses. Hence, any handoff operation is transparent to the upper layer protocols. When transport layer protocols have any data to send, they forward it to the virtual IP layer. It is the virtual IP layer who is responsible of monitoring and transforming virtual IP addresses to actual IP addresses. The dynamic mapping from virtual IP to actual IP can be seen analogous to the dynamic DNS mappings.

The critical issue here is to have accurate mappings between the virtual and actual IP addresses, especially when a node is performing a handoff during an active connection. When a node makes the decision of handoff, before switching the active interface, it notifies the other end of the active connection regarding this handoff. Note that using link layer notifications such as 802.21 Link Going Down primitive, it is possible for the node to have enough time to notify the connections regarding an imminent handoff. For successful seamless handoff, the moving node has to provide the peer endpoint with the new IP address that it will have.

There are several ways to provide the moving node a new IP address before it actually performs the handoff. One approach is to make use of a dynamic DNS like structure. In this approach, nodes are allocated a non-overlapping set of IP addresses for each interface during the initial network setup. This way the node may already have an IP address pool related to the new interface, and hence uses one of the available IP addresses. Otherwise, it can proactively contact a representative DHCP-like server or simply a neighbor in the new domain that might have a free IP address in its IP pool, in order to get a new IP prior to the handoff event for the new interface.

Alternatively, the node can also contact the DHCP server of the new domain using its active interface

(before the handoff) to periodically obtain an IP address. The obtained IP address can be valid for a limited period of time as a soft state unless the node actually performs the handoff and notifies the DHCP server through the new interface (after the handoff). As it can be seen, there are several ways of obtaining a new IP address for the new link interface before a handoff is actually performed. This will help enhance the overall handoff performance for the active connections.

It is important to note that the IP routing layer and hence the intermediate nodes along the path do not have to be notified immediately regarding this change in the mapping since they do not use the virtual IP addresses for forwarding purposes.

III. HANDOFF IN A SINGLE-INTERFACE WiFi MANET

In this section, we conduct a simulation study using a single-interface ad hoc WiFi network to showcase how to leverage the IEEE 802.21 MIH framework for handoffs in a MANET. The OLSR [6], a popular ad hoc routing protocol, is selected to be integrated with the MIH as an MIH user. A novel approach, *MIH-Hello-TC*, is proposed to improve the handoff performance using the capabilities of MIH Function (MIHF). The conventional OLSR is considered as the comparison baseline.

A. Introduction

In ad hoc networks, out-of-date paths may remain for certain duration at some nodes, in that most ad hoc routing protocols are not promptly responsive to the node mobility. Consequently there will be service degradation (such as packet losses and disruption time) during the transition period from the old route to the new one.

To mitigate this problem, a cross-layer framework for MIH is needed to better support handoff in MANETs. Particularly, the OLSR, a table-driven proactive protocol using the concept of multipoint relay, is considered in our study. In OLSR, the overhead depends on the Hello interval and TC interval (i.e., topology control interval, typically longer than Hello interval). The shorter the Hello interval is, the faster the link sensing takes place but with more overhead.

B. MIH Implementation in Ad Hoc Networks

NIST ns-2 models of the MIH [7] were originally designed for the infrastructure mode, where a mobile node can detect its access point(s) (AP) through APs' periodic beacon messages. Based on the receiving power level of beacons, the MIHF at the mobile node can help to make a suitable handoff decision. In MANETs, however, there are no APs. Thus we enhanced the NIST ns-2 models of the MIH to support the ad hoc mode.

We also modified the ns-2 OLSR model [8], and integrated it with the MIH in the ad hoc mode. Figure 4 illustrates our implementation, where the MIHF in an ad-hoc node interacts with both the MIH user (i.e., OLSR) at the upper layer and the 802.11 MAC/PHY layers. An interface is provided between the MIHF and OLSR, through which the MIHF provides the OLSR a trigger that contains an MIH event and the IP address of the

affected neighbor. Upon receiving the trigger, the OLSR can identify the MIH event and the affected link, and then take the handoff action accordingly.

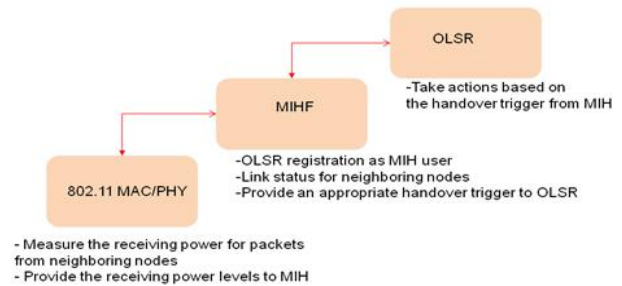


Figure 4. Implementation of MIHF support for OLSR.

In our implementation, the MIHF at each node detects new links and maintains the link status with respect to its neighboring nodes, by measuring the received (data and control) packets. In the ns-2 radio propagation models, the received signal power is estimated based on the PHY layer parameters. The estimation is then passed to the MIHF (e.g., via Link_SAP [3]) along with the sender's address (MAC and/or IP address). The MIHF may trigger a handoff for the OLSR if the received signal power is less than the predefined power level P_T (e.g., 95% of the received power threshold [7]).

For the links without data packets, this mechanism relies solely on control messages (Hello and TC) whose intervals are typically in seconds, and hence cannot obtain their link status in a real time manner. A possible solution is to introduce a short, fast-paced and dedicated signaling for link status at each node, which however will incur a substantial amount of overhead, especially in dense networks.

C. Routing Behavior in the Conventional OLSR

Figure 5 shows the considered scenario, where the source n5 sends packets to the destination n0 which is moving from n1 to n2. Initially n0 is within the coverage of n1 only. Through the exchange of Hello and TC-messages, n5 recognizes that n0 and n1 are 1-hop neighbors. The data packets from n5 are delivered to n0 in a route n5-n3-n1-n0.

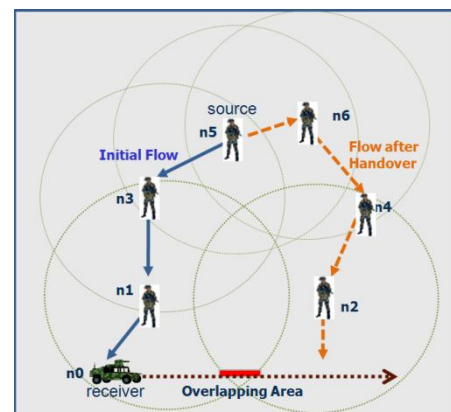


Figure 5. Mobility scenario in the OLSR ad hoc network.

Once n_0 moves into the coverage of n_2 only, the old route breaks and a new one (n_5 - n_6 - n_4 - n_2 - n_0) needs to be established. This routing convergence process takes some time. First through the exchanged Hello messages a new link is established between n_0 and n_2 , which triggers involved nodes to accordingly update their information base. Particularly, a TC-message from n_2 is flooded over the network through the old/new MPRs. At some point, n_5 receives this TC-message from n_2 and knows the existence of n_0 - n_2 link. However, n_5 does not delete its stored (old) TC information related to the link n_0 - n_1 . Instead, n_5 keeps both old and new TC information from n_1 and n_2 , respectively, as if n_0 is connected to both n_1 and n_2 simultaneously. This then leads to the (incorrect) selection of n_5 - n_3 - n_1 - n_0 (the old route) at n_5 during the routing calculation.

Such an incorrect route causes packet losses until n_5 receives from n_1 an updated TC-message advertising that n_0 is no longer connected to n_1 , which is generated only when n_1 confirms the break of n_0 - n_1 link (i.e., after a neighbor holding time).

D. MIH-Hello-TC Approach

It is highly beneficial to leverage the existing OLSR control messages to implement an interface between the OLSR and MIH agents (modules). So we propose an MIH-enabled approach, called *MIH-Hello-TC* approach, where the OLSR is triggered to invoke extra Hello messages and TC-messages by different MIH events.

In the *MIH-Hello-TC* approach, the MIH agent (at a node) generates a trigger to the OLSR agent to invoke the repeated Hello messages once detecting a *Link_Detected* event (i.e., a new link). For example, in the scenario shown in Figure 5, when the MIH agent at n_0 (n_2) detects that the receiving power level of packets sent by n_2 (n_0) is greater than a predefined constant P_{LD} , it triggers its OLSR agent to invoke extra Hello messages. Due to the required handshaking in the Hello messages, the extra Hello messages are broadcast more frequently than regular ones (e.g., 5 times per second) in a short time period (e.g., 2 seconds).

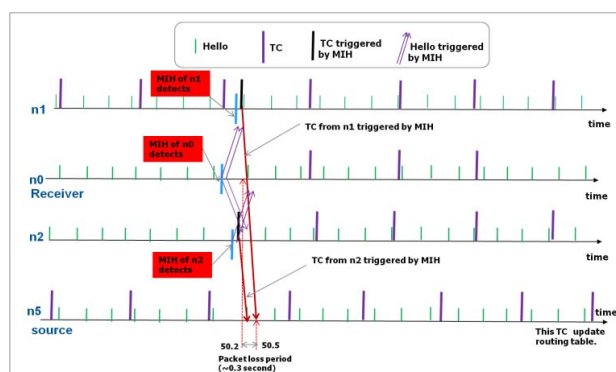


Figure 6. Route convergence of MIH-Hello-TC approach.

In addition, once detecting a *Link_Going_Down* event, the MIH agent (at a node) triggers the OLSR to remove the corresponding old link, and at the same time invoke an update TC-message. In Figure 5, when it is detected at n_0 (n_1) that the receiving power level of packets sent by

n_1 (n_0) is less than a pre-defined constant P_{LGD} , a *Link_Going_Down* event occurs. Once detecting this event, the MIH agent at n_1 (or n_0) triggers the OLSR to remove the n_0 - n_1 link, and at the same time invokes an update TC-message to reflect this removal. Figure 6 illustrates the above process.

E. Performance Evaluation

We conduct simulation study for the scenario shown in Figure 5, to evaluate the performance of the *MIH-Hello-TC* approach under different Hello intervals, in terms of service disruption time, number of packet losses, and control overhead. Table 1 shows operational parameters in our simulation.

TABLE 1.
OPERATIONAL PARAMETERS IN SIMULATION

Parameters	Values
Simulation duration	100 seconds
TC interval	3 seconds
Neighbor holding time	6 seconds
Data packet size	1000 bytes
Data rate (CBR)	10 packets/second
Speed of a mobile node	5m/second

Figure 7 shows the performance comparison of *MIH-Hello-TC* approach ("with MIH") over the baseline ("No MIH"). Compared with the baseline, the *MIH-Hello-TC* approach always has less service disruption time (and packet losses). Figure 7 suggests that for each scheme, longer Hello interval reduces overhead at a cost of increased disconnection time. However, MIH shifts the tradeoff curve to dramatically better options, with the reduced disconnection time, packet loss and control overhead simultaneously. For example, consider the *MIH-Hello-TC* approach in 2s Hello interval (Case 1) and the baseline in 1s Hello interval (Case 2). Case 1 has 0.3s disruption time and 397 Hello messages, while Case 2 has 8.8s disruption time and 742 Hello messages.

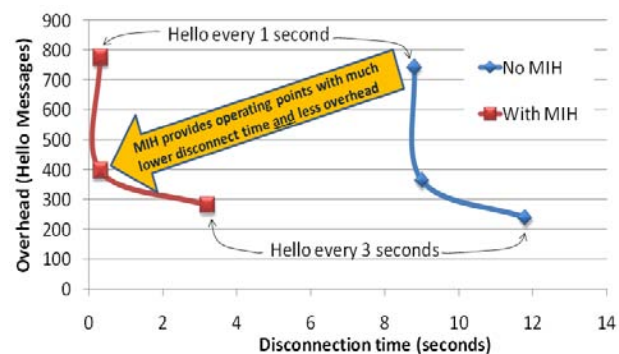


Figure 7. Performance comparison of MIH-Hello-TC approach over the baseline (i.e., conventional OLSR).

IV. HANDOFF SOLUTION IN A WiFi-WiMAX SETUP

In this section, we demonstrate the simulation study to show the validity of our handoff solution in a network

setup using both the ad hoc IEEE 802.11 (WiFi) and infrastructure-based WiMAX networks. AODV routing protocol [14] is used in the MANET. Three different scenarios are selected for investigation in our simulation. It is worth noting that parameters in this section are not the same as these in Section III, due to different setups.

A. Introduction

The integration of IEEE 802.16 and 802.11 has attracted a lot of attention recently [9][10][11]. A common framework was introduced in [9] to allow the inter-operation of 802.11 and 802.16 with optimal bandwidth sharing between a WiMAX BS and WiFi APs. An airtime-based link aggregation for WiFi and WiMAX was discussed in [10], where the airtime cost provides a way to measure the available resource of sharing links. In [11], a WiFi-WiMAX adaptation layer is proposed beyond the MAC layer to reduce the handoff delay in the network selection between a WiMAX BS and a WiFi AP. However, the above work considers only infrastructure-based networks. To the best of our knowledge, there are basically no previous works in the area of handoff in the heterogeneous network setup using *ad hoc* WiFi and WiMAX networks (WiFi-WiMAX, or Wi-Wi).

B. Implementation of IEEE 802.16e (Mobile WiMAX)

We implemented mobile WiMAX [4] in our in-house Java-based simulator (called Composable Cross Layer Network Simulator, or CCNS), including core MAC layer components and functionality, and a simplified PHY layer with tunable parameters (profiles). Our simulation methodology follows what is specified by [12]. An offline PHY layer simulation has been conducted in MATLAB to obtain certain parameters (profiles) and the simulation results are fed into the implemented models. This offline simulation utilizes a detailed system level simulator, similarly to [13].

Figure 8 depicts the results of our offline PHY layer simulation, where the contour of the coverage area for four modulation and coding scheme (MCS) levels are shown in different colors.

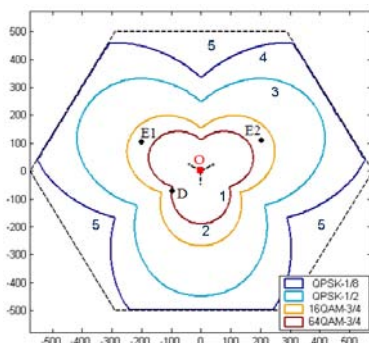


Figure 8. Coverage area of mobile WiMAX under different MCS levels.

In Figure 8, Zone 1 to Zone 4 represents the covered areas for 64QAM-3/4, 16QAM-3/4, QPSK-1/2 and QPSK-1/8, respectively, while Zone 5 represents the no-service area. For example, a stationary mobile station (MS) 1 located at point D, and a MS 2 moving from point

E1 to point E2 can both be served by the BS at point O using 16QAM-3/4.

The above results have been incorporated into our PHY layer WiMAX models in CCNS as a table to provide the mapping from the MS's position (relative to the BS) to the supported highest MCS level by the BS. The Downlink/Uplink (DL/UL) profiles for a given MS can then be determined accordingly as well as the other related PHY layer parameters. 16QAM-3/4 is set as the default MCS level and used in the simulation study.

Figure 9 shows the structure of our IEEE 802.16e MAC layer implementation at the BS's side, following [12]. The implementation at the MS's side is similar but with a simpler scheduler and frame map modules since it is the BS that broadcasts the control information and makes the decision about the UL and DL scheduling. It is worth noting that the service-specific convergence sublayer (CS) is not a separate sublayer in our implementation. Instead its functionality is distributed into the classifier, service flow and connection manager. It would not be difficult to extend our design for a separate CS in the future if necessary.

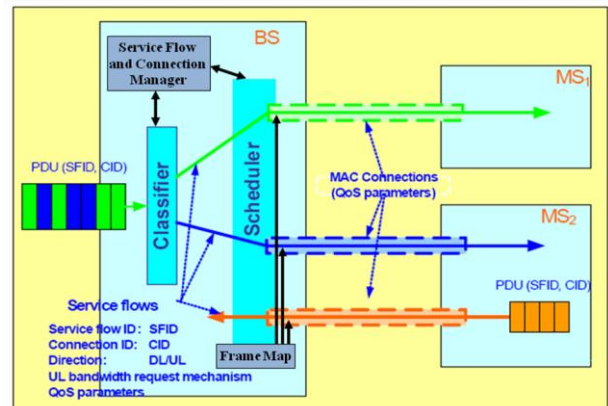


Figure 9. Structure of IEEE 802.16 MAC implementation.

C. Simulation Study of Handoff in a Wi-Wi Network Setup

Using the implemented mobile WiMAX models, we conducted the simulation study to show the validity of our solution in the Wi-Wi networks. The WiFi network consists of a number of nodes that form a MANET using the AODV [14] routing protocol. Certain nodes have dual wireless interfaces (i.e., WiFi and WiMAX) and may communicate with each other through a WiMAX BS once in its coverage area. Each node in the network (except the WiMAX BS) is moving based on the random waypoint models.

Three scenarios are considered in our study, such as: WiFi network using AODV (**AODV-WiFi only**), Wi-Wi networks using AODV (**AODV-WiFi+WiMAX**), and Wi-Wi networks using AODV with MIH support (**AODV-WiFi+WiMAX+MIH**).

Scenario 1: AODV-WiFi only

Figure 10(a) shows the **AODV-WiFi only** scenario where 12 nodes form a MANET using AODV routing

protocol. Each node has exactly one WiFi interface. Node A is the source node that generates packets at the rate of 10 packets per second. The packet size is 1000 bytes. Node E is the destination node. The Hello interval is 1 second and the allowed number of Hello packet losses is 2. The simulation duration is 180 seconds.

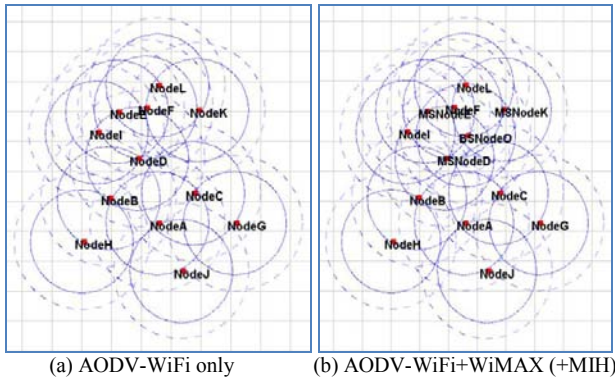


Figure 10. Three network scenarios in two mobility topologies.

In this scenario, most of the time the AODV protocol can handle node mobility through (re)routing processes. However, the AODV fails to handle the node mobility timely or simply collapses for a period of 38.6 seconds. This service disruption is due to the delayed detection of link breaks or the timeout of rerouting process when the maximum number of Route Request (RREQ) messages is reached. Consequently among the 1800 packets sent by Node A, only 1414 packets have been received at Node E. In our study, this scenario serves as a baseline for the following two scenarios.

Scenario 2: AODV-WiFi+WiMAX

Figure 10(b) illustrates the **AODV-WiFi+WiMAX** scenario. It is the same as the **AODV-WiFi only** scenario except that Node D, E and K also have a mobile WiMAX interface (MS side) each, and that a stationary WiMAX BS is located at point O. These dual-interface nodes may communicate with each other through the WiMAX BS once they are in BS's service area.

Compared with the baseline **WiFi-AODV only** scenario, after detecting a link break triggered by two consecutive HELLO packet losses, dual-interface nodes (D, E, and K) may choose to communicate with each other through the WiMAX BS. Hence, instead of sending out Route Error (RRER) messages and starting a re-routing process (which typically takes extra time), a new route may be selected to utilize the WiMAX connectivity. Further, the timeout of rerouting process is avoided due to the integration of WiMAX with AODV-WiFi. Totally 1120 packets have been received by Node E within the WiFi network, and another 660 packets through the WiFi-WiMAX networks. 20 packets are lost due to the delayed detection of link break in the conventional AODV.

Scenario 3: AODV-WiFi+WiMAX+MIH

The **AODV-WiFi+WiMAX+MIH** scenario, shown in Figure 10(b), has the same network configuration and simulation parameters as the **AODV-WiFi+WiMAX** scenario, except that certain capabilities of MIH, such as

Link_Going_Down event, are leveraged in our handoff solution to further improve handoff performance in the integrated WiFi-WiMAX networks.

The implementation of MIH capabilities in our CCNS is similar to what described in Section III for NS-2. In this scenario, an MIH *Link_Going_Down* event occurs at a node, when the node detects that the received signal power of packets sent by its neighbor is less than the predefined power level, P_{LGD} . In our simulation, P_{LGD} is set as $1.03 \times P_{min}$, where P_{min} is the minimum power level threshold required to successfully receive and decode a packet. Once detecting this MIH event, the handoff control module at the node is triggered to make the appropriate handoff decision either within the WiFi network (re-routing) or between the WiFi and WiMAX networks (interface switching) accordingly, based on the different types of nodes associated with this MIH event: 1) both nodes have dual interfaces, 2) both nodes have only WiFi interface, or 3) both nodes have only MS-side WiMAX interface.

Compared with the **AODV-WiFi+WiMAX** scenario, the **AODV-WiFi+WiMAX+MIH** can further improve the handoff performance by not only reducing the time to detect a link break, but also facilitating the nodes to make smarter handoff decisions accordingly. In the simulation, 1120 packets have been received by Node E through the WiFi-only network and the rest 680 packets through the WiFi-WiMAX networks. **No packets** are lost at all.

D. Performance Comparison and Discussion

Table 2 summarizes the obtained simulation results on the network performance in terms of the number of dropped packets and the service disruption time. It has been shown that the handoff performance is greatly improved through the integration of the ad hoc WiFi and the WiMAX. It is also obvious that the disruption time and the packet losses are further reduced by introducing the MIH support in our handoff solution for the integrated WiFi and WiMAX networks.

TABLE 2.
SIMULATION RESULTS IN A MOBILITY SCENARIO

Hello Interval: 1s Allowed Hello Losses: 2	AODV- WiFi only	AODV-WiFi +WiMAX	AODV-WiFi+ WiMAX + MIH
# of dropped packets	386	20	0
Service disruption time	38.6s	2s	0

Figure 11 gives a graphical display of the above performance comparison. It can be more clearly seen that the integration of WiMAX and MIH with AODV-WiFi dramatically improves the handoff performance.

V. HARDWARE TESTS IN A WiFi-CELLULAR SETUP

In this section, we extend our simulation-based work to the hardware-involved tests in the heterogeneous network setup with ad hoc WiFi and cellular (WiMAX, or GSM) networks, in order to showcase the validity of our handoff solution in the realistic environment.

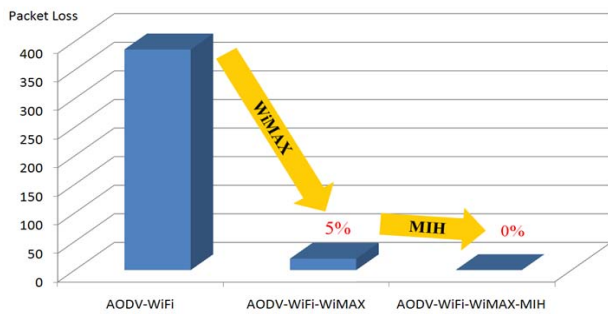


Figure 11. Performance comparison of three scenarios.

It is worth noting that neither extra buffer (except at the destination node) nor retransmission mechanisms are implemented in our tests presented in this section.

A. Wireless-Hardware-in-the-Loop (WHIL) Emulation

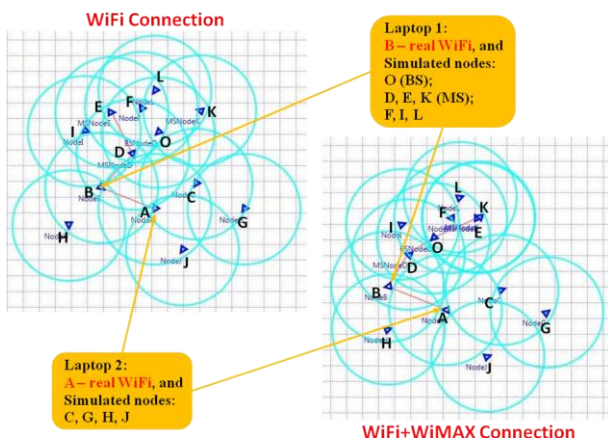
Our WHIL emulation testbed consists of two Lenovo laptops and a Cisco router. As an example we use the **AODV-WiFi+WiMAX+MIH** scenario shown in Figure 10(b) to describe the setup of our emulation testbed and the emulation process.

Figure 12(a) depicts the setup of our WHIL emulation testbed, while Figure 12(b) shows two snapshots of the network topology when our testbed emulates the **AODV-WiFi+WiMAX+MIH** scenario.

Each laptop represents a real node whose WiFi interface is a WiFi card. They, as real nodes, use their WiFi cards to send and receive data packets and AODV messages with each other over WiFi. Further, each laptop also serves as a container to simulate several other nodes. The two laptops use the wired connection (through the router) to exchange simulation information such as synchronization, node, link and connection status, etc.



(a) Setup of WHIL emulation testbed



(b) Snapshots of network topology on the screen of laptop 2

Figure 12. WHIL emulation in the WiFi-WiMAX networks.

A real-time video application is used in our emulation. The source node A (a real node represented by Laptop 2) retrieves packets from a local video file at a constant rate of 1.2 Mbps (15 packets/second). The destination node E (a simulated node in Laptop 1) receives the video packets through the emulated networks, and plays it in Laptop 1 in a real-time manner. The Hello interval is 3 seconds.

Figure 13 shows the successful throughput collected in our emulation. We focus on the **AODV-WiFi+WiMAX** and **AODV-WiFi+WiMAX+MIH** scenarios. It can be clearly seen that without the support of MIH, there is a disruption time for about 6 seconds. After the connection resumes, there is another disruption with a short time of period (2-3 seconds), due to the substantial packet losses in the networks and buffering at the destination. With the MIH support, there is no disruption at all; the throughput curve has only small amplitude of oscillation.

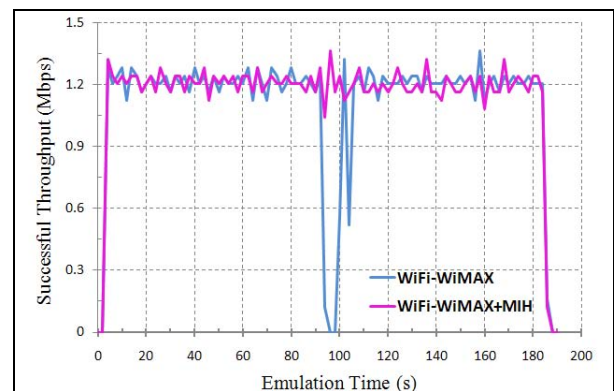


Figure 13. Successful throughput in the emulation.

Since neither extra buffer (except at the destination node) nor retransmission mechanisms are implemented in our emulation, the throughput curve reflects the changing of end-to-end delay (and jitter) in some sense. Also, we conducted several **AODV-WiFi+WiMAX+MIH** demos, each with a group of about 10 viewers watching the video. During these demos, no viewer has noticed any quality degradation of image. Some of them reported a slight voice distortion (described as a hiccup) within 1 second before or after the handoff. This voice distortion can be (and is typically) handled by a scheduler or buffer to shape/adjust the arrival difference of video packets from different wireless interfaces [16].

In summary, through our emulation, it has been further confirmed that the integration of WiMAX and MIH with AODV-WiFi dramatically improves the handoff performance (**no service disruption**). It has also been observed that the WiFi-WiMAX network without MIH support (i.e., **AODV-WiFi+WiMAX** scenario) performs not as well as it does in the simulation (presented in Section IV), due to the involvement of real WiFi cards, as well as the tight requirements of video application for high data rates and hard delay constraints.

B. Pure Hardware Experiments

We also built a hardware testbed that consists of two commercial-off-the-shelf (COTS) Android Dev Phone 2 (ADP2) with dual interfaces (WiFi + GSM), and a Vanu

Anywave GSM base station system (BSS) that operates at the GSM-1900 frequency band.

The ad hoc WiFi functionalities are not available in the then latest Android release (2.1, Éclair), nor the current release (2.2.1, Froyo). To enable the functionalities, we modified the Android framework for a custom build and then flashed the ADP2. The flashed ADP2 can connect to each other in a programmatic way without any assistance from the infrastructure (e.g., BS, AP or computer). Specifically, they can create an ad hoc WiFi network, discover an existing ad hoc network dynamically, and connect to it automatically.

We then developed an ad hoc WiFi network service in order to integrate the enabled ad hoc WiFi functionalities in ADP2. This service runs in background and provides autonomous network creation, discovery, establishment and maintenance. Specifically, HELLO messages were implemented for neighbor discovery and monitoring.

Furthermore, we developed a real-time voice over IP (VoIP) application, over a modified peer-to-peer version of Session Initiation Protocol (SIP). Either ad hoc WiFi or cellular can be the underlying wireless technology for our VoIP application. There is no SIP server, gateway or proxy in our testbed. Table 3 lists the SIP methods in our implementation.

TABLE 3.
IMPLEMENTED SIP REQUEST AND RESPONSE METHODS

Request	Description
INVITE	Indicate a client is being invited for a session
ACK	Confirm a successful session establishment
BYE	Terminate an ongoing session
CANCEL	Terminate a pending request
Response	Description
TRYING	Indicate that the extended search being performed may take a significant time (informational)
RING	Indicate the callee has been reached (informational)
OK	Indicate a successful response
BUSY	Indicate a client failure response

Finally, we implemented our handoff solution in these customized ADP2, with ad hoc WiFi functionalities and the peer-to-peer VoIP application, to enable seamless soft handoff between the cellular (GSM) and ad hoc WiFi networks. Specifically, IEEE 802.21 MIHF is leveraged to provide triggers for the handover, through two MIHF events (*Link_Going_Down* and *Link_Down*). In addition, handshaking messages between peers were implemented for handover, including the handover request (HO-REQ), response (HO-RSP) and acknowledgement (HO-ACK).

Figure 14 depicts a small-scale scenario of our experiments. Initially Soldier 1 (S1) reaches another soldier (S2) through the GSM BSS. The connection is S1 — BSS — S2. S1 and S2 then move away from the BSS to another location, which is out of the BSS' coverage area.

At some point, handoff will be triggered to allow S1 to connect to S2 directly. The connection is then S1 — S2. Two-way voice communication is used as the application.

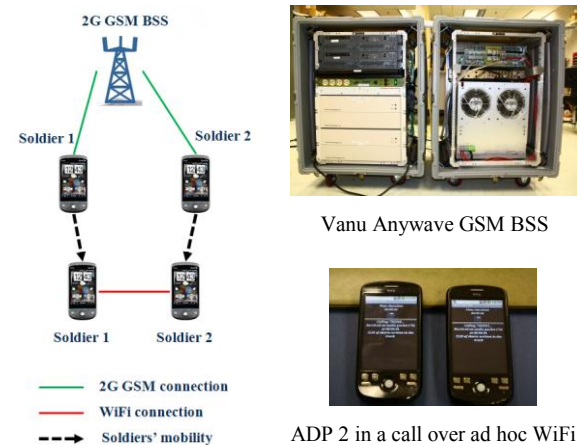


Figure 14. Seamless soft handoff in a WiFi-GSM setup.

We conducted indoor experiments using this small-scale scenario, and demonstrated them for three groups of visitors (5-12) from different government agencies, such as Army, DARPA, and Air Force, etc. Figure 15 depicts the floor map of place for our indoor experiments. Here we use Experiment 3 as an example; the details of our experiments are provided in Appendix A. In Experiment 3, two users (each with an ADP2) walked in the hallway to leave the range of GSM BSS, from the starting point (red circle) to the ending point (red square). Two users kept their distance within 2–10 m. At the handover places (orange crosses), one phone was losing the GSM signal; consequently a soft handoff is triggered to establish a new call between two phones through ad hoc WiFi.

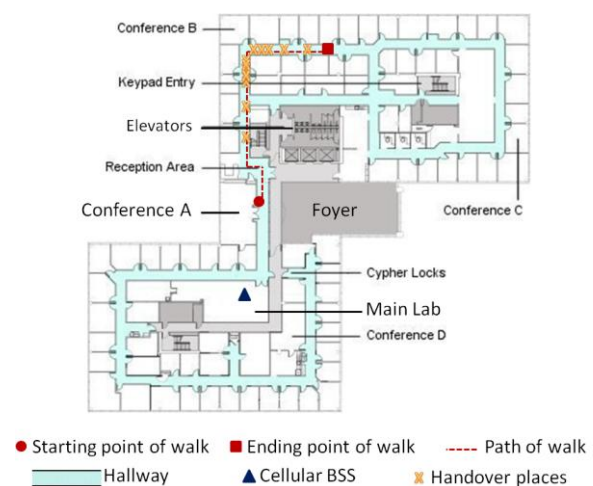


Figure 15. Floor map of place for indoor experiments.

Extensive indoor testing in our building hallway and conference room has confirmed that our handoff solution (WiFi + GSM + MIHF) can achieve seamless soft handoff (**no service disruption**) in the WiFi-GSM network setup. The users in call cannot even notice the switch between the cellular network and the ad hoc WiFi network, if the auto answer option is selected and the ring is disabled.

VI. CONCLUSIONS AND FUTURE WORK

In this paper, we first describe positions and approaches of how to extend our work on providing holistic handoff solutions for ad hoc networks. We then conduct performance evaluation of our proposed handoff solution through simulation, real wireless-hardware-in-the-loop emulation, as well as pure hardware experiments using Android phones and a GSM BSS. It is worth noting that neither retransmission mechanisms nor buffer (except at the destination) are implemented in our whole study. It has been shown through extensive study that transparent user application can be achieved using our handoff approach with low latency, minimum packet loss and only necessary control overhead. To the best of our knowledge, there is basically no previous work in this area.

As a future work, we will further develop our handoff solution, implement and test it (lab and field tests) with the WiFi-cellular network using the 3G WCDMA BSS. Extensive experiments will be conducted to evaluate the voice quality, using subjective and/or objective methods, such as Perceptual Evaluation of Speech Quality (PESQ), Mean Opinion Score (MOS), etc. In addition, ad hoc routing protocols (such as AODV) will be implemented to support the multi-hop networking of Android handsets.

APPENDIX A EXPERIMENTS USING ANDROID PHONES IN A WiFi-GSM SETUP

General Instructions for experiments are listed below:

- On the bottom of phone, there are 3 buttons in the first row: **Home**, **Menu**, and **Back** buttons.
- When the backlit screen is off, press **Menu** button to turn on the screen.
- On the desktop of phone there are 2 icons: **Settings** and **SshDroid** (our seamless handoff application).

Experiment 1 – Enable the ad hoc WiFi network

- 1) Press the **Home** button to return to home screen.
- 2) Touch the **Settings** icon.
- 3) Touch the **Wireless & networks** item.
- 4) Touch the **Wi-Fi settings** item.
- 5) Touch the **Wi-Fi (Turn on Wi-Fi)** item. The list of available wireless networks, including the ad hoc WiFi network (if any), will be shown.
- 6) Turn off the Wi-Fi by touching the **Wi-Fi** item.

Experiment 2 – Voice over ad hoc WiFi

- 1) Press the **Home** button to return to home screen.
- 2) Touch the **SshDroid** icon to start our Seamless Soft Handoff application.
- 3) Wait for a while to allow the application automatically enable the ad hoc WiFi network. You can check the status of WiFi and GSM services on the top notification panel.
- 4) Touch the **Menu** button.
- 5) Two options menu items pop up. Touch the **Call on Wi-Fi** item to start an ad hoc Wi-Fi call.
- 6) Once the call goes through successfully, a new in-call view appears with the in-call phone number

and time duration, etc. You can now talk with the other party.

- 7) You can disconnect the ongoing ad hoc WiFi call by pressing the **Back** button at any time, or wait for the termination of call by the other party.
- 8) Repeat steps 5) – 7) for another ad hoc WiFi call.

Experiment 3 – Seamless soft handoff in a GSM-WiFi setup (walking in the hallway)

- 1) After Experiment 2, you should be right in the root view of the SshDroid application. Otherwise repeat the steps 1) – 3) in Experiment 2.
- 2) Upon our instruction, press the **Call** button in the root view of the SshDroid application. This starts a GSM phone call.
- 3) Once the call goes through successfully, a GSM phone in-call view shows up to display the in-call information. You can now talk with the other party (in the GSM network).
- 4) Upon our instruction, start walking to the hallway.
- 5) Walk in the hallway to leave the GSM BSS range. At a breakpoint, one phone (say Phone 1) will be losing the GSM signal and hence the GSM call is being disconnected on this phone.
- 6) Almost immediately a seamless soft handoff is triggered in Phone 1; consequently a new call is started by Phone 1 through ad hoc WiFi, and then established after receiving auto answer (optional) from the other phone.
- 7) Now you are in an ad hoc WiFi call.
- 8) Touch the **Menu** button in the root view of SshDroid application, and then the **Exit** menu item to exit the application.

Experiment 4 – Seamless soft handoff in a GSM-WiFi setup (in the conference room A)

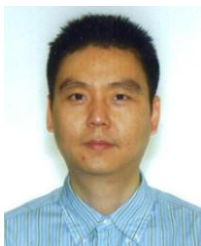
- 1) After Experiment 2 or 3, you should be right in the root view of the SshDroid application. Otherwise repeat the steps 1) – 3) in Experiment 2.
- 2) Upon our instruction, press the **Call** button in the root view of the SshDroid application. This starts a GSM phone call.
- 3) Once the call goes through successfully, a GSM phone in-call view shows up to display the in-call information. You can now talk with the other party (in the GSM network).
- 4) If you are the caller (i.e., the one who made this call), upon our instruction, press the **Back** button to minimize the GSM in-call view.
- 5) If you are the callee (i.e., the one who received this call), press the **Menu** button and then touch the **End Call** menu item.
- 6) Almost immediately a seamless soft handoff is triggered by the callee (GSM). Consequently a new call is started by the callee through ad hoc WiFi, and then established after receiving the auto answer (optional) from the peer.
- 7) Now you are in an ad hoc WiFi call.
- 8) Touch the **Menu** button in the root view of SshDroid application, and then the **Exit** menu item to exit the application.

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