A novel network mobility management scheme supporting seamless handover for high-speed trains

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1. Introduction

Automotive telematics has become an important technology for high-speed rail systems, which are becoming increasingly popular in this era of green technology. As the train speed increases, however, communications between the train and infrastructure encounter major difficulties of maintaining high quality communication. Handovers on high-speed trains occur more frequently and have shorter permissible handling times than for traditional vehicles. In this paper, the proposed 2MR network mobility scheme takes advantage of the physical size of high-speed trains to deploy two mobile routers (MRs) in the first and last carriages. This scheme provides a protocol to allow the two MRs to cooperate with a wireless network infrastructure in facilitating seamless handovers. Our simulation results demonstrate that compared to the traditional single MR schemes, the 2MR scheme noticeably improves the communication quality during handover by significantly reducing handover latency as well as packet loss for high-speed trains.
number of advantages in that it reduces the hardware and software system complexity and power consumption of MNNs, as well as the monetary cost involved in Internet access. Meanwhile, from the perspective of the network operator, it can reduce the processing and signaling overheads of Authentication, Authorization and Accounting (AAA) and network resource management.

Low quality train-to-infrastructure wireless links are not the only challenge to overcome in providing Internet access to MNNs on a high-speed train; the high speed of the train also results in frequent handover events, within and across subnets. Further, since the handover procedure is executed in the overlap area of adjacent BSs, the permissible handover time decreases as the train’s speed increases. Efficient mobility management and handover protocols across BSs are thus required to ensure the continuity of real-time communication sessions (e.g., VoIP and video conference).

In this paper, we take advantage of the long physical size of high-speed trains and propose the 2MR scheme. Unlike previous multiple-MR systems in which each router utilizes different access technologies [7], the proposed 2MR scheme deploys two equivalent MRs to share the communication loads and handle handovers cooperatively. The proposed network mobility management is designed on the IPv6 network so that the handover protocols provide seamless handover for the MNNs on the train. Although the WiMAX terminology and technology are used for exemplifying the design ideas and advantages, the design could be applied to other wide-area wireless access technologies, such as LTE-Advanced, with the appropriate modifications.

The remainder of this paper is organized as follows. Section 2 reviews the related work and background. Section 3 describes the architecture of the proposed 2MR scheme, and section 4 introduces the 2MR handover protocols. We detail the simulation results in Section 5. Then, in Section 6, we summarize our conclusions. Table 1 lists the abbreviations used in this paper to help the readers to follow the details of the paper.

2. Background and related work

2.1. Network mobility

The Internet Engineering Task Force (IETF) network mobility basic support protocol [1] (called NEMO-bs hereafter) is a simple and effective method for managing global network mobility. By establishing a bi-directional tunnel between the home agent of the MR (HA_MR) and the MR, and maintaining the same Mobile Network Prefix (MNP_con) in the mobile network, NEMO-bs provides mobility transparency for the MNNs. There have been proposed variants of NEMO-bs that provide route optimization by bypassing the HA_MR-MR tunnel [8] and [9] with additional components and functions. Two other network layer protocols, described in [2,10], allow MNNs to use geographically meaningful IP addresses by using the visiting network prefix. Beyond focusing on the network layer, there have also been recommended proposals for different protocol layers, such as HIP-based [11] and SIP-based [3,12] network mobility schemes.

LFMN communication targets, such as the train control center, are mostly located in the MR home network, and thus route optimization is not an issue for their traffic. In contrast, VMN communication targets are located on the Internet where route optimization is critical for reducing end-to-end transmission delay and jitter. MR mobility management support for LFMNs and VMNs should therefore be different. Whereas LFMNs rely on MR support given that they are designed to be simple, VMNs use their terminal mobility management protocols, such as Mobile IP(v6), Dynamic DNS, SIP, or Skype, because VMNs are owned by the passengers and it is unrealistic for the MR to support all the protocols. Furthermore, for security reasons, it is better to isolate the VMN from the LFMN because a VMN should not be able to monitor, contact or even access the LFMNs easily, and the communications between the train and its control center should not be interrupted by malicious VMN traffic.

Fig. 1. An example of using network mobility under a WiMAX wireless network operator.
A handover event is generally triggered by the detection of a change in BS, followed by the process of address reconfiguration and re-registration. The traditional mobility management systems discussed above are not sufficient for efficiently handling handover events, due to the short and frequent handover requirements of high-speed trains. For the systems with one single MR, the MR starts preparing handover when the signal strength degrades to a level such that if the handover is not completed in time, the communication would be disrupted. For high-speed trains, this time constraint is stricter due to shorter sojourn time in the overlapping area of the two adjacent BSs. Therefore, a new design to alleviate this problem is required.

### 2.2. Mobility management in WiMAX

In this section, we review the terminology and technology of WiMAX. The network reference model proposed by WiMAX Forum [13] is illustrated in Fig. 1. The Access Service Network (ASN), which provides radio access to WiMAX subscribers, consists of one or more ASN Gateways (ASN-GWs) and base stations (BSs). The ASNs are connected by the Connectivity Service Network (CSN), which provides IP connectivity services. To support IP mobility, WiMAX Forum, 3GPP and 3GPP2 employ the Proxy Mobile IPv6 (PMIPv6) protocol [14]. In WiMAX, the Localized Mobility Anchor (LMA) is located in the CSN and manages an LMA-Domain that owns a scope of network prefixes, and ASN-GW supports the Mobility Anchor Gateway (MAG) functionality. PMIPv6 supports the “per-MN-prefix model” and can be modified to support the “per-Mobile-Network-prefix model” as well. In the visiting network, the train’s mobile network is assigned a Mobile Network Prefix (MNPdyn) [15]. The QoS router cooperates with the MRh and the MRt to support seamless handover. This router is the default gateway of the VMN and the LFMN networks, and divides the uplink traffic from both the VMN and the LFMN network into the two categories of ULh and ULt flows, which are transmitted via the MRh and the MRt, respectively.

#### 3. The proposed 2MR scheme

In this section, we present the network architecture and components for high-speed trains. We also explain how the LFMNs and the VMNs connect to IP networks and maintain communication session during handover. Further details can be found in [15].

### 3.1. Network architecture and components for high-speed trains

Consider the high-speed train shown in Fig. 2. The VMNs and the LFMNs are organized as two independent networks, respectively called the VMN network and the LFMN network, which are managed in different ways (detailed in 3.2). Two MRs are deployed, one in the head carriage and one in the tail carriage, denoted as MRh and MRt, respectively. Each MR has a WiMAX interface for train-to-infrastructure communication. Adopting multiple interfaces, the 2MR scheme increases the uplink capacity in an asymmetric wireless network, like WiMAX.

The QoS router cooperates with the MRh and the MRt to support seamless handover. This router is the default gateway of the VMN and the LFMN networks, and divides the uplink traffic from both the VMN and the LFMN network into the two categories of ULh and ULt flows, which are transmitted via the MRh and the MRt, respectively.

### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>MR</td>
<td>Mobile router</td>
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<tr>
<td>MNN</td>
<td>Mobile network node</td>
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<td>LFMN</td>
<td>Local fixed and mobile node</td>
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<td>VMN</td>
<td>Visiting mobile node</td>
</tr>
<tr>
<td>NEMO-bs</td>
<td>The IETF network mobility basic support protocol</td>
</tr>
<tr>
<td>HAK</td>
<td>NEMO-bs home agent of the MR.</td>
</tr>
<tr>
<td>MNPdyn</td>
<td>A mobile network prefix assigned by the MR’s home network</td>
</tr>
<tr>
<td>ASNGW/CSNGW</td>
<td>The ASN/CSN gateway</td>
</tr>
<tr>
<td>REG-REQ</td>
<td>The registration request in WiMAX.</td>
</tr>
<tr>
<td>MOB_MSHO-REQ</td>
<td>The MS handover request in WiMAX.</td>
</tr>
<tr>
<td>MOB_HO-IND</td>
<td>The handover indication in WiMAX</td>
</tr>
<tr>
<td>HO_Cnf</td>
<td>The handover confirm in WiMAX</td>
</tr>
<tr>
<td>HO_Req</td>
<td>The handover request in WiMAX</td>
</tr>
<tr>
<td>PBU/PBA</td>
<td>The proxy binding, Update/acknowledgement in PMIPv6.</td>
</tr>
<tr>
<td>PBI/PBIA</td>
<td>The proxy binding inform and acknowledgement of 2MR.</td>
</tr>
</tbody>
</table>
To support the proposed 2MR scheme, several signaling messages are modified and the functionalities of the network components (e.g., BS, ASN-GW and LMA) in the infrastructure are altered. When the MRh and the MRt on a train enter a new network, they set the 7th bit in the Handover Supported field in the 802.16 Registration Request (REG-REQ) message [16] to 1, and put the information that is related to themselves in the message to indicate the use of the 2MR scheme. The subsequent authentication and registration messages in the WiMAX network entry procedure deliver the information about the MRh and the MRt to the BS, the ASN-GWs, and the servers in the CSN. On the completion of the network entry procedure, an MNP$_{dyn}$ (e.g., 2::/ in Fig. 1) is assigned to the mobile network on the train. The MRh and the MRt exchange information about their WiMAX and NEMO-bs registrations, such as the registration and authentication keys and the care-of addresses (CoA), with each other by using a 2MR defined layer-3 message, 2MRInfoExchange.

In the LFMN network, the LFMNs use the MNP$_{con}$ as their network prefix (see Fig. 2) during the train journey, and are managed by the MRs using NEMO-bs which provides mobility transparency to them and generally does not introduce sub-optimal route because the destination network of the LFMNs' traffic is located exactly in the MR's home network. The information security of LFMN network can be achieved by, for example, encrypting the NEMO-bs tunnel using IPSec at the two end points of the tunnel (i.e., the MR and the HA of the MR).

When entering a visiting network, an MNP$_{dyn}$ (e.g., 2::/ in Fig. 1) is assigned to the mobile network on the vehicle. The MR configures a CoA using the MNP$_{dyn}$ and performs NEMO-bs registration. In the meantime, the MRh broadcast the MNP$_{dyn}$ to the VMN network using Router Advertisement messages. The VMNs then configure geographically meaningful addresses and register with their own home servers. For example, a home server could be the home agent (HA) if Mobile IPv6 is used, or the REGISTRAR server if SIP is used. The VMNs use the addresses in subsequent communications with the CNs. Unlike the packets to and from the LFMN, those of the VMNs will be transmitted by using the underlying Internet routing mechanism instead of via the HA$_{MR}$-MR tunnel.

### 3.3. Continuous communication during handover

To provide continuous communication even when a new MNP$_{dyn}$ is assigned to the mobile network, the 2MR handover protocol (detailed in Section 4.2) redirects the packets destined to the old MNP$_{dyn}$ of the mobile network to the target BS attached by the MR. In this section, we detail the interaction between the MNNs and the MR during handover. Table 2 lists the types of MNN and the handover-detected levels when the MR performs intra- and inter-LMA domain handover.

For the LFMNs, since the MNP$_{con}$ remains constant, the LFMNs' IP addresses will not change, even when the MR uses a new MNP$_{dyn}$ to configure a new CoA that is used on the HA$_{MR}$-MR tunnel. See Fig. 3(a). Therefore, with the aid of the 2MR handover protocol and NEMO-bs, any type of LFMN can enjoy continuous communication.

For the VMNs, some global mobility management protocols have the potential to change the IP address during the communication without disconnecting it from its peer (we call this, IP-migration capable). For example, in Mobile IP, the application establishes a communication using the VMN's home address and will not be aware of the change of the CoA that is configured using the MNP$_{dyn}$. During handover, with the aid of the 2MR handover protocol, the VMN can receive packets when the MR attaches to a different BS, even when the packets are destined to its old CoA. In the meantime, if a new MNP$_{dyn}$ is assigned, the VMN's “Mobile IP layer” configures new CoA and re-registers to its home agent and the CN. The destination addresses of the packets from the VMN's peer are then changed to the VMN's new CoA without disturbing the application. See Fig. 3(b).

In Fig. 3(c), if a VMN's global mobility management protocol is not IP-migration capable, the infrastructure can also support continuous communication for the VMN. As we said before, the 2MR handover protocol redirects the packets destined to the old MNP$_{dyn}$ of the mobile network to the new BS attached by the MR, and the VMN can receives the packets destined to its old IP address that is configured by using the old MNP$_{dyn}$. If the redirection mechanism continues after the handover, the VMN can thus continue the communications with the cost of adding processing load to the network components of the infrastructure. A mechanism for deciding when to stop redirecting the packets destined to the old MNP$_{dyn}$ is required to prevent adding too much load to the network components.

### Table 2

Types of MNN and the handover-detected levels.

<table>
<thead>
<tr>
<th>Types of MNN</th>
<th>Network prefix</th>
<th>Handover detected when the MR handover w/o changing MNP$_{dyn}$</th>
<th>Handover detected when the MR handover w. changing MNP$_{dyn}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LFMN</td>
<td>MNP$_{con}$</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>IP-migration capable VMN</td>
<td>MNP$_{dyn}$</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Non IP-migration capable VMN</td>
<td>MNP$_{dyn}$</td>
<td>N</td>
<td>N</td>
</tr>
</tbody>
</table>

Fig. 2. 2MR network architecture in the train.
infrastructure, as well as for security issues. In the 2MR scheme, the traffic redirection mechanism will continue until there is no packet destined to the old MNP\textsubscript{dyn}.

4. 2MR handover protocols

Under the 2MR scheme, in the normal state, the QoS router forwards the ULh flows to the MRh and the ULt flows to the MRt, while the MRt receives the DL flows from the serving BS. During the handover period, this involves four steps:

1. The MRh initiates the handover procedure, and the serving BS negotiates with the target BS to reserve network resources for the DL, the ULt and the ULh flows.
2. The MRh disconnects from the serving BS, and the QoS router stops forwarding the ULh flows to the MRh.
3. The MRh attaches to the target BS, and starts to receive the redirected DL flows. In the meantime, the QoS router forwards the ULh flows to the MRt and the ULt flows to the MRh.
4. The MRt attaches to the target BS, and starts to receive the DL flows. The QoS router returns to the normal state.

In the next two sub-sections, we describe the Intra-LMA-Domain and Inter-LMA-Domain handover protocols in the 2MR scheme.

4.1. Intra-LMA-Domain handover

The Intra-LMA-Domain handover in WiMAX includes two types of handover: ASN-anchored and CSN-anchored. CSN-anchored handover consists of two phases: an ASN-anchored handover and an anchor ASN-GW relocation procedure. Since the anchor ASN-GW relocation procedure is transparent to the subscriber stations (i.e., the MR), as well as being independent of ASN-anchored handover and easier to achieve non-interrupted communication, we focus on the design of a seamless handover mechanism for ASN-anchored handovers. In this type of handover, when the MRh reaches handover conditions, it makes a request to reserve the network resources for the DL, the ULt and the ULh flows under the target BS. In WiMAX, a fully controlled handover includes the Preparation Phase and Action Phase [17].

The Preparation Phase starts with the layer-2 MS Handover Request (MOB\textsubscript{M}SHO-REQ, 1.1) message sent from the MR to the serving BS. See step 1 in Fig. 4. Then the serving BS sends layer-2 HO_Req messages (1.2) that eventually reach the candidate target BSs, which inform the anchor ASN-GW to check authentication and reserve network resources. Since the MRh has to reserve the required resources for itself and on behalf of the MRt, the MOB\textsubscript{M}SHO-REQ, the HO_Req, and other messages in the Preparation Phase will carry the context of the MRh and the MRt, including the QoS requirements of the DL, ULh and ULt flows.

The signaling sequence of the Action Phase of the ASN-anchored handover under the 2MR scheme is diagrammed in Fig. 4. In step 2, the MRh sends a layer-2 Handover Indication (MOB\textsubscript{H}O-IND, 2.1) message to the serving BS to start the Action Phase. It also sends a 2MR defined layer-3 message, 2MRhHO (2.2), to the QoS router, which will then stop forwarding ULh flows to the MRh. The 2MRhHO carries the MRh’s WiMAX access parameters used to access the serving BS, such as the CIDs and keys, which will be used by the MRt to transmit the ULh flow. When the serving BS receives the MOB\textsubscript{H}O-IND message, it sends a layer-2 HO_Cnf message (2.3) carrying the context needed for the MRh and the MRt handover to the chosen target BS, in order to confirm that the MRh is about to attach to it.

In step 3, after negotiating new CIDs and connecting with the target BS, the MRh sends a 2MR defined layer-3 message, 2MRh\textsubscript{Ready} (3.1), to inform the QoS router to start to forward ULt flows to the MRh, and to forward the ULh flows to the MRt. At this moment, the MRh sends ULt flows to the target BS, and the MRt sends ULh flows to the serving BS. Meanwhile, the target BS sends the layer-2 HO\textsubscript{Complete} message (3.2) to trigger the anchor ASN-GW to redirect the DL flows to the MRh via the target BS.

In step 4, when the MRt successfully attaches to the target BS, it sends a 2MR defined layer-3 message, 2MRt\textsubscript{HOComp} (4.1) to the QoS router and starts to receive DL flows using the WiMAX access parameters in the 2MRt\textsubscript{Ready}. The QoS router returns to the normal state.

4.2. Inter-LMA-Domain handover

The 2MR scheme supports Inter-LMA-Domain handover, which is not defined in the WiMAX standard. We consider a Mobile Network Operator that deploys multiple CSNs (i.e., multiple LMA-Domains). When the MRh is about to perform a handover to a target BS in another LMA-Domain with distinct MNP\textsubscript{dyn}, we propose establishing a forwarding tunnel from the serving LMA to the target LMA for the DL flows to reduce handover delay and packet loss. Before the MRh attaches to the target BS, the network resources for the DL, the ULh and the ULt flows in the target LMA-Domain will be prepared by the target LMA and MAG. When attaching to the target BS, the MRh performs the WiMAX network entry procedure, including the AAA procedure, and negotiates for new CIDs with the target BS. Before the MRh and the VMN configure new IP addresses using the new MNP\textsubscript{dyn} and re-register with their home servers and CNs, the on-going sessions can continue because of
using the LMA forwarding tunnel. We describe the procedures below.

In Fig. 5 step 1, the MRh prepares the handover by sending a MOB_MSHO-REQ (1.1) that triggers the BS to send a HO_Req message (1.2) to the anchor ASN-GW (i.e., the serving MAG). This MAG queries the topological database to determine whether the handover is an inter-LMA-domain handover. In the 2MR scheme, the serving MAG sends a layer-3 Proxy Binding Update (PBU, 1.3) containing the contexts of the MRh and the MRt, as well as information about the target MAG and the target LMA, to the serving LMA. Then, the serving LMA sends a 2MR defined layer-3 message, 2MRHI (1.4), with the contexts of the MRh and the MRt to the target LMA that then sends a 2MR defined layer-3 message, Proxy Binding Inform (PBI, 1.5), with the contexts of the MRh and the MRt (including the new MNP_dyn assigned by the target LMA) to the target MAG.

When it receives the PBI, the target MAG gets the information required for the mobile network, such as the AAA context and the new MNP_dyn. The target MAG responds with a 2MR defined layer-3 message, Proxy Binding Inform Acknowledgement (PBA, 1.6), to the target LMA that will then reply with a 2MR defined layer-3 message, 2MRHAck (1.7), to the serving LMA for the confirmation of establishing the LMA-level forwarding tunnel. The serving LMA responds with a layer-3 Proxy Binding Acknowledgement (PBA, 1.8) to the serving MAG to grant the handover request. At the end of the Preparation Phase, the serving BS sends a layer-2 BS Handover Response (MOB_BSHO-RSP, 1.9) message to the MRh to inform the MRh that it is ready for handover.

In step 2, after the MRh sends MOB_HO-IND (2.1) and attaches to the target BS, the target MAG first sends the new MNP_dyn (acquired from the PBI) to the MRh in order to advance the beginning of the re-registration of NEMO-bs and the VMN’s global mobility management. Meanwhile, the target MAG follows standard PMIPv6 procedure to send a PBU (2.2) to the (target) LMA that will then send a 2MR defined layer-3 message, 2MRFW (2.4), to the serving LMA. When the serving LMA receives the 2MRFW, it starts redirecting the DL flow to the target LMA through the LMA-level tunnel; and the DL flow is then forwarded to the mobile network via the target MAG and the MRh. When the MRh receives the new MNP_dyn (2.3) from the target MAG, it configures two new CoAs for the MRt and itself, and re-registers them with the HA_Mg. The MRh also provides the VMN network with the new MNP_dyn, so that the VMNs can configure new IP addresses and re-register with their home servers and the CNs, while continuing the on-going sessions.

In step 3, after the QoS router receives the 2MRhReady message (3.1), it forwards the ULt flows to the MRh. Since the subsequent procedures are conceptually the same as in step 4 for intra-LMA-Domain handover, we do not repeat them here. In the case that the MRt reaches the handover condition (e.g., signal strength decreases to a certain level) before the QoS router receives the 2MRh-Ready message, the serving MAG notifies the serving LMA that it will start redirecting the DL flow to the target LMA through the LMA-level tunnel. The DL flow is then forwarded to and buffered at the target MAG. Once the MRh is ready to receive the DL flow, the target MAG forwards the DL flow to the mobile network via the MRh.

5. Performance evaluation

To evaluate the performance of the 2MR scheme, we conducted several simulations on an ns2 simulator patched with IEEE 802.16e and Proxy Mobile IPv6 modules as well as our implementations of several mobility management schemes. We compared the
performance of the 2MR scheme with alternative models, under various real-life conditions.

The environmental settings of the handover simulations are detailed in Fig. 6. First, we use a train with length $L$ (300 is used in the following simulations if not otherwise specified) meters and speed $S$ km/h. The radius of a BS is 5 km, and the overlap of two adjacent cells is 400 m. In our configuration, the QoS router functions reside in the MRt. The transmission delay and.  

**Fig. 5.** The 2MR inter-LMA-Domain handover. 

**Fig. 6.** The environment and the settings of handover simulations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>One-way delay between BS and ASN</td>
<td>10 ms</td>
</tr>
<tr>
<td>One-way delay between MAG and LMA</td>
<td>5 ms</td>
</tr>
<tr>
<td>One-way delay between neighboring LMAs</td>
<td>2 ms</td>
</tr>
<tr>
<td>One-way delay between RRs</td>
<td>0.5 ms</td>
</tr>
<tr>
<td>Hop count from the LMA</td>
<td>3 hops</td>
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C-W. Lee et al. / Computer Communications 37 (2014) 53–63
processing overhead of each link, which are carefully selected to fit real-life conditions, are shown in Fig. 6. The performance of our 2MR scheme is compared with two other schemes: 1MR and 1MR-f. Whereas 1MR is the base case that deploys a single MR in the last carriage, 1MR-f has one MR with a forwarding tunnel between the serving BS and target BS established at the WiMAX Preparation Phase. In order to clearly demonstrate the handover effect between the different schemes, we use a 64 kbps constant bit rate (CBR) flow over UDP with a 10 ms packet interval sent from a CN. In the simulations, handover delay is defined as the time interval between the time that the train receives the last packet via the serving BS, and the time that it receives the next packet via the target BS.

5.1. Intra-LMA-Domain handover

First, the train moves from the coverage of BS1 towards BS2. Each case is run thirty times; the average handover delays of the 1MR, 1MR-f and 2MR schemes using different train speeds are shown in Fig. 7. When attached to the target BS, 1MR-f can receive forwarded packets immediately. In contrast, the 1MR scheme must wait for the target BS to tell the anchor ASN-GW to redirect the packet towards it, which incurs an extra 20–30 ms delay. In the 2MR scheme, prior to the MRt handover, the DL flow is redirected to the MRh via the target BS; the handover delay is contributed to only by the packet inter-arrival time and the link delay between the MRh and the MRt.

The end-to-end transmission delay and packet sequence trace of a speed of 450 km/h are illustrated in Fig. 8 and Fig. 9. Both the 1MR and 1MR-f schemes scan for candidate target BSs before handover. As a result, they cannot receive the DL flow from the serving BS, which explains the packet delay surges that occur before their handovers in Fig. 8. During handover, 1MR suffers from packet losses and 1MR-f experiences another packet delay surge, while 2MR has neither problem. From Fig. 9, the above phenomena can be observed from their packet sequence traces. The transmission bursts of 1MR and 1MR-f indicate that the BS must allocate additional wireless bandwidth to the train, which may be difficult in a congested or low link quality network. Packet disorder can be observed in 1MR-f from Fig. 9. For 2MR, there is no packet loss, no burst transmission and no disordered packets observed, at the cost of negligible additional link delay from the MRh to the MRt.

5.2. Inter-LMA-Domain handover

Fig. 10 shows the average handover delays in thirty simulations of inter-LMA-Domain handover for 1MR, 1MR-f and 2MR when the train moves from BS3 to BS4. In Fig. 10, 1MR must complete the re-registration to the HAMR before receiving the DL flow via the target BS.
BS, which results in a long (~240ms) handover delay. In contrast, the inter-LMA-Domain handover delays for 1MR-f and 2MR are similar to the intra-LMA-Domain handover, because both defer re-registration while using a forwarding tunnel to forward packets to the target BS. For the end-to-end transmission delay of the representative flow, Figs. 11 and 12 show similar delay curves and trends for 1MR, 1MR-f and 2MR when the speed is 450 km/h. In 1MR, the time gap in which the MR cannot receive packets are larger than that in Intra-LMA-Domain handover, causing a longer interruption on communication. Note that for 1MR-f, a forwarding tunnel can reduce handover delay, but adds extra end-to-end delay when packets are forwarded from the serving to the target BS, as observed in Fig. 11.

### 5.3. Performance of VoIP

In this section, we evaluate the performance of VoIP in 1MR, 1MR-f and 2MR schemes. In this simulation, there are seventeen CN-VMN pairs each holding a VoIP call, which means each call is a bi-directional real-time communication stream. The codec of the VoIP calls is G.729a (i.e., the one-way CBR throughput and packet interval are 8 kbps and 20 ms, respectively). In 1MR and 1MR-f, the MRs start handover at the 15.49th second; and in the 2MR scheme, the MRh and the MRt handover at the 12.98th and 15.49th second.

Packet inter-arrival jitter is derived from a function of changing in transmission delay which indicates the degradation of the quality of the communication when the value increases. Fig. 13 illustrates the average packet inter-arrival jitters of intra-LMA-Domain and inter-LMA-Domain handover. In 1MR and 1MR-f, the inter-arrival jitters start increasing due to the scanning process which temporarily increases the transmission delay. In 1MR, after experiencing packet loss, the jitter gradually decreases because the transmission delay is almost the same before handover. In 1MR-f, the jitter keeps increasing due to the surge of transmitting buffered packets under the target BS. In addition, the jitter peak of DL direction is higher than that of UL due to the packet-forwarding from the serving to target BS which adds extra transmission delay to packets. In the 2MR scheme, the switching of transmitting via the MRh and the MRt only causes two ignorable increments of the jitter both in intra- and inter-LMA-Domain handover, and thus do not introduce any factor that would affect the stability of transmission delay.

For a VoIP call, the quality of the reconstructed voice signal at the receiver peer is subjective and is therefore measured by the mean opinion score (MOS), which ranges from 1 (worst) to 5 (best). To provide a parametric estimation, the ITU-T E-Model [18] defines an R-factor that combines different aspects of voice quality impairment and a nonlinear mapping from the R-value to MOS. We use

![Fig. 11. The end-to-end transmission delay of inter-LMA-Domain handover.](image1)

![Fig. 12. The packet sequence trace of inter-LMA-Domain handover.](image2)

![Fig. 13. The average packet inter-arrival jitter of (a) intra- (b) inter-LMA-Domain handover.](image3)
the parameters in [19] and calculate the mean opinion scores (MOS) of both downlink (DL) and uplink (UL) direction.

In Fig. 14, the average DL and UL direction MOS of both intra-LMA-Domain and inter-LMA-Domain handover are illustrated. The G.729a codec compresses voice signal to save bandwidth at the cost of both incurring signal loss during compression and introducing extra delay time in compression and decompression; thus the MOS will not reach 5. During handover in 1MR and 1MR-f, packet loss and transmission delay increments degrade the MOS to 1. In our simulation, packet loss is a major factor that causes the degradation of the MOS, and it takes more time to recover to high MOS in inter- than in intra-LMA-Domain handover. In the 2MR scheme, the responsibilities of transmitting and receiving packets are smoothly switched between the MRh and the MRt. Handovers suffer from no dis-ordered packets and no packet loss, and there is no decrease in quality of the VoIP calls.

5.4. Permissible handover time

We denote $DW_{\text{WiMAX-Reg}}$ as the time interval between the time that the MR completes the ranging process and the time that it receives the REG-REP message of IEEE 802.16 from the target BS. During $DW_{\text{WiMAX-Reg}}$, the MR is authenticated and authorized by the target BS and some network components before it can use the network resources, and thereby transmit and receive packets. When performing intra-LMA-Domain handover, if 802.16e is used, the $DW_{\text{WiMAX-Reg}}$ can be very short because most parts of the handover procedure are done before the MR detaches from the old BS. However, when performing inter-LMA-Domain handover, the $DW_{\text{WiMAX-Reg}}$ is longer due to the time-consuming authentication and authorization processes.

Fig. 15 shows how the $DW_{\text{WiMAX-Reg}}$ affects the inter-LMA-Domain handover delays in the 1MR, the 1MR-f and the 2MR schemes. The train length is set to 300 m and the speed of the train is 450 km/h. In 1MR and 1MR-f, the handover delay increases when it takes more time in the WiMAX registration. In the 2MR scheme, the train’s length provides an advantage that gives the system more time to finish the WiMAX entry procedures.

Here we discuss the permissible time for a seamless handover for the 2MR scheme. The permissible handover time, denoted as $T_{\text{th}}$, is the time interval from the time that the MRh breaks down the wireless link with the serving BS to the time that the MRt breaks the link down in the 2MR handover protocol. If the MRh completes the network entry and re-entry procedure within $T_{\text{th}}$, the DL and UL flows can be handed over without disturbing the on-going sessions. $T_{\text{th}}$ can be derived by dividing the train’s length ($L$) by its speed ($S$). For instance, for a train with length 300 m and speed 360 km/h, $T_{\text{th}}$ is 3 s.

Let $DM_{\text{MRBHO}}$ be the time that the MRh finishes handover and it can be calculated by:

$$DM_{\text{MRBHO}} = DL_{\text{HO}} + DW_{\text{WiMAX-Reg}} + D_{2\text{MR} \cdot \text{inter-LMA}}$$ (1)

$DL_{\text{HO}}$ is the delay of physical radio switching. $I_{\text{inter-LMA}}$ is 1 when the handover is an inter-LMA-Domain handover; 0, otherwise. In inter-LMA-Domain handover, $D_{2\text{MR}}$ is the transmission and processing delays of PBU from the target MAG to the target LMA and 2MRFW.

The relationship between handover delay, $T_{\text{th}}$ and $DM_{\text{MRBHO}}$ when using the 2MR scheme is shown in (2):

$$\text{handover delay} = \begin{cases} DM_{\text{MRBHO}} - T_{\text{th}}, & \text{if } T_{\text{th}} \geq DM_{\text{MRBHO}} \\ DM_{\text{MRBHO}} - T_{\text{th}}, & \text{if } T_{\text{th}} < DM_{\text{MRBHO}} \end{cases}$$ (2)

and is illustrated in Fig. 16. $DM_{\text{MRBHO}}$ is the link delays from the MRh and the MRt to the QoS router, respectively, which are negligible. From the viewpoint of the train, when the $DM_{\text{MRBHO}}$ increases, it requires larger $T_{\text{th}}$ (meaning a longer train length or slower train speed) for seamless handover. In the event that $DM_{\text{MRBHO}} > T_{\text{th}}$, a seamless handover becomes unlikely, unless the MRt handover could be postponed, which implies a poor transmission quality in the extended period.

The success of a seamless handover is also affected by the length of two neighboring BSs’ overlap area, denoted as $L_{\text{op}}$. Before starting to switch radio to the target BS (i.e., $DL_{\text{HO}}$), the MRh has to scan and report information about the candidate target BSs.
to the serving BS, the handover decision has to be made, and the network components involved in this handover event have to negotiate for this handover event. We denote the time spent on all the tasks above as $D_{\text{pre-HO}}$ and denote $T_{\text{req}}$ as the time that the train traverses the overlap area, i.e., $L_{\text{req}}/S$. In the case that $T_{\text{req}} < D_{\text{pre-HO}}$, due to the lack of sufficient knowledge of each other, the MRs and the infrastructure (e.g., the target BS and the target MAG) have to perform an initial network entrance procedure, and the required time is denoted as $D_{\text{en}}$. The $D_{\text{MR-HO}}$ in (1) can thus be refined to $D_{\text{MR-HO}}'$ as in (3):

$$D_{\text{MR-HO}}' = \begin{cases} D_{\text{en}} + D_{\text{WMAX-Reg}} + D_{2MR} \cdot f_{\text{inter-LMA}} & \text{if } T_{\text{req}} \geq D_{\text{pre-HO}} \\ D_{\text{en}}, & \text{if } T_{\text{req}} < D_{\text{pre-HO}} \end{cases}$$

(3)

The effects of large $D_{\text{MR-HO}}$ are illustrated in Fig. 16.

6. Conclusion

Improvements in train speeds are clashing against similarly impressive achievements in smart mobile device technologies. Customers are increasingly desiring and expecting uninterrupted mobile Internet access, even on long train rides. However, providing broadband wireless communication to high-speed trains relies on the precision of BS planning, which demands high monetary and manpower costs. The proposed 2MR network mobility scheme takes advantage of the physical size of high-speed trains to deploy two mobile routers (MRs) and offers a protocol to allow the two MRs to cooperate with wireless network infrastructure in providing a seamless handover. The 2MR scheme effectively alleviates the problem of improper BS-planning, and is easy to deploy. By deploying two MRs at the first and last carriage, and designing new messages and functionalities in the PMIPv6-based infrastructure, the handover latency as well as packet loss is reduced while adding negligible extra data transmission delay.

Reference