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Research Article

Cross-Layer Design of the Inter-RAT Handover between UMTS and WiMAX

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In future mobile networks, different radio access technologies will have to coexist. IEEE 802.21 MIH (Media-Independent Handover) provides primitive mechanisms that ease the implementation of a seamless vertical handover (inter-RAT handover) between different radio access technologies. However, it does not specify any handover execution mechanism. The first objective of this paper is to propose a novel MIHF (Media-Independent Handover Function) variant, which is renamed interworking (IW) sublayer. IW sublayer provides a seamless inter-RAT handover procedure between UMTS and WiMAX systems. It relies on a new intersystem retransmission mechanism with cross-layer interaction ability providing lossless handover while keeping acceptable delays. The second objective of this paper is to design a new TCP snoop agent (TCP Snoop), which interacts with the IW layer in order to mitigate BDP (Bandwidth Delay Product) mismatch and to solve spurious RTO (Retransmission TimeOut) problems. The cross-layer effects on the handover performance are evaluated by simulations. Our results show that cross-layer interaction between IW layer and TCP Snoop smoothes the handover procedure for TCP traffics. Additionally, this novel inter-RAT cross-layer scheme has the merit of keeping existing TCP protocol stacks unchanged.

1. Introduction

The future fourth-generation (4G) systems will coexist with different radio access technologies, such as GSM/GPRS, UMTS, WiFi, and WiMAX. Multimode or multi-RAT MS (Mobile Station) shall have the ability to seamlessly roam among these heterogeneous networks without disrupting ongoing sessions or connections. Intensive research efforts have been made to define efficient seamless mobility procedures, commonly referred to as vertical handover or inter-RAT (Radio Access Technologies) handover. Hence, many proposals to solve the mobility management problems in heterogeneous wireless networks can be found in the literature. For example, [1] defines the Mobile IPv6 within the network layer to provide transparent support for host mobility. It introduces movement detection, IP address configuration, and location update procedures. However, many experiments and simulations have shown difficulties in efficiently maintaining sessions' continuity during handover, due to long latency and high packet loss rate issues [2]. Another typical and successful handover solution is the 3GPP inter-RAT handover solution in [3]. It can achieve lossless handover procedure by applying sequence number synchronization mechanism at LLC layer (Logical Link Control). Unfortunately, the 3GPP inter-RAT solutions only support inter-RAT handover between cellular networks, for example, between GSM (Global System for Mobile communications) and UMTS (Universal Mobile Telecommunications System). Hence, inter-RAT handover between 802-based networks and cellular networks, for example, between WiMAX (Worldwide Interoperability for Microwave Access) and UMTS, is not supported.

Thus, a seamless and smooth inter-RAT handover procedure does not only depend on the handover mechanism design, for example, the location update, address reconfiguration, and data flow rerouting, but it is also tightly related to several important network issues, as follows.

1.1. Coupling Approaches. When applying an inter-RAT handover scheme to the 802-based networks and non-802-based networks, a given interworking architecture, allowing some forms of coupling between these networks, shall be deployed. However, different interworking architectures provide different service qualities for data access and different levels for the seamless roaming. Therefore, one important issue about future wireless system is the design of the coupling architecture allowing the implementation of efficient inter-RAT handover schemes. Depending on the existence of the coupling point and where it is implemented, there are several interworking architectures, namely: no coupling, loose coupling, tight coupling, and very tight coupling (integrated coupling). Taking the interworking scenario between WiMAX and UMTS, for example, as illustrated in Figure 1, loose coupling indicates that the interworking point is behind the GGSN (Gateway GPRS Support Node). Tight and integrated coupling assume interworking at the UMTS SGSN (Serving GPRS Support Node) level or GGSN (Gateway GPRS Support Node) level, and at the UMTS RNC (Radio Network Controller) level, respectively.

Reference [2] summarizes existing handover solutions' performance in different coupling architectures. For example, in UMTS-WiMAX networks, in general, the loose coupling architectures often use Mobile IPv6 or part of Mobile IPv6 as the handover management protocol and require few complicated modifications of the existing UMTS architecture. However, loose coupling approaches often suffer from handover latencies, varying from hundreds of milliseconds to several seconds. Mobility management schemes for integrated and tight coupling approaches are often based on the existing mobility solutions of the UMTS network. Therefore, these approaches require significant modifications to the existing access network architectures and redesign of network protocols, for example, deployment of a NodeB emulator or an RNC emulator. However, integrated and tight coupling approaches can achieve a better handover performance compared to loose coupling approaches. For the design of future high reliable heterogeneous wireless networks, integrated and tight coupling architectures appear as the preferred option.

1.2. Context Transfer. Inter-RAT handover performance is usually evaluated with some recognized metrics, such as drop rate, blocking rate, handover delay, and packet loss. Since most of the future radio access networks are based on data technologies, eliminating packet losses becomes the primary objective. To achieve a lossless handover procedure, the most common solution is applying the context transfer mechanisms to forward context-related data and parameters from the source network to the target network. Thus, what are the most suitable context transfer schemes for a future inter-RAT handover procedure is another important issue.

In 3GPP UMTS network, the PDCP (Packet Data Convergence Protocol) sequence number synchronization procedure [4] is applied to guarantee reliable data transmission service during SRNS (Service Radio Network Subsystem) relocation. PDCP entity maintains PDCP sequence numbers to avoid any data loss. After a successful relocation, the data transmission starts from the (first) unconfirmed SDU (Service Data Unit) having a sequence number equal to the next expected sequence number by the PDCP entity. Unfortunately, in the case of inter-RAT handover, the PDCP sequence number synchronization mechanism cannot be used any more because non-3GPP systems usually do not have a similar synchronization mechanism, especially IEEE 802-based RATs, such as WiMAX or WiFi.

Moreover, buffering-and-forwarding is the most commonly used context transfer scheme for eliminating packet losses. During a handover period, the source network forwards unsent packets/frames to the target network as well as other connection-related parameters. Generally, this scheme cannot eliminate packet losses effectively. For example, if buffering-and-forwarding scheme is deployed at IP layer, during inter-RAT handover period, packets stored at lower layers of one RAT, for example, at link layer, usually cannot be retrieved by the IP layer. So, IP layer buffering-and-forwarding scheme cannot recover lost packets after handover, and the communication may be broken down.

Sachs et al. [5] proposes the SDU reconstruction scheme. In order to support lossless handover, segments stored in the PDU (Packet Data Unit) buffer of source link are first reconstructed back to an SDU and then forwarded to the target link as well as the SDUs from the SDU buffer. However, during the handover period, an SDU, whose corresponding PDUs have not been totally and successfully transmitted, cannot be reconstructed and will be discarded locally. This is because the successfully transmitted PDUs have been already removed before from the local PDU buffer. Therefore, the packet loss during handover period is generally unavoidable.

In [6], a retransmission mechanism is utilized to eliminate packet losses at a sublayer called R-LLC (Remote Link Layer Control) on the BTS for handover between GPRS and WiFi. In the downlink, when a handover is made, a retransmission timer is set for a transmitted packet at R-LLC sublayer. If the acknowledgement corresponding to a transmitted packet cannot be received before its retransmission timer expiration, R-LLC retransmits this unacknowledged packet that is lost during inter-RAT handover. The packet loss is only indicated by retransmission timer timeout, which is set to 5 sec. Unfortunately, the local retransmission window at R-LLC sublayer is not defined. So, buffer overflow at lower layers is unavoidable. Likewise, inter-RAT handover execution mechanism at R-LLC is not specified in [6].

1.3. TCP-Specific Handover Problems. In addition, for the TCP traffic, inter-RAT handover procedure faces some specific problems, such as BDP (Bandwidth Delay Product) mismatch, premature timeout, false fast retransmit, and spurious RTO (Retransmission TimeOut) [2]. These traffic-specific problems make many conventional handover schemes ineffective, because these schemes are generally based on the assumption of simplified traffic, for example, UDP traffics. Therefore, an effective and traffic-oriented inter-RAT handover scheme is desired for future heterogeneous networks.

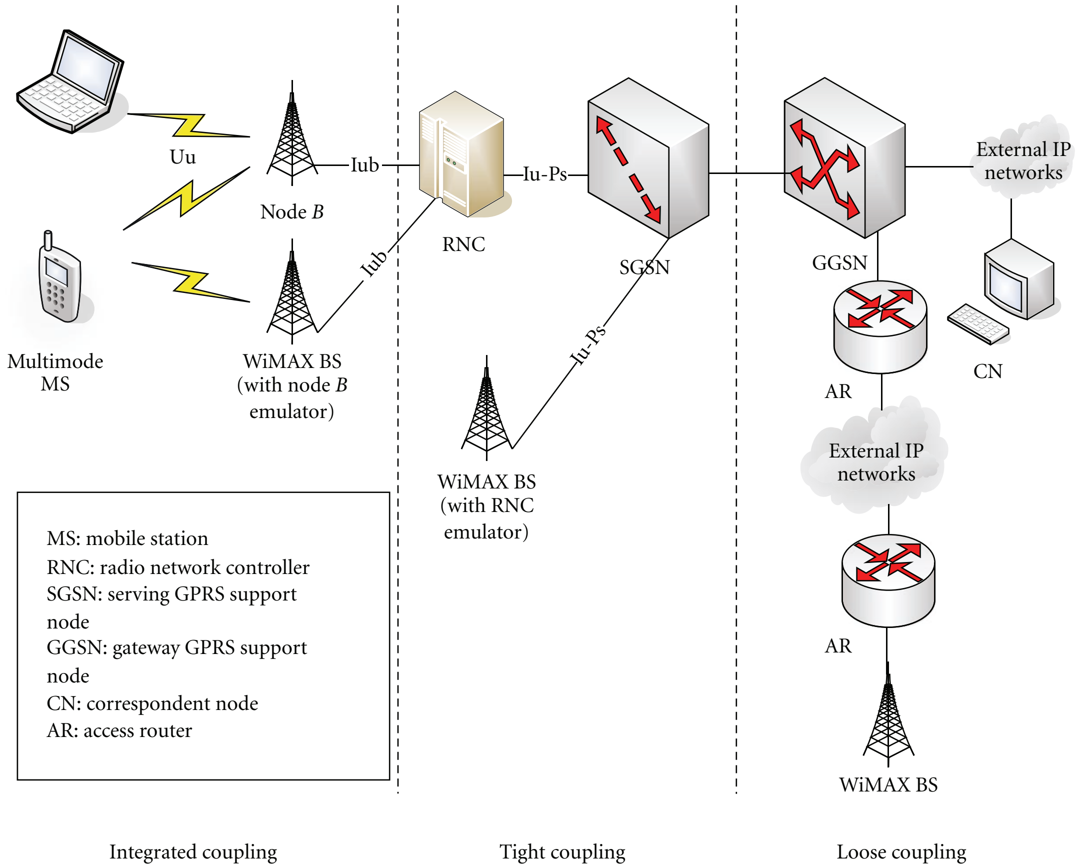


Figure 1: Different UMTS-WiMAX interworking approaches.

For TCP-specific handover problems, the existing solutions are generally classified into network-centric and receiver-centric approaches. Network-centric approaches, such as M-TCP [7], TCP proxy [8–10], and snoop protocol [11, 12] split a TCP connection between a CN (Correspondent Node) and an MS. In M-TCP, when a handover is detected, base station sends back the last byte's ACK with zero window size. This ACK forces TCP sender to enter into persist mode. In the persist mode, the values of congestion window (cwnd) and slow-start threshold (ssthresh) are frozen. When a new base station detects handover completion, it immediately notifies TCP sender to resume transmission with the frozen cwnd and ssthresh. Unfortunately, M-TCP is originally designed for horizontal handover and does not consider the wireless link BDP and RTT (Round Trip Time) variations. In [8], a TCP proxy is used to overcome problems of stemming from a large BDP of WCDMA wireless link. An improved TCP proxy is proposed for inter-RAT handover in [10], and yet it suffers from high signaling cost and cannot work in transparent mode after handover. In [11, 12], the snoop protocol introduces a module, called snoop agent at base station. This agent monitors every TCP packet for a connection in both directions and maintains a cache of TCP packets sent across wireless link that have not been acknowledged by MS. A packet loss is detected thanks to duplicate ACKs for MS or local timeout. On a packet loss, the snoop agent retransmits the lost packet if it has cached it on behalf of TCP sender. This snoop protocol is considered as a link-layer protocol that takes advantage of knowledge of TCP protocol. However, snoop protocols are not designed for handover among heterogeneous networks.

Other ways to solve TCP-specific handover problems are receiver-centric approaches. In these approaches, the MS knows the handover occurrence; thus, the MS takes charge of congestion control by modifying ACK message protocol header or feeding back specific ACK messages. For instance, in Freeze-TCP [13], the tasks of base station of M-TCP are shifted to the MS side.

1.4. Mobility Management Framework. IEEE 802.21 [14] is a standard to enable handover and interoperability between heterogeneous network types including both 802-based and non-802-based networks. It defines an extensible media-independent handover (MIH) framework enabling transparent service continuity as an MS roams among different access networks. In this framework, a logical entity MIH function (MIHF) is proposed between layer-2 and layer-3. It can provide cross-layer abstract services to the higher layers through a media-independent interface, and it can obtain cross-layer information from the lower layers through media-specific interfaces. These MIHF abstract services may be either local or remote, that is, local operation occurring within a protocol stack and remote operation occurring between two distant MIHF entities. Thus, MIHF is a very useful facility for link layer inter-RAT handover.

However, how to apply IEEE 802.21 framework to UMTS-WiMAX integrated and tight coupling architectures is still an open problem. In IEEE 802.21 standard, for coupling 802-based networks with cellular networks, generally the MIH PoS (Point of Service) resides deeper inside the access or core networks. Hence, when connected to a 3GPP network such as UMTS, an MS uses layer 3 IP transport to conduct signaling or messages exchanges [14]. This becomes a problem for UMTS-WiMAX integrated coupling architecture, because the layer 3 (IP layer) terminates at SGSN network entity, which is not included in this coupling architecture. In addition, IEEE 802.21 MIHF only defines abstract service model in control plane, and it does not attempt to specify the actual handover execution mechanism. Therefore, how to design an effective handover execution mechanism in user plane remains an implementation issue.

1.4.1. Our Contributions. According to above inter-RAT handover-related issues, in this paper, we propose our traffic-oriented inter-RAT handover as a complete solution. In consideration of the advanced features and limitations of IEEE 802.21 framework, a novel IEEE 802.21 MIHF variant is proposed to realize a seamless inter-RAT handover procedure for integrated and tight coupling architectures. Different from conventional IEEE 802.21 MIHF, this MIHF variant is deployed in both control plane and user plane. In the user plane, it introduces a new intersystem retransmission mechanism and applies cross-layer mechanism to resolve packet loss and long handover latency problems. In the control plane, it simplifies MIHF services model by only defining a few cross-layer triggers and information from lower layers or to upper layers. In order to differentiate it from standardized MIHF framework, this MIHF variant is renamed InterWorking (IW) sublayer scheme. Thus, the primary objective of this paper is to illustrate the flexibility and suitability of this IW sublayer scheme for future heterogeneous wireless networks. In the following, due to the simplified service model in the control plane in IW sublayer scheme, we will not deliberately differentiate control and user planes for the sake of simplicity.

In this paper, we also propose a new TCP snoop agent (TCP Snoop) solution with cross-layer mechanism. Different from enhanced TCP proxy in [10], new inter-RAT handover mechanisms are defined in TCP Snoop and only few pieces of signaling are needed. Furthermore, TCP Snoop can work in transparent or disabled mode after handover. Then, the secondary objective of this paper is to evaluate and highlight the benefits of cross-layer interaction between IW sublayer and the new snoop agent in achieving a smooth inter-RAT handover procedure for TCP traffics.

In our previous work [15, 16], only the IW sublayer itself was discussed. Compared with this previous work [10, 15, 16], the novelties of this paper are the enhanced IW sublayer with cross-layer mechanism and the new TCP Snoop. In the sequel, the terminologies "vertical handover" and "inter-RAT handover" will be used interchangeably with "handover." Likewise, we only consider the downlink. The remainder of this paper is organized as follows: in Section 2, firstly, we describe the common IW sublayer framework. Then, we specify the intersystem retransmission and cross-layer mechanisms at IW sublayer in the tight and integrated coupling architectures. Afterwards, in Section 3, the new TCP Snoop and its cross-layer interaction with IW sublayer are also specified in detail. The simulation results are given. Finally, our conclusions are drawn in Section 4.

2. Cross-Layer between Layer-2 Sublayers

2.1. The InterWorking (IW) Sublayer. In this section, we propose a novel MIHF variant at layer-2 for the inter-RAT handover between UMTS and WiMAX. This novel MIHF variant is named IW sublayer. Figure 2 describes integrated coupling and tight coupling architectures for UMTS-WiMAX handover scenario.

In the integrated coupling architecture, IW sublayer is introduced on top of PDCP sublayer of UMTS and MAC (Medium Access Control) sublayer of 802.16e, at both the terminal and RNC (Radio Network Controller) sides. The WiMAX BS (Base Station) is integrated with the RNC through the Iub interface. This common IW sublayer takes the role of LLC sublayer of conventional cellular networks, such as retransmission mechanism and handover support. The main functions of the IW sublayer include

(1) primitives mapping between the IW sublayer and the UMTS network, or between the IW sublayer and the WiMAX network in the case of inter-RAT handover;

(2) neighboring networks information acquisition, such as channel information, capacity, and MAC address, to facilitate handover,

(3) SR ARQ (Selective Repeat ARQ) retransmission mechanisms, including packet segmentation, resequencing, retransmission, and retransmission window size adjustment. For notation simplicity, we call this kind of ARQ mechanism IW ARQ.

In the tight coupling architecture, the WiMAX network may emulate an RNC or an SGSN. We consider RNC emulation in this paper. Thus, we introduce a new network component called RNC emulator for WiMAX (W-RNC) in the WiMAX access network. The W-RNC meets the UMTS core network at the Iu-PS interface, as shown in Figure 2 (right part). The W-RNC can also be realized by enhancing WiMAX BS with additional interface functionalities:

(1) realization of Iu-PS interface,

(2) performing signaling translation and message exchange between SGSN and WiMAX BS,

(3) in addition to the functions in integrated coupling architecture, the IW sublayer located on W-RNC has another new function—IW context transfer. When a handover takes place, the source IW sublayer transfers IW contexts to target IW sublayer, such as received IW ACK messages, unsent and unconfirmed IW blocks, and ARQ parameters at the IW sublayer.

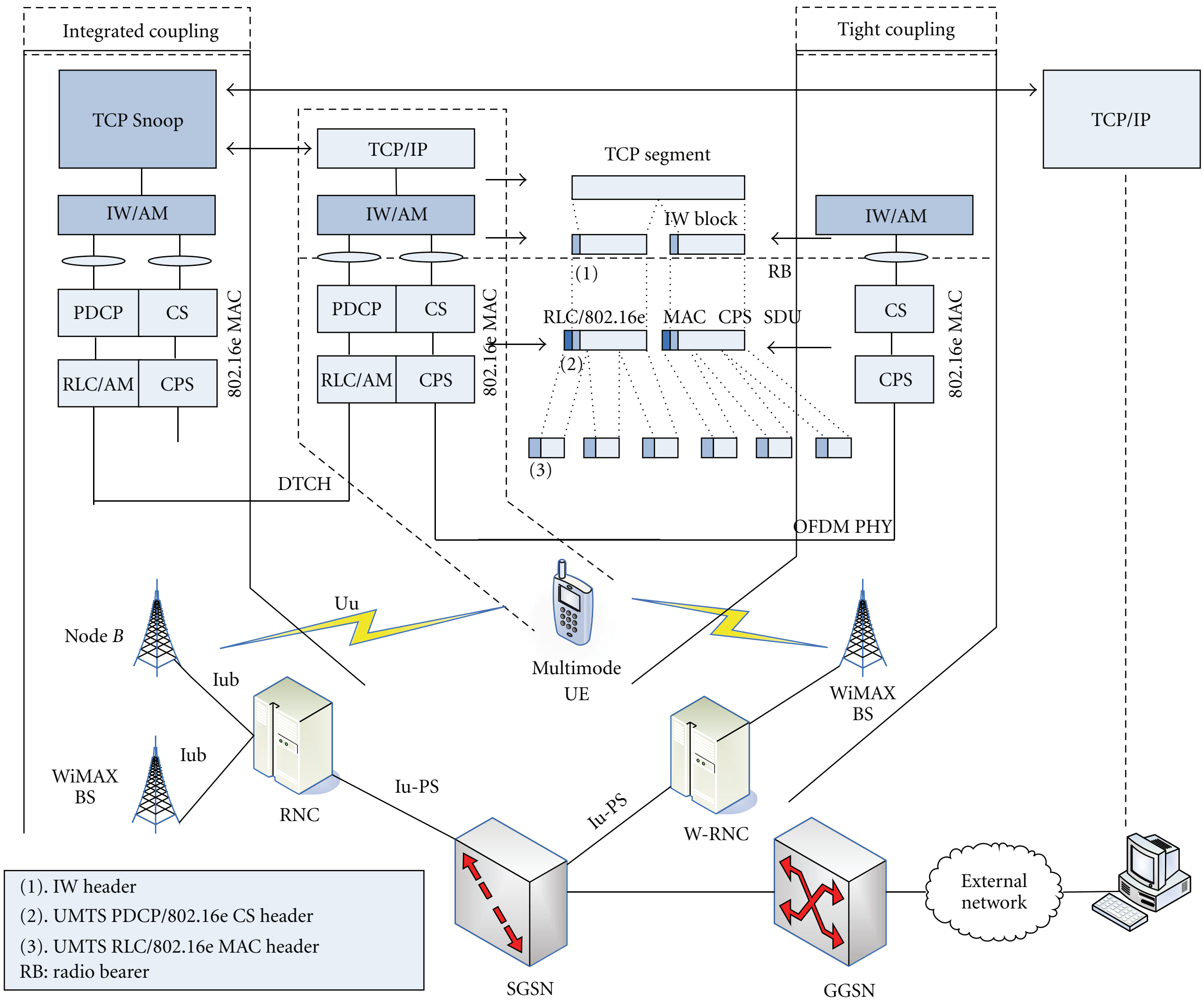


FIGURE 2: User plane protocol stacks in integrated coupling (left) and tight coupling (right) architectures.

Here, there are two reasons to apply ARQ mechanism at IW sublayer in addition to PDCP context transfer of conventional RNC:

(1) when an inter-RAT handover takes place, there may exist packet sequence number desynchronization between the source and target networks. It is necessary to design a common packet sequence number synchronization mechanism for the two systems to provide a lossless handover;

(2) the second reason is that the WiMAX supports cell reselection initiated by MS for active traffics (corresponding to dedicated mode in UMTS), which is not the case in UMTS. Hence, the packets lost during cell reselection from WiMAX to UMTS may not be retransmitted by target UMTS network.

Compared with MIHF network entity of IEEE 802.21 framework, the IW sublayers in the control plane in the integrated and tight coupling architectures are similar to MIHF, but the service models of MIH are simplified considerably. Only few cross-layer triggers and cross-layer information are required for a lossless and prompt inter-RAT handover procedure. These necessary cross-layer triggers and cross-layer information will be specified in the following sections. Due to the operation and function similarities of IW sublayer in the integrated and tight coupling architectures, in the left of this paper, only the IW sublayer of integrated coupling is described in detail.

2.2. IW ARQ Context Transfer Mechanism. For the sake of achieving lossless inter-RAT handover, we apply a modified Selective Repeat ARQ (SR ARQ) with a cross-layer mechanism at the IW sublayer level during the handover period. The IW ARQ is an error control mechanism that involves error detection and retransmission of lost or corrupted packets. When a packet is accepted from upper layer, it is first segmented into smaller IW blocks, each of which is assigned a sequence number (see Figure 3). This new IW subheader

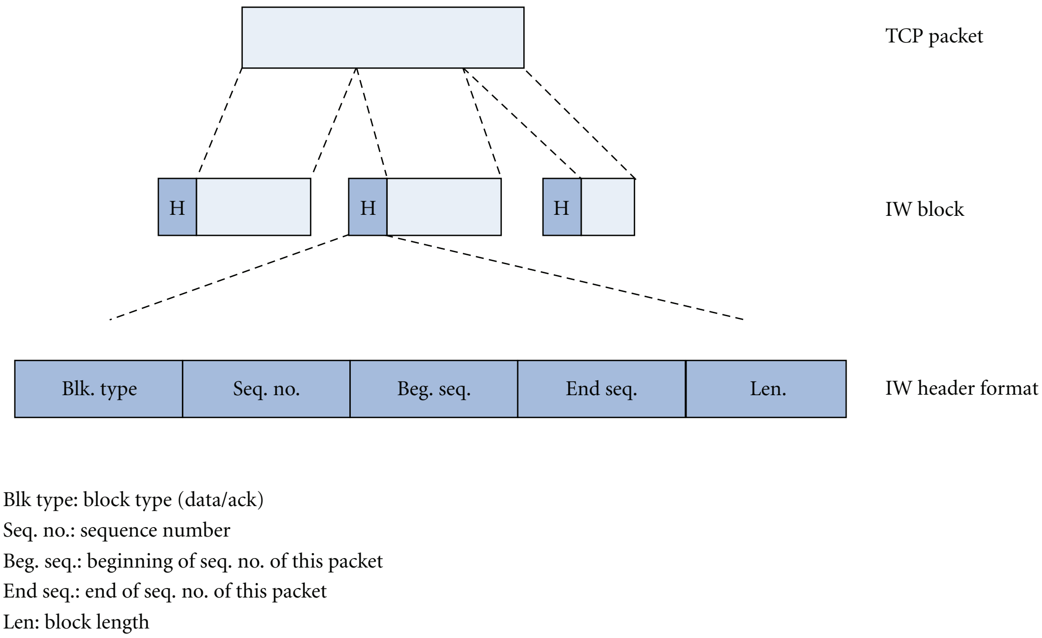


Figure 3: IW block header format.

is used for block loss detection and block resequencing in the receiver to guarantee in-sequence delivery. Then, these IW blocks are stored in a local block buffer. When some IW blocks are transmitted through the UMTS or the WiMAX interface according to a retransmission window size, they are also queued in a retransmission queue (Different from conventional retransmission queue definition, in this paper, the retransmission queue refers to the queue that stores transmitted but not acknowledged blocks.) in order to be scheduled for possible retransmission. The IW ARQ transmitter maintains an adaptive retransmission window size that is set to current network buffer size, or wireless BDP size, or simply a default value. When handover begins, IW sublayer just stops transmitting blocks. It segments every incoming packet and keeps blocks in the block buffer. When handover completes (e.g., on receipt of Link_Up trigger), IW sublayer resumes block transmission immediately.

On the receiver side, when an IW block is received by the receiver, a positive or negative acknowledgement (ACK/NACK) is sent back immediately for the purpose of reducing handover latency. These received and buffered IW blocks are reordered to form their corresponding packets. Then packets are delivered to upper layer in sequence.

In addition, in order to avoid dead lock due to IW ACK/NACK losses during a handover period, a timer is set when the receiver sends an ACK/NACK. When this timer expires, the receiver sends back a status report (ARQ feedback bitmap) providing the receipt status. This status report is a map of the acknowledgement or negative acknowledgement of each IW block within the window. The status timer duration is set to a default system parameter, for example, 2.5 sec. When an abnormal handover takes place, for example, Link_Up trigger is lost or long delayed, status timer mechanism can eliminate data packet losses after system recovers from this abnormal handover procedure.

Compared with conventional Selective Repeat Request ARQ (SR ARQ) mechanism, the IW ARQ has following new features:

(i) supporting Link_Up (LU) trigger: when a MS finishes target network entry procedure, the target network signals the IW sublayer with a Link_Up trigger. On receipt of this trigger, the IW sublayer retransmits blocks in retransmit queue to avoid unnecessary waiting for a timeout of status report timer.

(ii) adaptive window size: in order to avoid any buffer overflow in the target network when the IW sublayer retransmits the unacknowledged blocks on Link_Up trigger, the IW ARQ retransmission window size can be optionally set to the buffer size or wireless BDP size of the target network.

2.3. An Example of IW ARQ Operation for Handover from UMTS to WiMAX. In Figure 4, an example of the IW ARQ mechanism is depicted. On Link_Up trigger, the IW sublayer retransmits unacknowledged blocks from sequence number 3. The R-LLC retransmission scheme is also depicted on the right part of this figure. In this figure, the differences between IW ARQ and R-LLC can be noticed. Firstly, the lost blocks are retransmitted when retransmission timers expire in R-LLC scheme, while IW ARQ scheme retransmits blocks not only on status report timer expiration but also on Link_Up trigger. Secondly, the amount of unacknowledged blocks is limited to the retransmission window size during handover procedure in IW ARQ scheme, while there is no retransmission window mechanism in R-LLC.

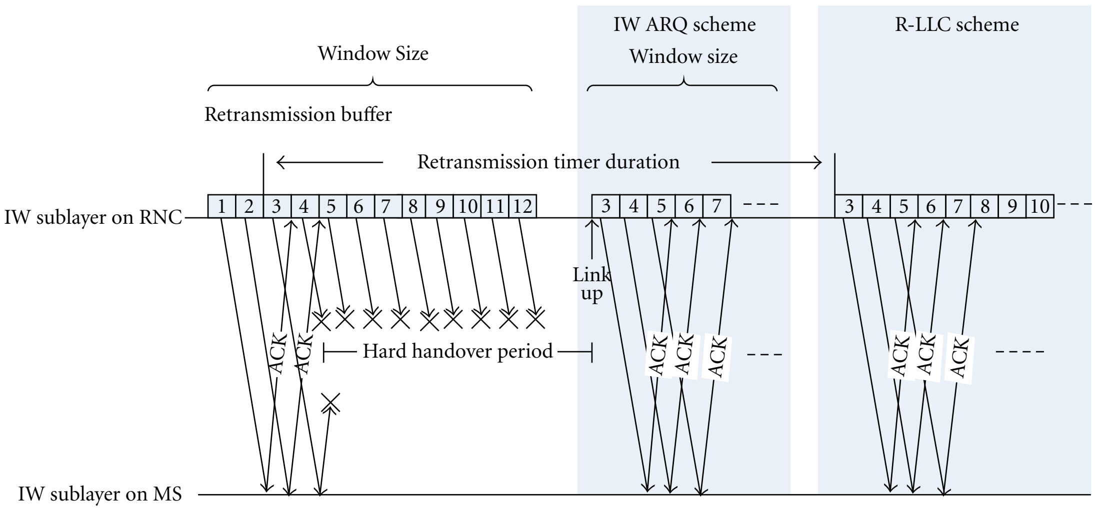


Figure 4: IW ARQ and R-LLC: an example of time evolution.

2.4. Signaling and Primitives. Since a new common IW sublayer is introduced to both UMTS and WiMAX systems, the original handover procedures of these systems shall be modified to accommodate the newly added cross-layer primitives. In general, the inter-RAT handover consists of handover preparation phase and handover execution phase. In the case of a handover from UMTS to WiMAX, when the inter-RAT handover conditions, for example, low RSSI or load increase, are met, the MS is instructed by the RNC to perform measurement of target link. Measurement results are reported to RNC in Measurement Reports message. Afterwards, the inter-RAT handover enters into the execution phase if the RNC makes a positive handover decision. In the case of a handover from WiMAX to UMTS, the MS provides measurement report in scanning report message to the network after the scanning period.

The signaling procedure of handover from UMTS to WiMAX is depicted in Figure 5(a). Firstly, based on measurement reports and knowledge of the RAN (Radio Access Network) topology, the source RRC (Radio Resource Control) decides to initiate an inter-RAT handover and sends Link_Going_Down (LGD) trigger to IW sublayer. On LGD trigger from UMTS RRC sublayer, IW sublayer negotiates the location of the dedicated initial ranging transmission opportunity with WiMAX MAC for the MS. When the MS receives handover command from the network, it switch off UMTS transceiver and switch on WiMAX transceivers. Afterwards, upon receipt of Link_Up trigger from WiMAX MAC, the IW sublayer resumes block transmission immediately and handover completes.

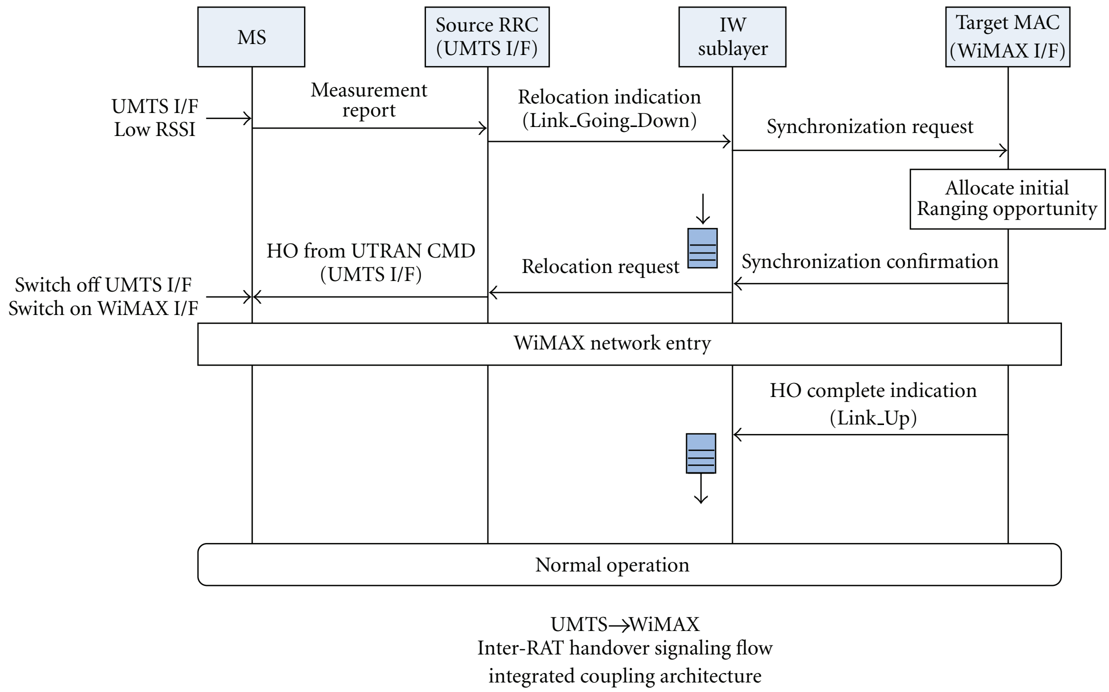
The handover procedure from WiMAX to UMTS is illustrated in Figure 5(b). Before IW sublayer sends handover request message to source WiMAX MAC, it must demand resource reservation with RRC sublayer for the MS on LGD trigger. Afterwards, the MS is instructed by WiMAX network to switches off WiMAX transceiver and switches on UMTS transceiver. After the MS finishes UMTS radio link setup procedure, the IW sublayer resumes block transmission immediately on Link_Up trigger.

Table 1: Simulation parameters.

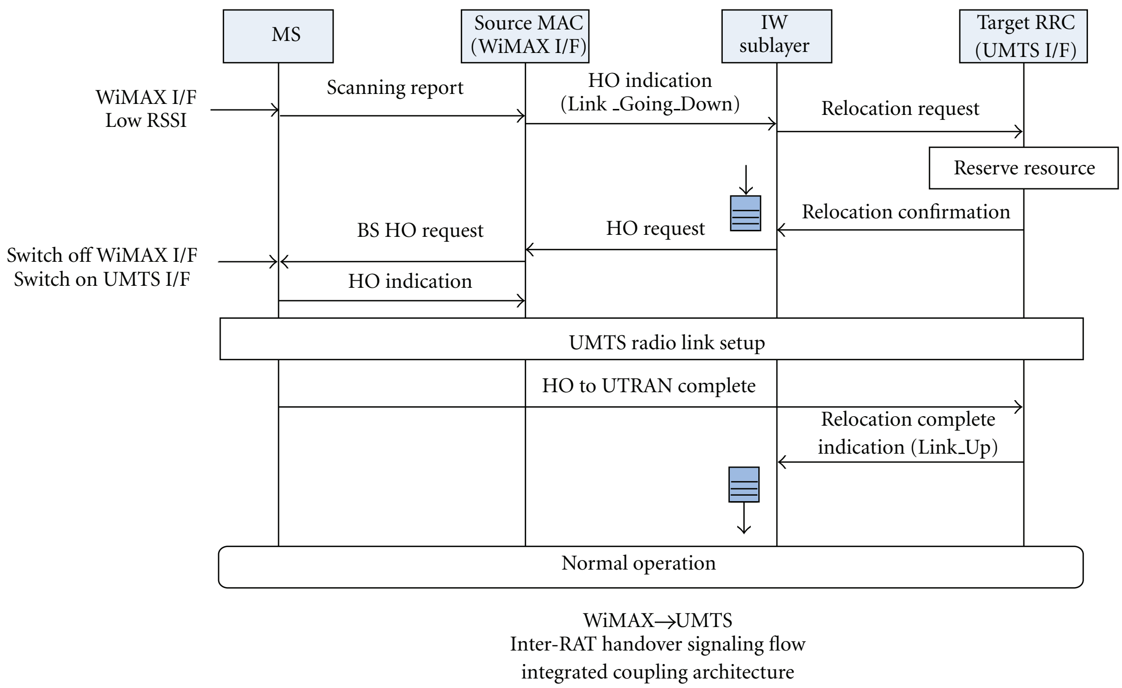
Parameter	Setting
IW fragment switch	OFF
IW default window size	30 blocks
IW status report timer period	2.5 sec.
UMTS PHY data rate	64, 1024 Kb/s
UMTS PDCP queue length	25
WiMAX queue length	50 blocks
WiMAX PHY data rate	2 Mb/s
TCP variant	Reno
TCP MSS	512 bytes
TCP default congestion window	32 segments
TCP minimum RTO timer period	0.2 sec.
Application type	FTP

2.5. Simulation Environment and Results. In this section, we present the results of our simulations on NS2 platform. We conduct this simulation to highlight the benefits of IW ARQ context transfer scheme with cross-layer mechanism. The integrated coupling scenario used for simulation analysis is illustrated in Figure 2, and the simulation parameters are shown in Table 1. There is only one MS with two transceivers and no other background traffics in this "clean" scenario. The transmission delay and bandwidth in the wired network are set to 2 ms and 10 Mb/s, respectively. An FTP session is examined, with the CN designated as the sender and the MS designated as the receiver. The FTP session starts at 0.4 sec, and the MS starts performing hard handover at about 4 sec after it enters into the coverage region of WiMAX or UMTS.

2.5.1. Inter-RAT Handover from UMTS to WiMAX. When the inter-RAT handover is from UMTS to WiMAX, at about 4.035 sec the WiMAX network entry procedure is completed and the IW sublayer on the RNC receives a Link_Up trigger. Figure 6(a) shows the TCP congestion window comparison



(a)



(b)

Figure 5: Inter-RAT handover signaling procedures: (a) UMTS → WiMAX; (b) WiMAX → UMTS.

among three kinds of context transfer schemes: R-LLC, SDU Reconstruction, and IW ARQ.

The R-LLC scheme does not support Link_Up trigger, so R-LLC retransmits the last unacknowledged block on the timeout of local retransmission timer (retransmission timer period is set to 2.5 sec in our simulation scenario). During this period, the TCP RTO timer expires and the congestion window shrinks to one, as shown in Figure 6(a). The SDU Reconstruction scheme suffers from one unsuccessful SDU reconstruction. The remaining out-of-order SDUs (TCP segments here) are forwarded to WiMAX network after handover on RNC and trigger TCP's fast retransmit process. Then the TCP congestion window shrinks to half of congestion window size of steady state. In IW ARQ scheme,

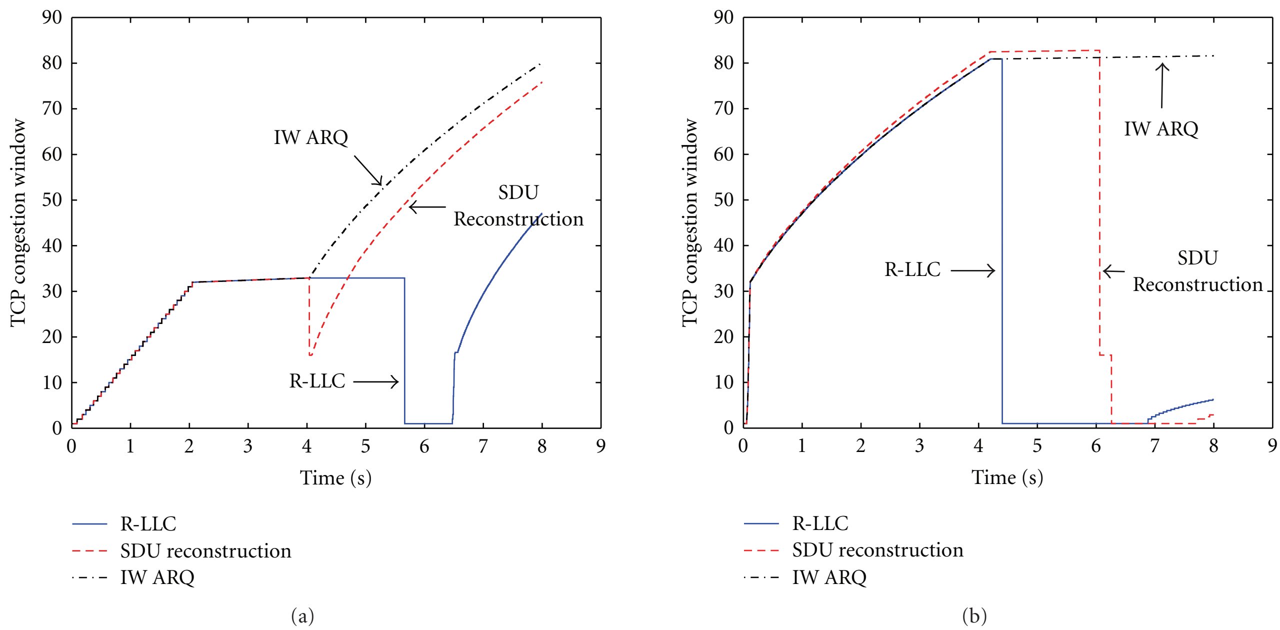


Figure 6: TCP congestion window comparison (UMTS data rate 64 kb/s): (a) UMTS → WiMAX; (b) WiMAX → UMTS.

IW sublayer can set its local retransmission window size to the target network's buffer size when handover is made. On receipt of Link_Up trigger, it immediately forwards the IW blocks in its retransmission queue. So, there are no packet losses during handover period.

2.5.2. Inter-RAT Handover from WiMAX to UMTS. When handover is from high-speed WiMAX network to low-speed UMTS network, the buffered TCP segments forwarded from WiMAX to UMTS overflow the UMTS queue in SDU Reconstruction scheme, because the queue in WiMAX may buffer more TCP segments than the queue size of UMTS. In Figure 6(b), the buffer overflow in UMTS after handover leads to TCP retransmission starting at about 6.0 sec, and the corresponding TCP window shrinks. In R-LLC scheme, the long local retransmission timer period leads to TCP RTO timer expiration. A segment is retransmitted by TCP sender for three times before this local retransmission timer expires, whereas there are no packet losses in IW ARQ scheme and handover procedure is accelerated thanks to the introduction of Link_Up trigger.

3. Cross-Layer between Layer-2 and Layer-4

In the former sections, we apply intersystem retransmission mechanism at common IW sublayer and cross-layer mechanism between layer-2 sublayers to resolve packet loss and long handover latency problems. In this section, we evaluate and highlight the effects of cross-layer mechanism in resolving typical TCP-specific inter-RAT handover problems, such as BDP mismatch and premature timeout/spurious RTO.

Among the existing inter-RAT handover schemes for TCP traffics, network-centric approaches have the advantage of being transparent to both TCP sides in comparison with receiver-centric approaches. Furthermore, the snoop protocol is a TCP-aware link layer scheme, and it can take advantage of information from lower sublayers. For these reasons, in this section, we choose the snoop protocol approach as the basis of our inter-RAT handover performance evaluation for TCP traffic. We first propose a snoop agent with new ACK delaying mechanism and cross-layer mechanism. This new snoop agent runs on RNC and is renamed TCP Snoop in this paper. Then through the evaluation, the necessity and effectiveness of cross-layer mechanism between IW sublayer and TCP Snoop are illustrated in resolving TCP-specific handover problems.

In this section, we assume that (1) the only bottleneck in the path of the TCP connections occurs at the RNC/NodeB; (2) The wireless RTT of WiMAX system is smaller than that of the UMTS system. The BDP size of WiMAX system is bigger than that of the UMTS system; (3) only inter-RAT handover from WiMAX to UMTS is considered. Generally, the BDP mismatch and spurious RTO/premature timeouts problems are not severe for handover from UMTS to WiMAX.

3.1. TCP Snoop Working Mechanism. In Figure 2, a TCP Snoop lies on top of IW sublayer on RNC in the integrated coupling architecture. The TCP Snoop location on RNC not only facilitates the interaction between IW sublayer and TCP Snoop but also makes this TCP Snoop applicable to the 3GPP LTE (Long Term Evolution) network. In the flat IP-based 3GPP LTE network, eNB (Evolved NodeB) provides user plane protocols (PDCP/RLC/MAC/PHY) and control plane (RRC) protocol which terminate towards the MS. Therefore, our TCP Snoop can be implemented directly on the 3GPP LTE eNB entity.

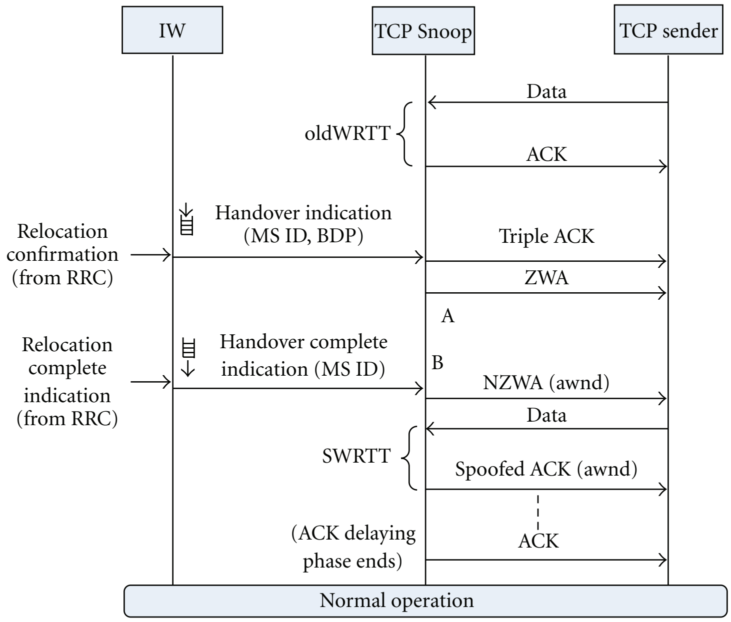


Figure 7: Cross-layer primitives between IW sublayer and TCP Snoop.

3.1.1. Handover Preparation. TCP Snoop is disabled when there is no handover. When an inter-RAT handover becomes possible due to, for example, signal strength degradation, TCP Snoop is invoked and informed of current network wireless BDP size by IW sublayer. Afterwards, the TCP Snoop works in the transparent mode. In the transparent mode, a local queue in TCP Snoop is maintained for a TCP connection. This local queue maximal length is set to current network wireless BDP size. Every incoming TCP segment is buffered in this queue and forwarded to the MS as well. When an ACK is from the MS, TCP Snoop not only forwards this ACK to TCP sender but also deletes corresponding TCP segments from this local queue. TCP Snoop may also estimate wireless RTT of current network (oldWRTT in Figure 7) in terms of the classical Jacobson RTT estimation algorithm [17].

3.1.2. Handover Execution. When an inter-RAT handover is made, a handover indication primitive is sent from IW sublayer to TCP Snoop (see Figure 7). In this primitive, the MS and target wireless network BDP sizes are indicated. Depending on the access network wireless BDP size variation after handover, firstly, TCP Snoop may decide to send several triple ACKs to TCP sender. Upon receipt of the triple ACKs, TCP sender reduces congestion window size by half and performs fast retransmission. Then, the TCP Snoop sends a Zero Window Advertisement (ZWA) message to the TCP sender to freeze its RTO timer and force it to enter the persist mode.

When a handover complete indication primitive is received from IW sublayer, TCP Snoop resumes segment forwarding to the MS. When the local queue length is below a predetermined length (In our simulation scenario, during handover period, this predetermined length is set to half of wireless BDP size of target network to accelerate the following ACK delaying procedure.), TCP Snoop sets maximal local queue length to the target network wireless BDP size. Afterwards, TCP Snoop feeds back a Nonzero Window Advertisement (NZWA) message to TCP sender to make it exit persist mode. After that, TCP Snoop enters into ACK delaying phase.

In ACK delaying phase, for every new incoming TCP segment, TCP Snoop creates a corresponding spoofed ACK timer. This timer period (SWRTT) is set to former wireless RTT (oldWRTT) plus an incremental change, as follows:

$$\mathrm{SWRTT}(i) = \mathrm{oldWRTT} + a * \mathrm{oldWRTT} * i, \quad i \in [1, +\infty], \tag{1}$$

where oldWRTT is the wireless RTT estimation of the WiMAX link before handover, and the index "i" is the number of spoofed ACK. The constant a is set to a very small value deliberately in order to reduce possibility of RTO timer expiration in TCP sender. For example, a is set to 0.05 in our simulation scenario.

When one spoofed ACK timer expires, the TCP Snoop "spoofs" the TCP sender by feeding back a TCP ACK message. In this spoofed ACK message, the advertised window size (Awnd) field is set to current free queue length in the TCP Snoop. This explicit window notification (EWN) mechanism is used to control incoming TCP segment amount to avoid possible buffer overflow in TCP Snoop.

When the arrival of an ACK from the MS is before the expiration of the corresponding spoofed ACK timer, it means the RTO value of TCP sender has been adjusted to an appropriate one. Then, TCP Snoop cancels all spoofed ACK timers and the ACK delaying phase ends. Subsequently, the TCP Snoop can work in a transparent mode for next possible handover or just is disabled to release buffer resource. In the transparent mode or disabled mode, it is the TCP congestion

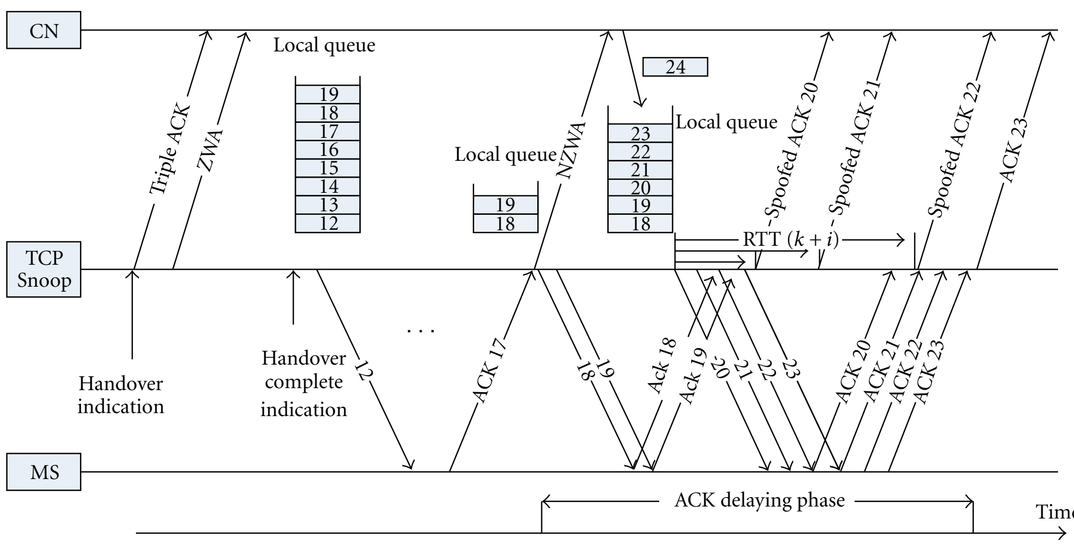


Figure 8: An example of TCP Snoop working procedure.

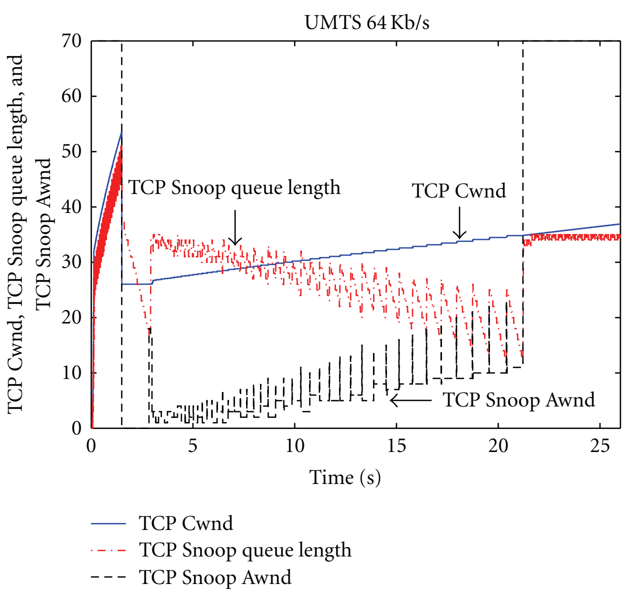


Figure 9: The variations of local queue length and advertised window size (UMTS data rate 64 Kb/s, local queue length 35 after handover).

control mechanism on the sender side that controls TCP transmission rate.

If a new handover is forthcoming when current ACK delaying phase is still in progress, TCP Snoop cancels all spoofed ACK timers and switches back to the transparent mode for this new handover.

The whole cross-layer primitives and messages during handover procedure are described in Figure 7.

3.2. An Example of TCP Snoop Working Procedure. An example of TCP Snoop working procedure is given in Figure 8. When an inter-RAT handover takes place, the TCP Snoop receives a handover indication primitive from IW sublayer. On this primitive, TCP Snoop sends triple ACKs to adjust TCP sender congestion window size. Then it sends the ZWA message to the TCP sender to make it enter the persist mode. When layer-2 handover is complete, the IW sublayer sends handover complete indication primitive to TCP Snoop. On this primitive, TCP Snoop continuously forwards stored segments to the MS until its local queue length is below a threshold. In this example, this threshold is set to 2. After that, the TCP Snoop sends the NZWA message to TCP sender to make it exit persist mode. Afterwards, TCP Snoop enters into the ACK delaying phase. When TCP Snoop receives segments from number 20 to 23, corresponding spoofed ACK timers of these segments are created. The period of each spoofed ACK timer is set to former wireless RTT plus an incremental change, as shown in (1). When one of these timers expires, the TCP Snoop feeds back a corresponding spoofed ACK to TCP sender on behalf of MS. The Awnd field of this spoofed ACK is set to free buffer size of local queue in TCP Snoop. When the arrival of the ACK of segment 23 from the MS is before the expiration of this segment's corresponding spoofed ACK timer in TCP Snoop, ACK delaying phase ends. Subsequently, the TCP Snoop works in a transparent mode or disabled mode.

Note that during handover period, there are no TCP segment losses in the wireless link. Therefore, sequence numbers of spoofed ACKs and sequence numbers of ACKs from MS will not mismatch, thanks to IW sublayer retransmission mechanism.

3.3. Performance Evaluation. The simulation scenario and simulation parameters are, respectively, the same as Figure 2 and Table 1. An FTP session starts at 0.4 s, and the MS starts to perform handover at about 1.5 s after its entering into the coverage region of UMTS. The handover type is hard handover. At about 1.535 sec, the UMTS network entry procedure is finished and the IW sublayer on the RNC

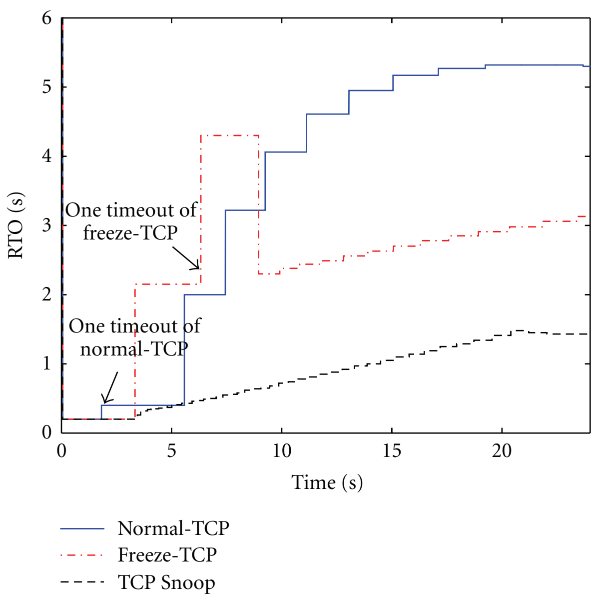


Figure 10: The variations of RTO value in TCP sender (UMTS data rate 64 Kb/s, local queue length 35 after handover).

informs TCP Snoop of the handover completion. We realize three solutions—normal TCP, Freeze-TCP, and the proposed TCP Snoop in this NS2 simulation platform.

3.3.1. Awnd and TCP Snoop Local Queue. Figure 9 shows the variations of the TCP Snoop local queue length and Awnd size during handover period. In the ACK delaying phase, the queue length looks like a "saw-tooth"—it increases abruptly and decreases at a constant rate. This is because the Awnd size in a spoofed ACK from TCP Snoop limits the amount of segments from TCP sender. TCP sender sends a succession of segments only when TCP Snoop opens up its Awnd size in a spoofed ACK.

At the time 21.5 sec, when an ACK from MS arrives before the expiration of its corresponding spoofed ACK timer at TCP Snoop, TCP Snoop completes current handover procedure—the EWN and ACK delaying mechanisms are disabled. Then, TCP Snoop works in transparent mode or disabled mode.

3.3.2. TCP Snoop Advantages. Figure 10 shows RTO variations of three TCP variants during a handover procedure. Due to long handover latency and abrupt wireless RTT increase after handover, normal TCP suffers from one RTO timer expiration, and congestion window size shrinks to one. After RTO timer expiration, TCP exponential backoff mechanism is invoked and the RTO value doubles.

In Freeze TCP, because of lack of buffer management mechanism and reduced UMTS wireless BDP size, multiple packet losses caused by UMTS buffer overflow after handover also lead to one RTO timeout.

As in the TCP Snoop solution, the EWN mechanism avoids buffer overflow in TCP Snoop and in the target wireless network during a handover period. The ACK delaying mechanism can gradually increase TCP RTO value and avoid RTO timer expiration. Therefore, thanks to TCP Snoop and IW sublayer, the whole handover procedure is smooth (no spurious RTO) and seamless (no packet losses).

From the above simulation analyses, we can say that TCP Snoop and IW sublayer are reasonable choices for the convergence of future heterogeneous wireless networks.

4. Conclusion

This paper evaluates and highlights the cross-layer effects for the seamless inter-RAT handover between UMTS and WiMAX networks on the basis of the integrated and tight coupling architectures. We first review existing context transfer schemes, coupling approaches, TCP-specific handover problems, and IEEE 802.21 MIH framework. Because the standardized MIHF does not specify actual handover execution mechanism, a novel MIHF variant—IW sublayer—is introduced. This common IW sublayer is added on top of PDCP (UMTS) and MAC (WiMAX) sublayers on RNC and MS in the integrated coupling architecture. Thanks to the introductions of intersystem retransmission and cross-layer mechanism, the IW sublayer scheme can achieve lossless and prompt handover procedure for UDP traffics. Furthermore, for TCP traffics, on top of IW sublayer, a new TCP Snoop is also introduced on the RNC. With TCP Snoop, the ACK delaying mechanism, explicit window notification mechanism, and cross-layer mechanism are utilized to resolve BDP mismatch and spurious RTO problems that often appear in the inter-RAT handover scenarios. Finally, the simulation results carried out on the NS2 emulator validate the handover performance improvement thanks to the cross-layer mechanism.

References

[1] D. Johnson, C. Perkins, and J. Arkko, "IP Mobility Support in IPv6," Tech. Rep. 3775 , Internet Engineering Task Force (IETF), June 2004, http://www.ietf.org/rfc/rfc3775.txt.

[2] G. Lanpropoulos, N. Passas, L. Merakos, and A. Kaloxylos, "Handover management architectures in integrated WLAN/cellular networks," *IEEE Communication Survey & Tutorials*, vol. 7, no. 4, pp. 30–44, 2005.

[3] 3GPP, "Technical Specification Group RAN; UTRAN functions, examples on signaling procedures, (Realease 7)," Tech. Rep. TR 25.931, V7.4.0.

[4] 3GPP, "Technical Specification Group Radio Access Network; Packet Data Convergence Protocol (PDCP) specification, (Release 7)," Tech. Rep. TS 25.323, V7.5.0.

[5] J. Sachs, B. S. Khurana, and P. Mähönen, "Evaluation of handover performance for TCP traffic based on generic link layer context transfer," in *Proceedings of the IEEE 17th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC '06)*, pp. 1–5, September 2006.

[6] N. Dailly, P. Martins, and P. Godlewski, "Performance evaluation of L2 handover mechanisms for inter-radio access networks," in *Proceedings of the IEEE 63rd Vehicular Technology Conference (VTC '06)*, pp. 491–495, Melbourne, Australia, May 2006.

[7] K. Brown and S. Singh, "M-TCP: TCP for mobile cellular networks," *ACM SIGCOMM Computer Communication Review*, vol. 27, no. 5, pp. 19–43, 1997.

[8] M. Meyer, J. Sachs, and M. Holzke, "Performance evaluation of a TCP proxy in WCDMA networks," *IEEE Wireless Communications*, vol. 10, no. 5, pp. 70–79, 2003.

[9] F. Ren, X. Huang, F. Liu, and C. Lin, "Improving TCP throughput over HSDPA networks," *IEEE Transactions on Wireless Communications*, vol. 7, no. 6, pp. 1993–1998, 2008.

[10] B. Liu, P. Martins, A. E. Samhat, and P. Bertin, "A cross-layer scheme for inter-RAT handover from WiMAX to UMTS," in *Proceedings of the IEEE Global Telecommunications Conference (GLOBECOM '08)*, pp. 1–6, December 2008.

[11] J. C. Moon and B. G. Lee, "Rate-adaptive snoop: a TCP enhancement scheme over rate-controlled lossy links," *IEEE/ACM Transactions on Networking*, vol. 14, no. 3, pp. 603–615, 2006.

[12] J. H. Hu, G. Feng, and K. L. Yeung, "Hierarchical cache design for enhancing TCP over heterogeneous networks with wired and wireless links," *IEEE Transactions on Wireless Communications*, vol. 2, no. 2, pp. 205–217, 2003.

[13] T. Goff, J. Moronski, D. S. Phatak, and V. Gupta, "Freeze-TCP: a true end-to-end TCP enhancement mechanism for mobile environments," in *Proceedings of the 19th Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM '00)*, pp. 1537–1545, March 2000.

[14] V. Gupta et al., "IEEE802.21 standard and Metropolitan Area Networks: Media Independent Handover Services," IEEE std 802.21-2008, January 2009.

[15] B. Liu, P. Martins, A. E. Samhat, and P. Bertin, "A layer 2 scheme of inter-RAT handover between UMTS and WiMAX," in *Proceedings of the 68th Semi-Annual IEEE Vehicular Technology (VTC '08)*, pp. 1–5, September 2008.

[16] B. Liu, P. Martins, P. Bertin, and A. E. Samhat, "Inter-RAT Handover between UMTS and WiMAX," in *Radio Communications*, pp. 1–28, INTECH, 2010.

[17] H. Huang and J. Cai, "Adding network-layer intelligence to mobile receivers for solving spurious TCP timeout during vertical handoff," *IEEE Network*, vol. 20, no. 6, pp. 24–31, 2006.