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Timely Effective Handover Mechanism in Heterogeneous Wireless Networks

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Abstract Next-generation wireless networks should be able to coordinate and integrate different communication systems. It has been a challenging problem to support a seamless handover in these diverse wireless network environments. Link level triggers can provide information about events which can help handover decision and layer 3 entities better streamline their handover related activities. In most conventional layer 2 triggering approaches, a pre-defined threshold for a specific perspective such as the received signal strength is used. This may cause too late or too early handover executions. In this paper we propose a new predictive handover framework that uses the neighbor network information to generate timely the link triggers so that the required handover procedures can appropriately finish before the current link goes down. First we estimate a required handover time for the given neighbor network conditions, then using a predictive link triggering mechanism the handover start time is dynamically determined to minimize handover costs. The handover costs are analyzed in terms of the total required handover time and the service disruption time. The numerical analysis and simulation results show that the proposed method significantly enhances the handover performance in heterogeneous wireless networks.

Keywords Seamless handover · Link triggers · Prediction · Heterogeneous wireless networks

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1 Introduction

The rapid expansion of mobile communications over the last decade has spawned a number of different wireless communication systems. Also wireless devices are becoming increasingly multimodal, containing multiple communication interfaces such as the Wireless Local Area Network (WLAN) [1] and the Worldwide Interoperability for Microwave Access (WiMAX) [2,3]. This allows users to communicate without the geographical coverage limitations of individual communication systems and to choose an optimum wireless network interface in accordance with the desired requirements in terms of transmission rate, quality of service (QoS), communication price, and so on. In the new generations of wireless networks, seamless mobility support across heterogeneous networks is very important. Seamless mobility is referred to as the event when all sessions of an MN continue to maintain their connection even as an MN changes its point of attachment (PoA). If seamless mobility is supported, an MN can roam across heterogeneous networks and keep its connections active.

Handovers typically cause layer 2 (L2) switching and/or layer 3 IP mobility latencies and hence may disrupt current services. This is unacceptable for time-sensitive and real-time applications. For handovers to be seamless, timely information accurately characterizing the network conditions is needed in order for appropriate actions to be taken. This is provided by the so-called link layer triggers that are fired at the Medium Access Control (MAC) sub-layer and communicated either to a handover management functional module such as the Media Independent Handover Function (MIHF) of IEEE 802.21 [4], or to a network control layer protocol. Link layer information is critical to layer 3 and above entities in order to better streamline handover-related activities such as the initiation and the execution of fast mobile IP procedures. Hence effective link-layer trigger mechanisms and the timely firing of link triggers can significantly influence the handover performance and is key in determining whether the handover completes successfully [5]. In particular, in several "break before make" networks such as WLAN and WiMAX, the role of link triggers in the initiation of a proper handover is significant in mitigating handover service disruptions. The Link_Going_Down (LGD) trigger implies that a broken link is imminent. The Link_Going_Down trigger time greatly influences the handover performance in terms of the packet loss rate, handover delay, and communication cost. Essentially, the handover process will not make the correct decision and execution unless adequate and timely Link_Going_Down trigger information is delivered. Therefore, a method that effectively and adaptively detects the f link quality decay in order to trigger a handover is a key issue.

A number of methods have been proposed for generating LGD triggers [6–11]. However, most of these methods use a pre-defined threshold of a specific metric such as received signal strength indication (RSSI). For example, if the received signal strength is less than a pre-defined threshold, the Link_Going_Down trigger is generated. However, due to several parameters changing over time such as the wireless channel conditions, the mobile node (MN) speed, and the time required for performing a handover, determining the optimal threshold in advance is difficult, often resulting in either an early or late handover initiation.

The IEEE 802.21 media independent handover (MIH) framework [4] currently under development provides link layer intelligence and other related network information to upper layers to optimize handovers between heterogeneous media. It supports cooperative use of information available at the mobile node and within the network infrastructure. The information server of the IEEE 802.21 provides a framework and corresponding mechanisms by which a MIH function entity can discover and obtain network information available within a geographical area to facilitate the handovers. In the proposed handover architecture, we make use of the IEEE 802.21 functionality.

In this paper we propose a predictive handover architecture based on neighbor network information. First, we discuss methods for estimating the required handover time for different neighbor network topologies, QoS support, and current network conditions. In this estimation step for the required handover time, we also set up an appropriate handover policy and determine the exact handover procedures used to achieve a seamless handover. The estimated handover time is used to generate timely LGD triggers. A predictive link trigger mechanism is used to start and finish the required handover procedures before the link actually goes down. Unlike the handover initiations of most previous handover algorithms that depend on a specific measurement metric and generate link triggers with pre-determined trigger thresholds, in our proposed timely and effective handover mechanism, any link quality metric can be applied and the LGD trigger is adaptively invoked based on the estimated required handover time.

The remainder of this paper is organized as follows: Section 2 presents the proposed predictive handover architecture. Neighbor network aware handover procedure is shown with an example scenario based on IEEE 802.21 MIHF. In Sect. 3, estimates for the time it takes to complete a handover are derived for different handover types and various neighbor network conditions. In Sect. 4, analysis for the horizontal and vertical handover costs are derived. In accordance with the different link down time, the corresponding service disruption time and total handover time are presented. In Sect. 5, numerical analysis and simulation results show that the proposed method significantly enhances the performance of handovers. We conclude this paper in Sect. 6.

2 Predictive Handover Architecture Based on Neighbor Network Information

In this section we propose a cross-layer based predictive handover architecture and mechanism after investigating late or early link trigger costs for handovers. The proposed mechanisms are implemented in the context of the IEEE 802.21 media independent handover architecture.

2.1 Link Trigger Costs

For seamless handover in heterogeneous wireless networks, service continuity and minimal handover disruption time are the primary goals for handovers. To achieve this goal, link layer triggers aid the handover preparation and execution [1–4,12,13]. Link triggers are delivered to a handover decision module and a mobility control protocol in layer 3 to indicate changes in link quality (signal strength, link level QoS, or link connectivity). Specifically, the Link_Going_Down trigger that implies "broken link is imminent" greatly influences the handover performance because it is generally used to start the required handover procedure. Essentially, the handover process will not make the correct decision and execution unless adequate and timely Link_Going_Down trigger information is delivered. Most previous LGD trigger algorithms [6–11] are based on pre-defined thresholds associated with the received signal strength or QoS metrics. If the measured link quality crosses a pre-defined threshold TH_{LGD}, then the Link_Going_Down trigger is generated and the handover process starts.

When the minimum link quality (TH_{LD}) is given (i.e., if the received link quality is less than TH_{LD}, then the current link is considered as broken), usually the pre-defined threshold for the LGD trigger is calculated as

$$TH_{LGD} = \alpha \times TH_{LD}, \quad \alpha \geq 1.0 \tag{1}$$

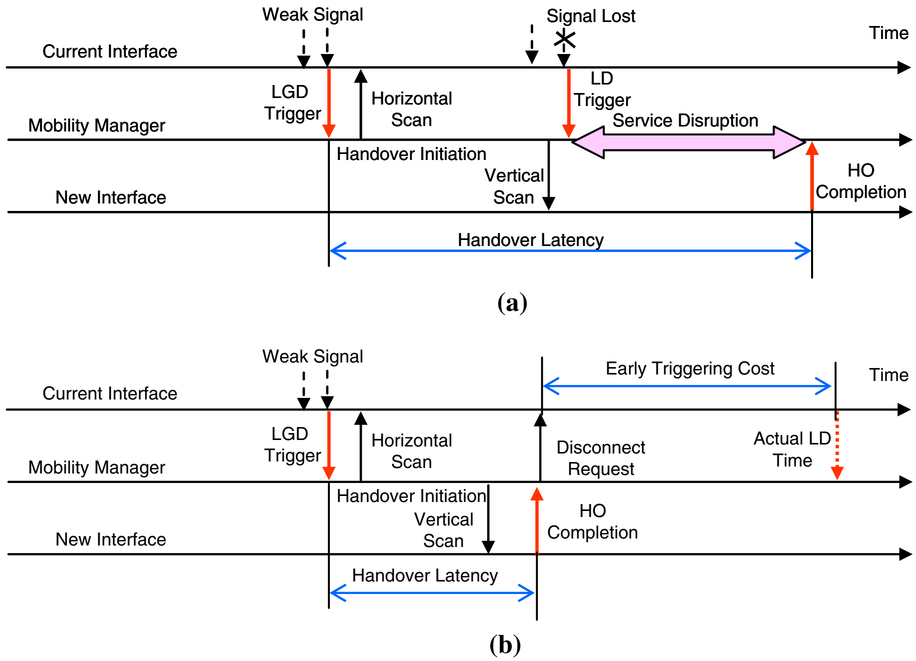


Fig. 1 Link_Going_Down trigger cost. **a** Too late LGD triggering. **b** Too early LGD triggering

The wireless link quality depends on many time varying factors: wireless channel conditions due to fading and shadowing, MN moving speed and direction, traffic loads, network types, and so on. For example, the link quality slowly decreases as the MN moves away from the current point of attachment (PoA) assuming free space channel condition, slow MN speed, and low traffic load. However in the urban area, high MN speed, and high network loads, the link quality of the current PoA will rapidly drop to the minimal level within a short time. Therefore, it is very difficult to formulate the α value in advance.

Figure 1 shows the cost of an improper Link_Going_Down trigger. In Fig. 1a the LGD trigger occurs too late to initiate the vertical handover from WLAN to WiMAX properly, and before finishing the handover to the WiMAX network, the connection to the WLAN is lost. This may lead to a long service disruption, and some incoming packets may be lost or delayed during this outage. A cost function can be determined using the total required handover latency and the total service disruption time. The different time gaps between the LGD and Link_Down (LD) triggers can cause different handover latencies also different service disruption times. In Sect. 4 we will show the handover cost analysis for late triggering.

The cost for an LGD trigger that was generated too early is also significant as shown in Fig. 1b. It may force the handover execution to a new interface even when the link quality of the old interface is still strong enough to decode data, resulting in a loss of the benefits of the preceding interface, which can include such factors as the bandwidth, QoS, and communication price. When there is a large time gap between the LGD and the LD, frequent event roll-backs or handover cancellations may also occur. Early LGD triggering cost is a function of the time difference between the handover completion time and the actual link down time. The actual link down time is the time that the current link goes down when the MN does not perform a handover. In fact, in real communications we cannot measure the exact actual link down time because the MN already changed its PoA. In Sect. 5, we will show the early trigger cost comparisons for some simulation scenarios.

2.2 Neighbor Information Based Predictive Handover Architecture

In this section, we present a new timely effective handover architecture based on the neighbor network information. Figure 2 shows the proposed predictive handover architecture based on the cross layer design for the seamless handover. The PHY/MAC layer is responsible for the link quality measurement, channel switching, link prediction, and trigger generation. Below the L3 mobility protocol, there exist the handover engine and the media independent handover function module that are for obtaining neighbor network information, configuring handover related parameters, estimating the required handover time, and deciding a handover target and policy.

In the proposed architecture, we estimate the exact required handover time (t_h) based on the current neighbor network conditions. The neighbor network information can be obtained by the information service of the IEEE 802.21 MIHF [4] that provides a query/response type of mechanism for neighbor network information transfer. It contains both static (e.g., neighbor network topology) and dynamic (e.g., QoS condition) information. In addition to the IEEE 802.21 MIHF, some wireless MAC protocols such as WLAN [13] and WiMAX [2] also provide a certain level of neighbor network information for the network systems of the same type. The neighbor network information may include:

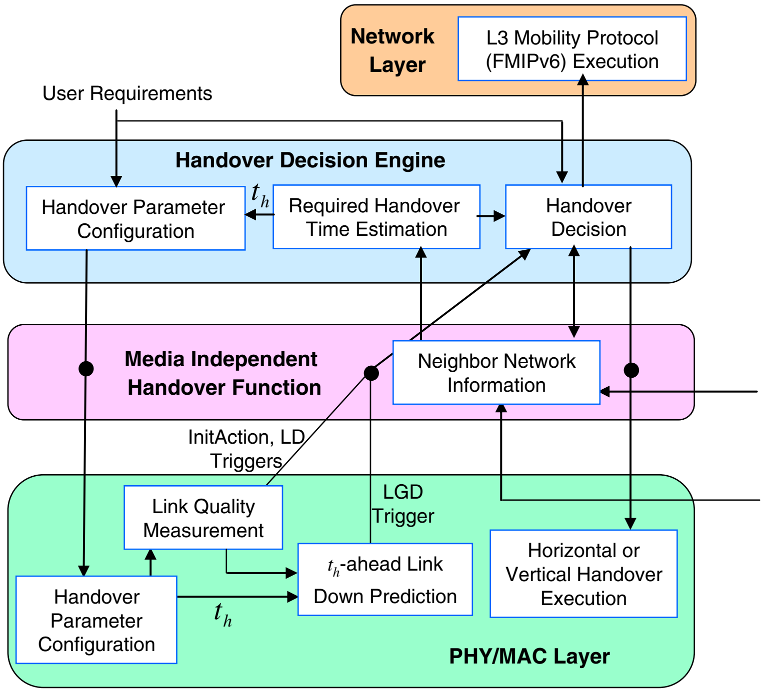


Fig. 2 The proposed predictive handover architecture based on the neighbor network information

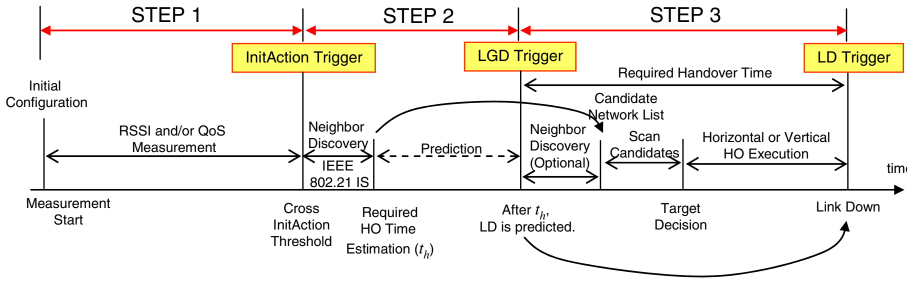


Fig. 3 Predictive handover time sequence

- The list of neighbor networks: neighbor network types, MAC and IP level addresses, currently used channel id, and other system parameters (e.g., modulation method and timing information);
- QoS support level: current network loads, supportable QoS classes, currently supported QoS performance, and other QoS related metrics;
- Network layer information: mobility support protocol types and mobility related parameters.

From this neighbor information, the MN (or PoA) can estimate the required handover type (horizontal or vertical) and the required handover time to finish all handover procedures. The estimated handover time and neighbor network information can be also used to set up a dynamic handover policy. For example, if the estimated service disruption time due to the required horizontal scanning is greater than the user requirement, then MN may decide an immediate vertical handover to meet the desired performance instead of a possible horizontal handover. The required handover time, t_h, is delivered to the MAC layer to configure the condition for the LGD trigger.

In our mechanism, the LGD trigger is adaptively generated based on the estimated handover required time. The LGD trigger should be invoked prior to an actual link down event by at least the time required to prepare and execute a handover. Unlike the previous triggering methods using a pre-defined threshold, in our approach the MN forecasts whether the current link goes down or not after t_h time. If it is predicted, then LGD is generated. Once the handover decision engine receives the LGD trigger event, it starts the required handover procedures both on the MAC/physical layer and network layer.

As shown in Fig. 3, the predictive handover consists of three steps: (i) the initial configuration and measurement step, (ii) the neighbor discovery and prediction step, and (iii) the handover execution step.

2.2.1 STEP 1: Initial Configuration and Measurement Step

During this step, some initial parameters for measurement and handover are configured. Measurement related parameters may include the required link quality, measurement metrics, measurement interval, and so on. Typical handover related parameters are InitAction and Link_Down thresholds. InitAction threshold is used to start neighbor discovery and prediction (STEP 2) and it is configured to a conservative value to ensure enough time for STEP 2 before the LGD trigger. The proposed mechanism does not depend on a specific measurement metric. Any performance metrics for a handover decision can be used for a link quality measurement such as the received signal strength indication (RSSI) or a set of QoS measurements. Weak RSSI caused by deep fading and/or moving away from the current PoA may cause a handover. Handovers due to the poor QoS performance in terms of packet delay, delay jitter, loss rate, and transmission rate can be caused by weak RSSI, heavy network load, and/or strong interference from other systems. For QoS based handover, a "*QoS satisfaction degree*" is defined as a link quality metric in this paper. It is a function of QoS metrics as defined in (2). The QoS satisfaction degree can be defined as a minimum value from the all QoS components or a weighted average as shown in (3) depending on the user requirements.

$$QoS_{m,c}^{n,k}(t) = F\,(\text{delay,loss,jitter, rate}) \tag{2}$$

$$\begin{aligned} F(\bullet) &= \min\left\{\frac{M\_delay_{m,c}^{n,k}(t)}{R\_delay_c}, \frac{M\_loss_{m,c}^{n,k}(t)}{R\_loss_c}, \frac{M\_jitter_{m,c}^{n,k}(t)}{R\_jitter_c}, \frac{R\_rate_c}{M\_rate_{m,c}^{n,k}(t)}\right\} \\ \text{or} &= w_c(d)\frac{M\_delay_{m,c}^{n,k}(t)}{R\_delay_c} + w_c(l)\frac{M\_loss_{m,c}^{n,k}(t)}{R\_loss_c} + w_c(j)\frac{M\_jitter_{m,c}^{n,k}(t)}{R\_jitter_c} \\ &+ w_c(r)\frac{R\_rate_c}{M\_rate_{m,c}^{n,k}(t)}\quad w_c(d) + w_c(l) + w_c(j) + w_c(r) = 1\ \left(\forall c \in \bar{C}\right) \end{aligned} \tag{3}$$

where, m is a mobile node index; c is a service class index from the service class set $\bar{C}$; n is a network type (e.g., WLAN or WiMAX); k is the current PoA index; $w_c(\Theta)$ is a weight for the QoS metricΘ of class c . $M\_\Theta_{m,c}^{n,k}(t)$ is the measured QoS value for the metric Θ for the class c of the mobile node m at the k PoA of the network type n at time t. R_Θ_c is the required QoS performance for the metric Θ for the class c.

2.2.2 STEP 2: Neighbor Discovery and Prediction Step

If the measured link quality crosses the pre-defined InitAction threshold, then the neighbor network discovery procedure starts using the IEEE 802.21 information server. However this does not trigger the actual execution of a handover. After obtaining the neighbor information, the MN (or PoA in case of network initiate handover) can form a candidate network list. From this information, the MN can decide handover type (horizontal or vertical), the number of candidate PoAs (or channels) to be scanned, and whether the layer 3 handover is required or not. The MN estimates the required handover time t_h based on the neighbor information. During this estimation, if the expected handover time or service disruption time is greater than the user requirement, then the handover decision engine can change the handover policy. The required handover time is configured in layer 2 using MIHF primitives and t_h-ahead prediction starts. If after t_h a Link_Down event is expected, then a predictive LGD trigger is generated to initiate the required handover procedure. Prediction is performed at each t_m measurement interval. For discrete time prediction process, we define a prediction interval k_h as in (4).

$$k_h = \left\lceil \frac{t_h + \Delta_h}{t_m} \right\rceil \tag{4}$$

where Δ_h is a marginal time (≥ 0).

Any prediction mechanism can be used to trigger the LGD event. In this paper we consider two prediction techniques. Least mean square (LMS) adaptation algorithm monitors the prediction error $e(n)$ and attempts to minimize the mean squared prediction error, $E\left\{e(n)^2\right\}$, by adapting prediction weights, as (5). The pth order linear predictor is concerned with the estimation of $x(n + k_h)$ using a linear combination of the current and previous values of link quality vector $\mathbf{X}(n)$. $\mathbf{W}_n$ is the time-varying coefficient vector. Considering that at time n the value of $x\ (n + k_h)$ is not available to compute $e\ (n)$, $e\ (n - k_h)$ is used instead as in [14]. The step size μ is an adaptation parameter that determines convergence speed. In a normalized LMS, if $0 < \mu < 2$, then the LMS will converge to the mean.

$$\hat{x}(n + k_h) = \sum_{l=0}^{p-1} w_n(l)x(n - l) = \mathbf{W}_n^T \mathbf{X}(n) \tag{5}$$

$$\begin{aligned} &\mathbf{X}(n) = [x(n), x(n-1), \ldots, x(n-p+1)]^T \\ &\mathbf{W}_n = [w_n(0), w_n(1), \ldots, w_n(p-1)], \mathbf{W}_{n+1} = \mathbf{W}_n + \mu \times e(n)\frac{\mathbf{X}(n)}{\|\mathbf{X}(n)\|^2} \\ &e(n) = x(n+k) - \hat{x}(n+k_h) \approx e(n-k_h) = x(n) - \hat{x}(n) \end{aligned} \tag{6}$$

As a simpler prediction method, a linear slope estimation of link quality degradation is considered in this paper. We assume that during the relatively short time period (handover time—from hundreds milliseconds to few seconds) the link quality degradation can be approximated as a linear line. With the nth and $(n - 1)$th link quality measurements, the service degradation slope at time n is derived as (7).

$$s\ (n) = x\ (n) - x\ (n - 1) \tag{7}$$

And the expected service degradation slope $\bar{a}\ (n)$ using the previous slope estimations is given in (8).

$$\bar{a}\ (n) = \eta \cdot s\ (n) + (1 - \eta) \cdot \bar{a}\ (n - 1) \tag{8}$$

where η is a weight for the current measured slope. Therefore, the predicted link quality value for k_h time ahead is derived as (9).

$$\hat{x}\ (n + k_h) = \bar{a}\ (n) \cdot k_h + x\ (n) \tag{9}$$

2.2.3 STEP 3: Handover Execution Step

After the LGD trigger, the MN can optionally re-perform the neighbor network discovery. This is especially useful when there is large time gap between the InitAction trigger and LGD trigger so that the MN needs to obtain updated neighbor information. When there are multiple candidate PoAs (or channels) and/or the MN needs to check the connectivity and resource availability of PoAs, the MN starts the scanning procedure with the (updated) candidate neighbor network list. After the MN decides on a target PoA, a horizontal or vertical handover is followed.

The proposed predictive handover approach has two main benefits for seamless handovers. (i) Since the MN can know the handover type to perform and the neighbor network list to scan, the handover preparation and execution time can be optimized. This also minimizes the service disruption time. During the required handover estimation, the MN can setup a handover policy to meet the user requirement based on the estimated handover time. (ii) Based on the estimated required handover time, the MN generates the LGD trigger at the appropriate time that ensures finishing all the required handover procedures before the actual link goes down. Therefore, it successfully reduces possible service disruptions due to the link break before finishing the handover procedures.

2.3 Implementing the Predictive Handover Mechanism in the Context of the IEEE 802.21 Media Independent Handover Architecture

The IEEE 802.21 defines two link configure thresholds: (i) InitAction threshold to start "setup-type" activities and (ii) ExecuteAction threshold to take appropriate action for a handover. For the proposed mechanism, the IEEE 802.21 concept can be used as shown in Fig. 4.

In the proposed predictive handover mechanism, the InitAction threshold (T_{init})is used to initiate a neighbor discovery procedure and to start the link quality prediction. Any link quality metric such as the received signal strength or QoS satisfaction degree can be used for the threshold configuration. The MIH_Configure_Link.request and Link_Configure_Threshold.request primitives carry T_{init}, T_{min}(the minimum link quality level), and the measurement related parameters. If the measured link quality is less than T_{init}, then InitAction trigger is generated by the link layer and it is delivered to MIHF user by Link_Parameter_Report.indication and the MIH_Link_Parameter_Report. indication primitives. The MIHF user initiates the neighbor network discovery by sending an MIH_Get_Information Request message to the IEEE 802.21 information server. Based on the neighbor information the MN estimates the required handover time (t_h) and then the MIHF user configures t_h to the link layer as an ExecuteAction threshold. Upon receipt of the Link_Configure_Threshold.request primitive for the ExecuteAction threshold configuration, the link layer starts t_h-ahead link quality prediction. It should be noted that in this approach, a pre-determined threshold is not used for LGD threshold configuration. Instead, the MIHF user passes the required handover time t_h that is dynamically computed based on the neighbor network information. During the

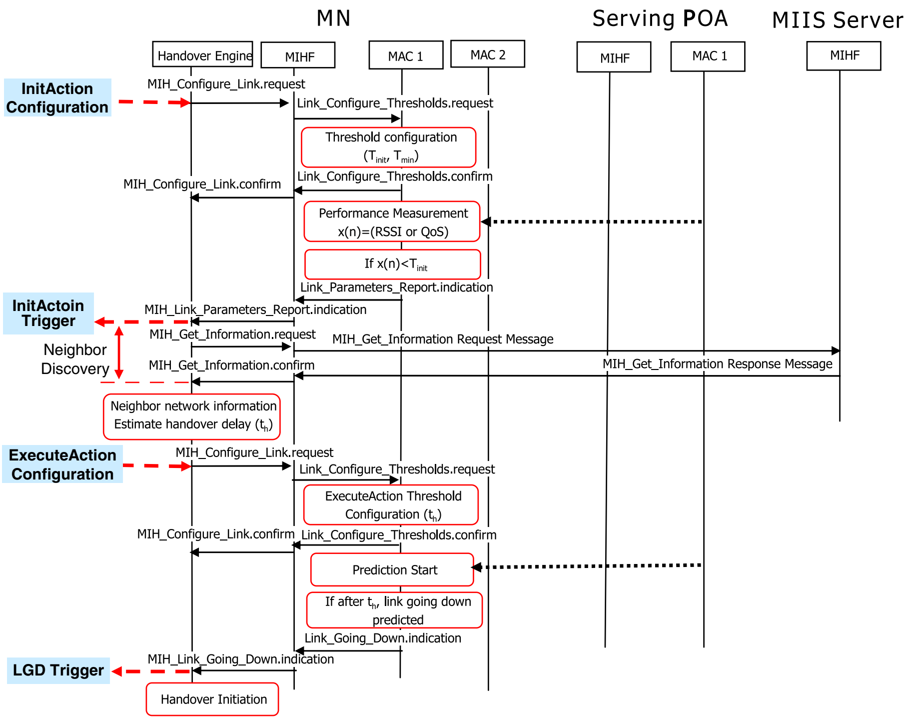


Fig. 4 Predictive handover scenario using IEEE 802.21 MIHF architecture

prediction, if after t_h Link_Going_Down is expected, then Link_Going_Down.indication primitives are delivered to the MIHF user and the MIHF user initiates the required handover procedure. MAC layer scanning to the candidate PoAs is followed. The IEEE 802.21 has defined a handover indication message exchange procedure when a target PoA is determined. The MN sends an MIH_MN_HO_Commit Request message to the current PoA and the current PoA forwards it to the target PoA with an MIH_NET_HO_Commit Request message. The handover indication is finished by receiving a MIH_MN_HO_Commit Response message from the target PoA through the current PoA.

3 Required Handover Time Estimation

In this section, the required handover time estimation methods for various neighbor network conditions are presented. For some case studies, we use WLAN and WiMAX overlay network environments, but it should be noted that the following estimation methods can be applied to any other wireless networks. Since the link layer switching of WLAN and WiMAX networks are typically operated in a "break before make" manner, accurate handover time estimation is more important for achieving seamless handovers.

As was mentioned earlier, an LGD trigger should be fired at least in the required handover time before the Link_Down event. The required handover time is different according to the network topologies considered, layer 3 handover protocols, and handover policies of the neighbor networks. Due to the mobility involved, these parameters can be dynamic in time so that t_h is configurable adaptively.

Depending on the neighbor information, we have classified the handover estimation cases as follows:

- HO_Case 1 (horizontal handover): When the MN knows that there exists at least one candidate PoA with the same link type that can support the MN's link quality requirements, the MN estimates the required handover time for the horizontal handover.
- HO_Case 2 (vertical handover): When the MN knows that there is no available PoA for a horizontal handover but there exists at least one PoA with a different link type, the MN estimates the required handover time for the vertical handover.
- HO_Case 3 (horizontal or vertical handover): The MN obtains candidate PoAs both of the same and different link interface systems, but the MN is not able to decide whether a horizontal handover or vertical handover should be executed.
- HO_Case 4 (no neighbor information): In this case, the MN does not have the neighbor information. It may be caused by some network conditions such that the IEEE 802.21 information server is not reachable or neighbor networks are not connected to the information server. The MN estimates the required handover time to the maximum value to prepare the worst case scenario.

3.1 HO_Case 1 (The Required Time Estimation for a Horizontal Handover)

For the case of a horizontal handover and using a single interface (hard handover), the MN cannot be serviced in parallel by more than one PoA (access point (AP) or base station (BS)) and therefore has to break its communication with its current PoA before establishing a connection with a new one. This break in communication is from a layer 2 perspective. Service disruption cannot be avoided. To reduce the service disruption time and possible packet loss and delay, the MN needs to finish the layer 3 handover before the link breaks. FMIPv6 [12] is designed to reduce the handover delay by preparing the layer 3 handover in advance. An LGD trigger is required for this anticipation and handover initiation. The handover required time for the horizontal handover consists of the L3 handover time (t_{L3}) and the L2 handover preparation time (t_{L2p}) before the actual link switching to the new PoA. If FMIPv6 is used as a layer 3 mobility protocol and the target PoA is not on the same subnet, then the L3 handover time is a fast handover execution time (t_{FH}).

$$t_{L3} = \begin{cases} t_{FH} & \\ 0, & \text{if the target PoA is on the same subnet.} \end{cases} \tag{10}$$

The L2 handover preparation time at the current PoA may include:

- $t_{L2p-nbr}$: Message exchange time to obtain the neighboring information. The IEEE 802.11 k and IEEE 802.16 e have defined frame formats for this. The IEEE 802.21 defines query/response messages to/from the information server.
- $t_{L2p-scn}$: Scanning time to scan the candidate PoAs (or channels).

$$t_{L2p-scn} = N_{p-nbr} \times t_{p-s} \tag{11}$$

  where N_{p-nbr} is the number of candidates and t_{p-s} is the scanning time for one candidate.
- $t_{L2p-ind}$: Handover indication message exchange time to the current PoA. For the IEEE 802.16 e handover mechanism it includes sending a MOB_HO-IND MAC frame to the old BS. The IEEE 802.21 specification also defines message exchanges to indicate the handover execution.

The scanning is required when there is one or multiple candidate PoAs and the MN needs to check the connectivity (or resource availability) to the PoAs after obtaining the neighbor information. In this paper, the term scanning is used to check the availability of the PoAs for any media type. The scanning is a media dependent behavior. For WiMAX, scanning includes all processing sequences from the scan request to the scan report. For WLAN, it includes active or passive scanning procedures. With the help of IEEE 802.21 MIHF protocol, the MN may check the resource availability for candidate PoAs during the scanning period. After the scanning, the MN can select a target PoA. $t_{L2p-nbr}$ and $t_{L2p-scn}$ can be performed earlier than the LGD trigger using periodic message exchanges and channel scanning. In this case t_{L2p} includes only $t_{L2p-ind}$.

The maximum and minimum required handover times for horizontal handover are given in (12). Figure 5 shows the WiMAX horizontal handover scenario combined with FMIPv6.

$$t_h = t_{L2p} + t_{L3}, \quad \begin{cases} t_{h-\max} = t_{L2p-nbr} + t_{L2p-scn} + t_{L2p-ind} + t_{FH} \\ t_{h-\min} = t_{L2p-ind} \end{cases} \tag{12}$$

3.2 HO_Case 2 (The Required Time Estimation for a Vertical Handover)

For a vertical handover, before the current link is down, a new link with the target network can be established if the LGD trigger is generated on time in a "make before break" manner. During the set up period for the new link, the MN can continue to send and receive data using the current network link. Therefore, a service disruption can be avoided by an appropriate estimation of t_h. The required vertical handover time consists of:

- t_{hp}: Handover preparation time for L2 and L3 with the current network PoA. For a vertical handover between WLAN and WiMAX, unlike a horizontal handover case, t_{L2p} does not

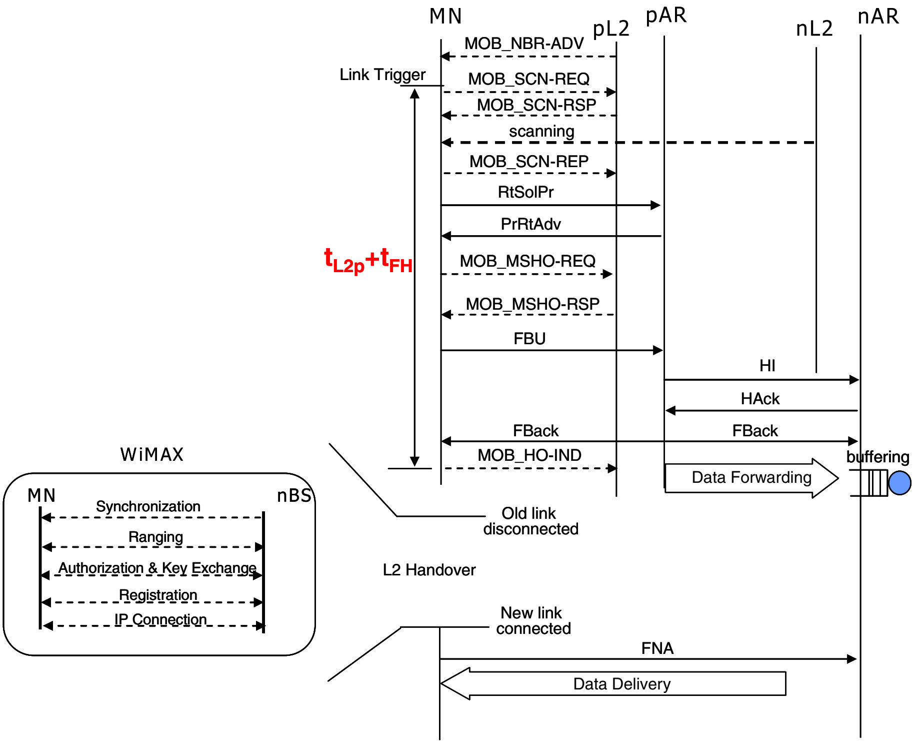


Fig. 5 Horizontal handover scenario for WiMAX and the required handover time

include $t_{L2p-scn}$ because scanning is performed at a different network interface and the t_{FH} time is typically required for the layer 3 handover because the target PoA is generally not on the same subnet of the previous PoA.

$$t_{hp} = t_{L2p} + t_{FH} = t_{L2p-nbr} + t_{L2p-ind} + t_{FH} \tag{13}$$

- t_{hn}: Handover execution time with the new network PoA using the new interface. For WLAN, t_{hn} includes vertical interface scanning, authentication, and association times. For WiMAX it includes scanning, synchronization & ranging, basic capability negotiation, key exchange & authorization, and registration times.

$$t_{hn} = \begin{cases} t_{L2n-scn} + t_{auth} + t_{assc}, & \text{WLAN} \\ t_{L2n-scn} + t_{rng} + t_{cap} + t_{key} + t_{reg}, & \text{WiMAX} \end{cases} \tag{14}$$

$$t_{L2n-scn} = N_{n-nbr} \times t_{n-s} \tag{15}$$

where N_{n-nbr} and t_{n-s} are the number of candidate PoAs (or channels) and the scan time per one candidate with the new link interface, respectively.

After the neighbor information exchange using the previous interface and scanning the candidate PoAs using the new interface, the MN can select the target PoA. The required procedures in the previous and new interface can be performed separately using different interfaces—for example the handover indication and fast mobile IP handover can be performed using the previous interface and synchronization and association (registration) can

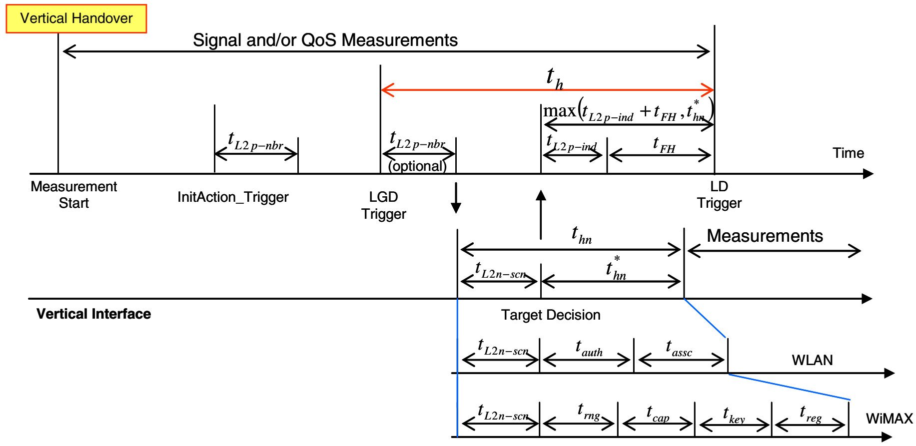


Fig. 6 Vertical handover timing relationship

be done using the new interface. Therefore, the total required handover time for a vertical handover is given in (16). The handover execution using the new interface can be finished before or after the fast handover procedure using the current interface.

$$t_h = t_{L2p-nbr} + t_{L2n-scn} + \max\left\{t_{L2p-ind} + t_{FH},\ t_{hn}^*\right\} \\ t_{hn}^* = \begin{pmatrix} t_{auth} + t_{assc} : \text{WLAN} \\ t_{rng} + t_{cap} + t_{key} + t_{reg} : \text{WiMAX} \end{pmatrix} \tag{16}$$

Figure 6 shows a vertical handover timing relationship for WLAN and WiMAX.

3.3 HO_Case 3 (The Required Time Estimation for a Horizontal or Vertical Handover)

If the MN can not determine the exact handover type using the candidate PoAs, then the MN should estimate the required handover time that is enough to scan all candidate PoAs for both horizontal and vertical interfaces and to perform any of horizontal or vertical handover. The required handover time is derived in (17). We assume that vertical scanning is performed only if there is no PoA for horizontal handover after horizontal scanning.

$$t_h = t_{L2p-nbr} + t_{L2p-scn} + t_{L2n-scn} + \max\left\{t_{L2p-ind} + t_{FH},\ t_{hn}^*\right\} \tag{17}$$

3.4 HO_Case 4 (Handover Without the Neighbor Network Information)

When the MN does not have the neighbor information for a handover, the horizontal scanning ($t_{L2p-scn}$) is performed first for all possible channels of the current communication system. If the MN cannot find a horizontal handover target, it starts the vertical scanning ($t_{L2n-scn}$) and executes a vertical handover. Therefore, the required handover time in this case should be sufficient, as in (18).

$$t_h = t_{L2p-nbr} + t_{L2p-scn(\max)} + t_{L2n-scn(\max)} + \max\left\{\left(t_{L2p-ind} + t_{FH}\right),\ t_{hn}^*\right\} \tag{18}$$

where $t_{L2p-scn(\max)}$ and $t_{L2n-scn(\max)}$ are the maximum channel scanning time for the current and new interface types, respectively.

In WLAN, the scanning time requires 10–80 ms [15,16] depending on the number of channels to scan when active scanning is used; for authentication and association it may require <10 ms [10]. In [15], it is shown that Mobile IPv6 (MIPv6) layer 3 handover latencies range from 80 to 150 ms. When FMIPv6 is used with link layer triggers, the layer 3 handover delay (data forwarding delay) can be much shorter than that of MIPv6. In WiMAX, from the scanning to the registration this requires from tens of ms to a few seconds [17,18]. The dominant measurement of this time is for synchronization, and this depends on the UCD/DCD (Uplink/Downlink Channel Descriptor) broadcasting interval of the target BS.

4 Handover Cost Analysis

In this section, we evaluate the handover costs in terms of the total handover time and the total service disruption time during the handover for various handover conditions. In our analysis the handover costs measure the amount of time required to perform the handover. First we will derive an analytic cost function for the proposed mechanism. Then, we will show the handover costs for the case in which a predefined LGD threshold is used and no neighbor network information is available.

4.1 Cost Analysis for Each Handover Procedure

In this section we present a handover cost model and derive a handover cost for each handover time component of Sect. 3. In this analysis a transmission cost represents a time delay for handover control message exchanges including transmission, propagation, and processing delays. For this analysis, the network model in Fig. 7 and model parameters of Table 1 are used.

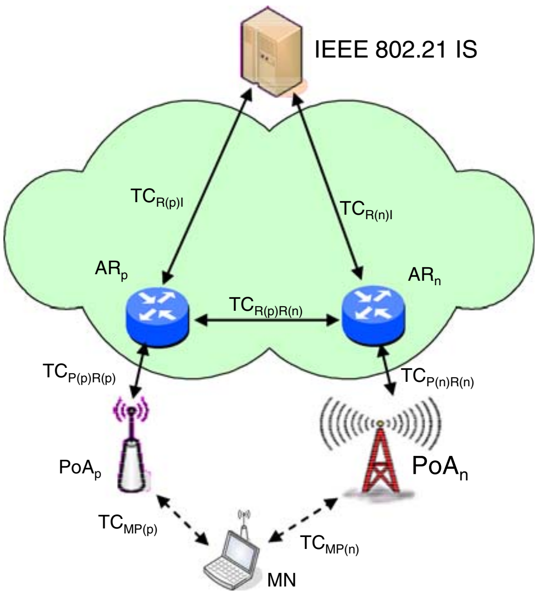


Fig. 7 Network model for handover cost analysis

Table 1 Network model parameters

Parameter	Definition
TC_{RI}, TC_{IR}	Transmission cost between access router (AR) and IEEE 802.21 information server (IS)
TC_{RR}	Transmission cost between current and target access routers
TC_{PR}, TC_{RP}	Transmission cost between PoA and access router
TC_{MP}, TC_{PM}	Transmission cost between MN and PoA
H_{RI}	Hop count between access router and information server
H_{RR}	Hop count between current and target access routers
H_{PR}, H_{RP}	Hop count between PoA and router
H_{MP}	Hop count between MN and PoA
ϕ	Transmission cost per one hop
δ	Weighing factor for wireless link
N_{p-nbr}, N_{n-nbr}	The number of candidate PoAs to scan for horizontal and vertical handovers, respectively
γ_p, γ_n	Scanning cost (time) per single PoA for horizontal and vertical systems, respectively
θ_n	Association or registration cost (time) after scanning with the new communication interface
HC_χ	Handover cost for procedure χ

Let ϕ be the unit message transmission cost and δ be the weight for a wireless link to capture some overhead in wireless medium such as access delay and collisions (for the wired link, the weight is 1). It is assumed that the link between the MN and PoA is wireless with one hop and the link between PoA and access router is wired with one hop. Other assumptions include the following. The transmission costs are symmetric for up and down links; the transmission costs of the paths on the previous and new networks are the same as in (19).

$$TC_{MP(p)} = TC_{MP(n)},\ TC_{P(p)R(p)} = TC_{P(n)R(n)},\ TC_{R(p)I} = TC_{R(n)I} \tag{19}$$

The transmission cost is proportional to the hop count on the path as (20).

$$\begin{aligned} &TC_{MP} = TC_{PM} = \delta \cdot \phi \cdot H_{MP} = \delta \cdot \phi \quad \leftarrow H_{MP} = 1 \\ &TC_{PR} = TC_{RP} = \phi \cdot H_{PR} = \phi \quad \leftarrow H_{PR} = 1 \\ &TC_{RR} = \phi \cdot H_{RR}, \quad TC_{RI} = TC_{IR} = \phi \cdot H_{RI} \end{aligned} \tag{20}$$

In the following, we derive the handover cost HC_χ for each time component χ of Sect. 3. First for the neighbor network discovery, we only consider the message exchanges to query and to respond between the MN and the IEEE 802.21 information server as shown in Fig. 7 (MN $\leftrightarrow$ PoA(p) $\leftrightarrow$ AR(p) $\leftrightarrow$ IS). *The neighbor discovery cost* is derived as (21).

$$\begin{aligned} HC_{nbr} &= t_{L2p-nbr} = TC_{MP} + TC_{PR} + TC_{RI} + TC_{IR} + TC_{RP} + TC_{PM} \\ &= 2 \times (\delta\phi + \phi + \phi H_{RI}) = 2\phi\,(\delta + 1 + H_{RI}) \end{aligned} \tag{21}$$

The handover cost for the handover indication is to send and to receive handover commitment request and response messages to/from the target PoA through the current PoA (MN $\leftrightarrow$ PoA(p) $\leftrightarrow$ AR(p) $\leftrightarrow$ AR(n) $\leftrightarrow$PoA(n)). The *handover indication cost* is given in (22).

$$\begin{aligned} HC_{ind} = t_{L2p-ind} &= TC_{MP} + TC_{PR} + TC_{RR} + TC_{RP} \\ &\quad + TC_{PR} + TC_{RR} + TC_{RP} + TC_{PM} \\ &= 2 \times (\delta\phi + \phi + \phi H_{RR} + \phi) = 2\phi\,(\delta + 2 + H_{RR}) \end{aligned} \tag{22}$$

In real communication environments, for the neighbor discovery and handover indication the MN may perform additional network dependent MAC level frame exchanges.

The *scanning cost* includes the MAC level media scanning and/or the explicit resource query to the candidate PoAs using IEEE 802.21 MIHF. It depends on the communication system scanning mechanism and implementation parameters. Let γ_ξ and $N_{\xi-nbr}$ be the scanning time for one PoA and the number of neighbor PoAs to scan for communication system type ξ, respectively. Then the scanning cost is given as (23).

$$HC_{scn} = \begin{cases} t_{L2p-scn} = N_{p-nbr} \times \gamma_p & : \text{ horizontal scan} \\ t_{L2n-scn} = N_{n-nbr} \times \gamma_n & : \text{ vertical scan} \end{cases} \tag{23}$$

If the neighbor network information is not available, then the number of PoAs to scan is the maximum number of channels operated by the communication system.

The *fast handover cost* of (24) is for layer 3 message exchanges from RtSolPr (Router Solicitation for Proxy Advertisement) to FBack (Fast Binding Acknowledgement) between the MN, previous AR, and new AR.

$$\begin{aligned} HC_{FH} = t_{FH} &= TC_{RtSolPr} + TC_{PrRtAdv} + TC_{FBU} + TC_{HI} + TC_{HACK} + TC_{FBack} \\ &= (TC_{MP} + TC_{PR}) + (TC_{RP} + TC_{PM}) + (TC_{MP} + TC_{PR}) \\ &\quad + TC_{RR} + TC_{RR} + \max\left[TC_{RR}, (TC_{RP} + TC_{PM})\right] \\ &= 3TC_{MP} + 3TC_{PR} + 2TC_{RR} + \max\left[TC_{RR}, (TC_{RP} + TC_{PM})\right] \\ &= \phi\left\{3\delta + 3 + 2H_{RR} + \max\left[H_{RR}, (1+\delta)\right]\right\} \end{aligned} \tag{24}$$

The *handover execution cost* of (25) is a time amount for a connection establishment using a new communication interface. It depends on the network type, used AAA (Authentication, Authorization, and Accounting) mechanism, and network topology. In case of WLAN it includes authentication and association time. For WiMAX, it is for synchronization & ranging, basic capacity negotiation, key exchange & authorization, and registration. Layer 3 FNA (Fast Neighbor Advertisement) message transmission to the new PoA after the MN established a new link connection is included in this cost. Let θ_ξ be the handover execution delay for the communication system ξ.

$$HC_{HO-exe} = t^*_{hn} = \begin{cases} t_{auth} + t_{assc} = \theta_{WLAN} & : \text{WLAN} \\ t_{rng} + t_{cap} + t_{key} + t_{reg} = \theta_{WiMAX} & : \text{WiMAX} \end{cases} \tag{25}$$

4.2 Horizontal and Vertical Handover Cost Analysis

The horizontal handover cost in terms of the handover time (t_{HO}) for the proposed mechanism is given in (26). Since the service disruption only occurs during the link scanning time in the horizontal handover of the proposed mechanism when the Link_Down prediction is correct, the handover cost in terms of the service disruption time (t_{SD}) is given in (27).

$$\begin{aligned} t_{HO} &= t_{L2p} + t_{L3} \\ &= \begin{cases} t_{HO-\max} = t_{L2p-nbr} + t_{L2p-scn} + t_{L2p-ind} + t_{FH} \\ \qquad = 2\phi(\delta + 1 + H_{RI}) + N_{p-nbr}\gamma_p + 2\phi(\delta + 2 + H_{RR}) \\ \qquad\quad + \phi\left\{3\delta + 3 + 2H_{RR} + \max\left[H_{RR}, (1+\delta)\right]\right\} \\ \qquad = \phi(7\delta + 9 + 4H_{RR} + 2H_{RI}) + N_{p-nbr}\gamma_p + \phi\left\{\max\left[H_{RR}, (1+\delta)\right]\right\} \\ t_{HO-\min} = t_{L2p-ind} = 2\phi(\delta + 2 + H_{RR}) \end{cases} \end{aligned} \tag{26}$$

$$t_{SD} = t_{L2p-scn} = N_{p-nbr}\gamma_p \tag{27}$$

For the vertical handover of the proposed method, the handover time is derived in (28) and the service disruption time is zero when the Link_Down prediction is correct.

$$\begin{aligned} t_{HO} &= t_{L2p-nbr} + t_{L2n-scn} + \max\left\{ t_{L2p-ind} + t_{FH}, \begin{pmatrix} t_{auth} + t_{assc} : \text{WLAN} \\ t_{rng} + t_{cap} + t_{key} + t_{reg} : \text{WiMAX} \end{pmatrix} \right\} \\ &= 2\phi\,(\delta + 1 + H_{RI}) + N_{n-nbr}\gamma_n + \max\left\{\phi\,[3\delta + 3 + 2H_{RR} + \max\{H_{RR}, (1+\delta)\}],\ \theta_n\right\} \end{aligned} \tag{28}$$

4.3 Handovers with a Pre-defined LGD Threshold and no Neighbor Information

In this section, we derive the handover cost for a vertical handover without neighbor network information and using a pre-defined LGD threshold. Without neighbor information, the MN cannot know whether it should perform a horizontal or vertical handover in advance. Therefore, first it should scan all horizontal channels and if there is no available channel, then it will activate vertical interface and scan the vertical channels. When the MN uses a pre-defined LGD threshold, due to the dynamic nature of the wireless channel, the MN speed, and the network conditions the LGD time may be too early or too late. In late LGD trigger, the MN cannot finish the necessary handover procedures before the actual link down. This causes long handover delay and service disruption time.

The Link_Down can occur any time from the LGD trigger to the actual handover finishing time. Figure 8 shows the vertical handover timing diagram. Because we have assumed that the MN does not use neighbor network information with IEEE 802.21 information server, the neighbor discovery handover cost $t_{L2p-nbr}$ is not included in the total handover time. In Fig. 8 the dotted arrows indicate the possible actual Link_Down times. If the LD occurs before or during FMIPv6 procedure, it is assumed that the MN needs to start a reactive fast handover operation [12] for data forwarding from the previous access router after it registered to the target network. The additional handover time for the reactive mode is derived as (29) to send an FBU (Fast Binding Update) and to receive an FBack to/from the previous access router.

$$\begin{aligned} t_{reactive} &= t_{FBU} + t_{FBack} = (TC_{MP} + TC_{PR} + TC_{RR}) + (TC_{RR} + TC_{RP} + TC_{PM}) \\ &= 2\phi\,(\delta + 1 + H_{RR}) \end{aligned} \tag{29}$$

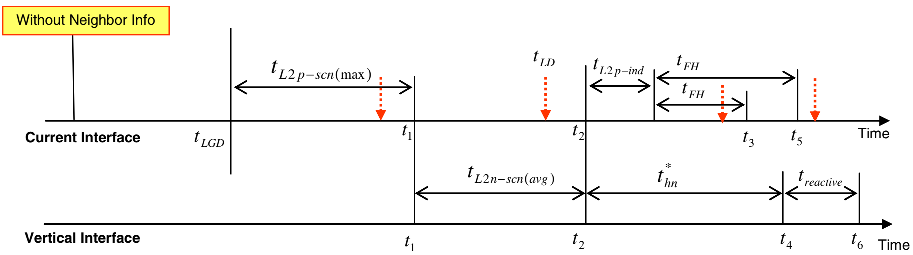


Fig. 8 Vertical handover timing diagram

Time points from t_1 through t_6 of Fig. 8 are derived as,

$$\begin{cases} t_1 = t_{L2p-scn(\max)} = N_{p(\max)} \times \gamma_p \\ t_2 = t_{L2p-scn(\max)} + t_{L2n-scn(avg)} = N_{p(\max)} \times \gamma_p + N_{n(avg)} \times \gamma_n \\ t_3 \text{ or } t_5 = t_{L2p-scn(\max)} + t_{L2n-scn(avg)} + t_{L2p-ind} + t_{FH} \\ \qquad = N_{p(\max)} \times \gamma_p + N_{n(avg)} \times \gamma_n + 2\phi\,(\delta + 2 + H_{RR}) \\ \qquad\quad + \phi\,\{3\delta + 3 + 2H_{RR} + \max\,[H_{RR}, (1+\delta)]\} \\ t_4 = t_{L2p-scn(\max)} + t_{L2n-scn(avg)} + t^*_{hn} = N_{p(\max)} \times \gamma_p + N_{n(avg)} \times \gamma_n + \theta_n \\ t_6 = t_{L2p-scn(\max)} + t_{L2n-scn(avg)} + t^*_{hn} + t_{reactive} = N_{p(\max)} \times \gamma_p \\ \qquad + N_{n(avg)} \times \gamma_n + \theta_n + 2\phi\,(\delta + 1 + H_{RR}) \end{cases} \tag{30}$$

where $N_{p(\max)}$ and $N_{n(avg)}$ are the maximum number of channels for the horizontal scan and the average number of channels to be scanned until the MN first finds an available channel during the vertical scan, respectively.

The total handover time is,

$$\text{(i) } t_{L2p-ind} + t_{FH} \le t^*_{hn}$$
$$t_{HO} = \begin{cases} t_6 - t_{LGD}, & \text{if } t_{LD} < t_3 \\ t_4 - t_{LGD}, & \text{if } t_{LD} \ge t_3 \end{cases} \tag{31}$$

$$\text{(ii) } t^*_{hn} < t_{L2p-ind} + t_{FH}$$
$$t_{HO} = \begin{cases} t_6 - t_{LGD}, & \text{if } t_{LD} \le t_4 \\ (t_{LD} - t_{LGD}) + t_{reactive}, & \text{if } t_4 < t_{LD} < t_5 \\ t_5 - t_{LGD}, & \text{if } t_5 \le t_{LD} \end{cases} \tag{32}$$

As in (31) and (32), if the LD occurs before finishing the FMIPv6, then after vertical handover the reactive mode fast handover is followed so that the total handover time is increased.

The total service disruption time is given as,

$$\text{(i) } t_{L2p-ind} + t_{FH} \le t^*_{hn}$$
$$t_{SD} = \begin{cases} t_6 - t_{LGD}, & \text{if } t_{LD} \le t_1 \\ (t_1 - t_{LGD}) + (t_6 - t_{LD}), & \text{if } t_1 < t_{LD} < t_3 \\ (t_1 - t_{LGD}) + (t_4 - t_{LD}), & \text{if } t_3 \le t_{LD} < t_4 \\ t_1 - t_{LGD}, & \text{if } t_4 \le t_{LD} \end{cases} \tag{33}$$

$$\text{(ii) } t^*_{hn} < t_{L2p-ind} + t_{FH}$$
$$t_{SD} = \begin{cases} t_6 - t_{LGD}, & \text{if } t_{LD} \le t_1 \\ (t_1 - t_{LGD}) + (t_6 - t_{LD}), & \text{if } t_1 < t_{LD} \le t_4 \\ (t_1 - t_{LGD}) + t_{reactive}, & \text{if } t_4 < t_{LD} \le t_5 \\ t_1 - t_{LGD}, & \text{if } t_5 < t_{LD} \end{cases} \tag{34}$$

Basically, since during the horizontal channel scanning $(t_1 - t_{LGD})$ the MN cannot send and receive data, the service is disrupted. As the worst case, if the LD occurs during the horizontal scanning, then the service will be disrupted during the entire handover time up to t_6 time point.

5 Simulation Results

In this section, handover costs including the total handover time and the service disruption time are evaluated for various network conditions. We compare the handover costs for two handover mechanisms: (i) the proposed predictive handover and (ii) the handover without

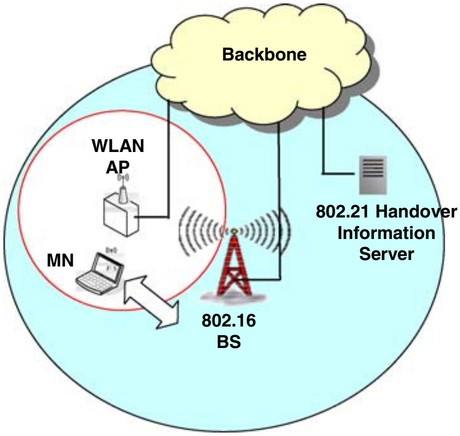


Fig. 9 Handover scenario for 'Case Study 2' and 'Case Study 3'

Table 2 Simulation parameters

ϕ	2	δ	3 ms	γ_{WLAN}	10 ms
γ_{WiMAX}	8 ms	θ_{WLAN}	20 ms	θ_{WiMAX}	100 ms, 250 ms
$N_{\text{WLAN(max)}}$	11 channels	$N_{\text{WiMAX(max)}}$	10 channels	H_{MP}	1
H_{PR}	1	H_{RR}	2 (horizontal), 5 (vertical)	H_{RI}	5 (Case Study 2 and 3)

neighbor information and with a pre-defined LGD threshold. Three case studies are performed. First, the required handover time variations for different network model parameter values are evaluated. Second, the handover time and service disruption time are analyzed using Eq. (31)–(34) for a given handover scenario. Third, we have simulated the handover performance when the mobile node speed and channel condition vary in time.

Figure 9 shows the handover scenario applied to 'Case Study 2' and 'Case Study 3' in which the MN moves away from the WLAN to the WiMAX network so that a vertical handover is expected. Table 2 shows the simulation parameter values [10, 15–18] that are used in this section.

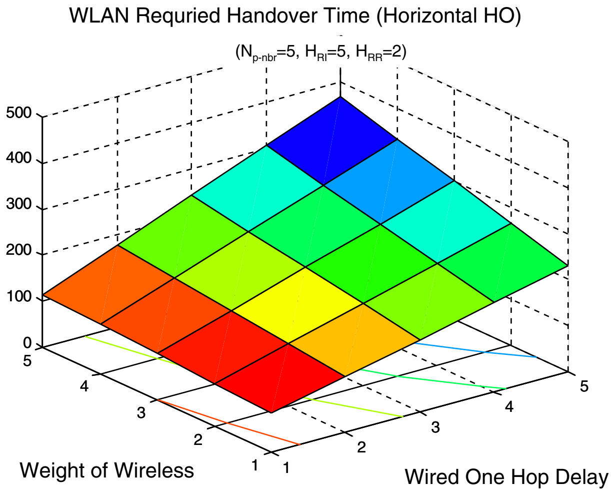
5.1 Case Study 1: The Required Handover Time for Different Network Conditions

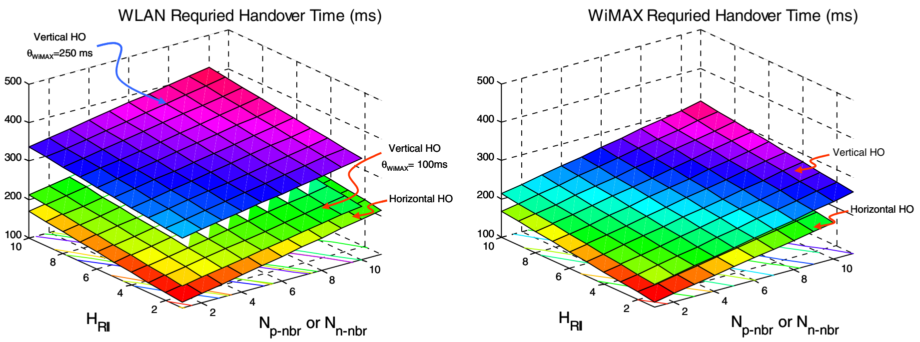
For horizontal and vertical handovers within and between the WLAN and WiMAX, the required handover time of the proposed method is evaluated. The hop counts between the previous access router and the new access router are set to 2 and 5 for horizontal and vertical handovers, respectively. Figure 10 shows the required handover time variations of WLAN horizontal handover case for different ϕ and δ values. $N_{p-nbr} = 5$ and $H_{RI} = 5$ are used. As shown in Fig. 10, the required handover time depends more on ϕ than δ because of many message exchanges on the backbone. Figure 11 shows the required handover time variations for different H_{RI} values and different number of neighbor PoAs for both WLAN and WiMAX.

5.2 Case Study 2: Actual Handover Time and Service Disruption Time

For this case study, the handover scenario of Fig. 9 in which the MN moves away from the WLAN AP to the WiMAX network domain. The total handover time and the service disruption time for this network condition are evaluated. Without the neighbor network information,

Fig. 10 The required handover time for different ϕ and δ values





(a) **(b)**

Fig. 11 The required handover time for WLAN and WiMAX. **a** WLAN. **b** WiMAX

the MN performs scanning of all 11 WLAN channels and then it starts to find an available WiMAX channel. In average it will find an available channel after $N_{\text{WiMAX(max)}}/2 = 5$ channel scanning trials. When a pre-determined LGD trigger threshold is used, the LD occurs any time after the LGD trigger time. Depending on the LD time, the total handover time is different as we derived in (31) and (32). Basically, the latter LD time causes the shorter handover time as shown in Fig. 12.

During t_4 and t_5 of Fig. 12a, the MN has finished the required procedures at the vertical interface but it waits to finish the FMIPv6 operation with the current interface. Since the LD occurs before finishing FMIPv6, the MN starts a reactive mode FMIPv6 with the new interface. In the proposed mechanism, if the predictive LGD trigger is timely generated, then the required handover time is derived as (35).

$$t_h = 2\phi\left(\delta + 1 + H_{RI}\right) + \gamma_{\text{WiMAX}} + \max\left\{\phi\left(5\delta + 7 + 5H_{RR}\right), \theta_{\text{WiMAX}}\right\} \tag{35}$$

The total service disruption time is shown in Fig. 13. The later LD time causes the shorter service disruption time. For the proposed mechanism, if the predictive LGD trigger is timely generated, then there is no service disruption because no horizontal scanning is necessary.

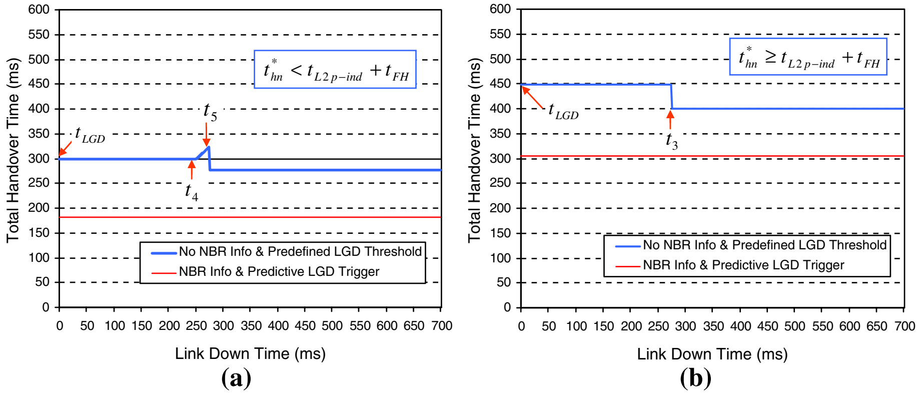


Fig. 12 The total handover time. **a** $t^*_{hn} < t_{L2-ind} + t_{FH}$. **b** $t^*_{hn} \geq t_{L2-ind} + t_{FH}$

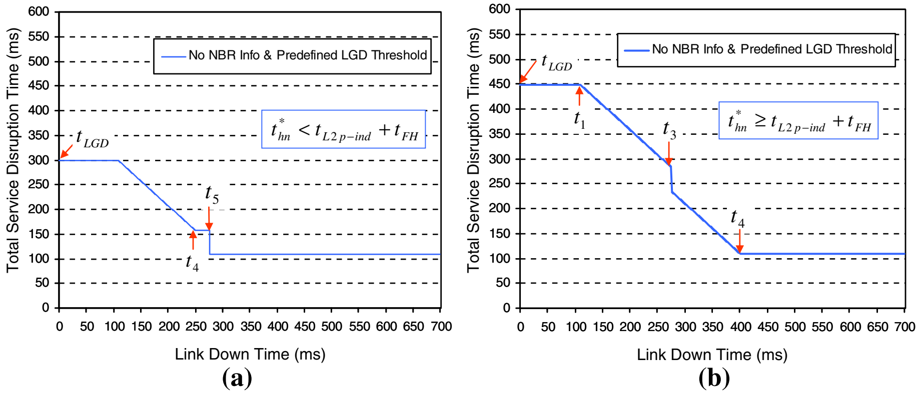


Fig. 13 The total service disruption time. **a** $t^*_{hn} < t_{L2-ind} + t_{FH}$. **b** $t^* \geq t_{L2-ind} + t_{FH}$

5.3 Case Study 3: Signal Strength-based Handover Simulation

In this case study, the link quality is measured by the received signal strength and it is obtained from the following Fritz path loss model [19] of (36), in which the received signal power depends on the path loss exponent β and distance d from the transmitter.

$$\left.\frac{P_r(d)}{P_r(d_0)}\right|_{dB} = -10\beta \log\left(\frac{d}{d_0}\right), \quad P_r\,(d_0) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2\, d_0^2 L} \tag{36}$$

where, $P_r(d)$ denotes the received signal power level in watts at distance d; $P_r\,(d_0)$ is the received power at the close-in reference distance d_0; P_t is the transmitting power, G_t and G_r are the transmitting and receiver antenna gains, respectively; λ is the wavelength of the radio signal; L is the system loss factor.

For the performance comparison, a pre-determined LGD threshold method of (37) is compared with the proposed mechanism.

$$TH_{LGD} = \alpha \times T_{LD} \tag{37}$$

The performance is evaluated in terms of (i) the signal prediction accuracy using the LMS and the linear slope estimation, (ii) LD time difference, (iii) actual service disruption time, and (iv) early triggering cost. In this section, the following three performance metrics are defined. $PredError_{dB}$ is the average dB scale prediction error. $P_r\,(i)$ and $\hat{P}_r\,(i)$ are the observed signal power and k_h-step predicted signal power, respectively; n_p and n_d are the sample sequence number at the prediction start time and at the actual Link_Down time, respectively. In (39), the desired LD time means the smallest LD time that can minimize the service disruption time after LGD trigger. The negative and positive $LD\_Time\_Difference$ values indicate the early- and the late- LGD triggering, respectively. The early triggering cost simply represents the loss of benefit of the previous network in terms of time. $Early\_LGD\_Trigger\_Cost$ represent the degree of the loss of benefit of previous interface. In (40) the actual link down time implies the time that the received signal power crosses the minimum power level T_{LD} if the MN does not explicitly perform the vertical handover.

$$PredError_{dB} = \left(\sum_{i=n_p}^{n_d} \left| \left[\frac{P_r(i)}{\hat{P}_r(i)} \right]_{dB} \right| \right) \Big/ \left(n_d - n_p\right) \tag{38}$$

$$\begin{aligned} LD\_Time\_Difference = {} & \text{(the desired LD time)} \\ & - \text{(the actual link down time)} \end{aligned} \tag{39}$$

$$\begin{aligned} Early\_LGD\_Trigger\_Cost = {} & \max\{\text{(the handover finishing time)} \\ & - \text{(the actual link down time)}\,,\ 0\} \end{aligned} \tag{40}$$

Table 3 shows the parameter values used in this simulation. Table 4 shows the parameter sets for various channel and movement condition simulations. From SET 9 to SET 12, β and ν are changed over time linearly during the simulation time of 100 s.

Figure 14 shows the prediction performance of LMS and the linear slope estimation. The mean power difference between the observed signal and k_h-ahead predicted signal is very small for both predictors at <0.35 dB. The simple linear slope estimation method is little better than the LMS prediction because channel and movement condition is monotonically decaying function so that the linear slope estimation well follows the observed signal traces. Also LMS needs a convergence time.

Figures 15–17 show performance comparisons for *LD_Time_Difference*, the total service disruption time, and *Early_LGD_Trigger_Cost*, respectively. For the linear slope estimation, $\eta = 0.3$ is used. The LD_Time_Difference of Fig. 15 indicates the time difference between the desired LD time and the actual link down time. The negative LD_Time_Difference means too early handover execution so that it may result in a loss of the benefits of the current interface

Table 3 Simulation parameters

$P_t G_t$	100 mW	G_r	1
L	1	d_0	1 m
λ	0.124 m	$T_{\min} = T_{LD}$	$3.162 * 10^{-11}\,W = -75$ dBm
T_{init}	−70 dBm	LMS prediction order p	10
Δ_h	10 ms	LMS step size μ	0.015
α	1.0–2.0	η	0.2, 0.3
β	3–5	MN speed ν	1–5 m/s

Table 4 Simulation cases and parameter sets

Parameter SET	Initial β	Final β	Initial υ	Final υ	θ_{WiMAX} (ms)
SET 1	3	3	1	1	100
SET 2	3	3	1	1	250
SET 3	3	3	5	5	100
SET 4	3	3	5	5	250
SET 5	5	5	1	1	100
SET 6	5	5	1	1	250
SET 7	5	5	5	5	100
SET 8	5	5	5	5	250
SET 9	5	3	5	1	100
SET 10	5	3	5	1	250
SET 11	3	5	1	5	100
SET 12	3	5	1	5	250

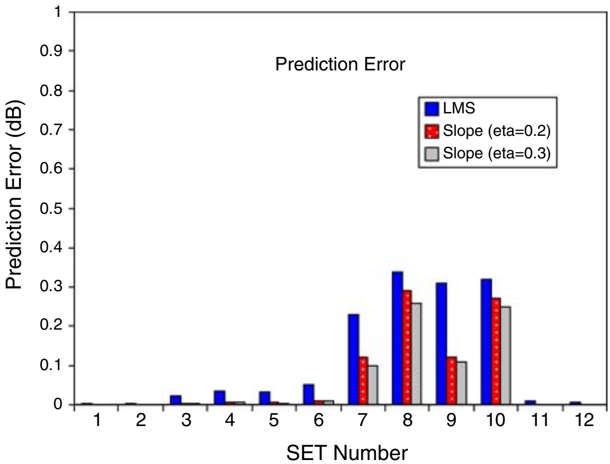


Fig. 14 Prediction performance

and cause frequent event roll-backs or handover cancellations. The positive LD_Time_Difference represents too late handover execution and it results in a long service disruption. Therefore, some incoming packets can be lost or delayed during this time difference. Since the large packet loss and delay during the handover is critical to the time sensitive applications such as voice over IP service, the service disruption time should be minimized. As shown in Fig. 15, in the proposed mechanism the desired LD time is always close to the actual LD time. Therefore, the total service disruption time is also very small compared with the pre-determined LGD threshold case as in Fig. 16. For SET 7 through SET 10, the actual link down occurred little before the expected LD time for LMS prediction case about 45 ms to 55 ms so that after the vertical handover a reactive mode fast handover is required. The *Early_LGD_Trigger_Cost* of the proposed method is close to ideal value (zero) as shown in Fig. 17. For the pre-determined LGD threshold method, depending on the α values, large performance variations are observed. The more conservative α (larger value) shows the smaller service disruption time but the larger LD time difference and early LGD triggering cost.

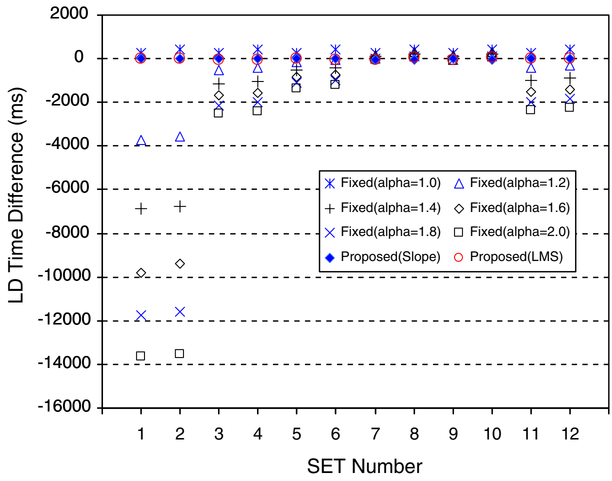


Fig. 15 LD_Time_Difference

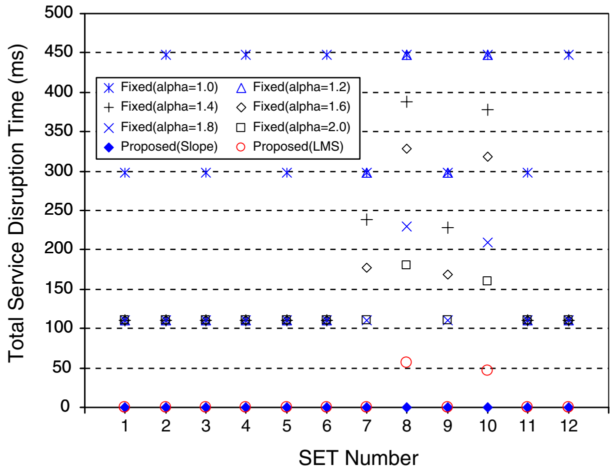


Fig. 16 Total service disruption time

6 Conclusions

Effective and timely link-layer trigger mechanisms can significantly influence the handover performance. An LGD trigger should be fired at least in the required handover time before the Link_Down (LD) event. The required handover time is different according to the topologies, layer 3 handover protocols, and handover policies of the neighbor networks. Due to the mobility involved, these parameters can be dynamic in time so that the required handover time should be configurable adaptively. Too late handover initiation may lead to a long service disruption, and some incoming packets may be lost or delayed during this outage. A cost function can be determined using the total required handover latency and the total service disruption time. On the other hand, too early handover initiation may force the handover

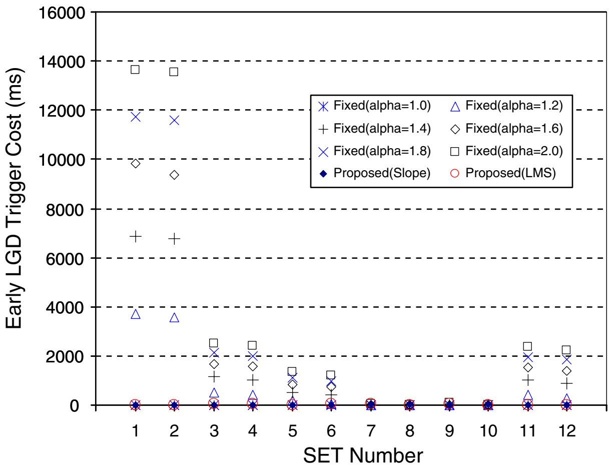


Fig. 17 Early_LGD_Trigger_Cost

execution to a new interface even when the link quality of the old interface is still strong enough to decode data, resulting in a loss of the benefits of the preceding interface.

In this paper, a new predictive handover mechanism is proposed for the seamless handover across heterogeneous wireless networks. The neighbor network information is used to decide the desired handover policy and the required handover procedure. Given that various newly defined IEEE standards support information exchanges for neighbor network topology, network conditions, and handover policies before the handover, it is possible to derive the required handover time in advance. From the analysis of the required handover procedures based on the obtained neighbor information, we presented the required handover time estimation methods for various handover types. To generate timely the LGD trigger, the estimated required handover time(t_h) is applied to the link down prediction. Unlike the previous pre-defined threshold-based LGD triggering in which the LGD trigger may result in too late or too early handover initiation depending on the channel condition and movement pattern, in the proposed method, if the LD event is expected after t_h, then the predictive LGD trigger is generated to initiate the required handover procedures. The proposed predictive handover mechanism can be successfully implemented within the new IEEE 802.21 media independent handover architecture.

This adaptive and accurate LGD trigger time control provides the low handover cost in terms of the total handover time and the service disruption time. Handover cost analysis is performed for horizontal and vertical handovers. In the simulation study, we evaluate the prediction performance of the LMS and the linear slope estimation. Both prediction methods can estimate t_h future link quality at <0.35 dB for various conditions so that LGD trigger is timely generated to finish the required handover procedures before the current link goes down. For the WLAN to WiMAX vertical handover case, the service disruption time of the compared conventional method is at most 450 ms while the proposed method is at most 55 ms. For the early triggering cost, the proposed method is very close to zero, but the compared method shows large variation in accordance with the pre-defined LGD threshold values. Several experimental case studies demonstrate that the proposed method achieves seamless and proactive mobility for various network environments.

The proposed effective handover mechanism with the estimation of the required handover time and the prediction of the link quality can timely initiate and finish the all handover procedures in accordance with the current network environments so that it minimizes the service quality degradation during the handover over heterogeneous wireless networks.

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