# Predictive Link Trigger Mechanism for Seamless Handovers in Heterogeneous Wireless Networks

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### Abstract

Effective and timely link-layer trigger mechanisms can significantly influence the handover performance. The handover process will not perform the correct decision and execution unless adequate and timely link-layer trigger information is delivered. In this paper, a predictive link trigger mechanism for seamless horizontal and vertical handovers in heterogeneous wireless networks is proposed. Unlike previous link trigger algorithms based on pre-defined signal level thresholds, the link layer triggers in this study are adaptively and timely fired in accordance with the network conditions. Firstly, the time required to perform a handover is estimated based on the neighboring network conditions. Secondly, the time to trigger a Link_Going_Down to initiate a handover is determined using a least mean square linear prediction in which the prediction interval ($k_h$) is dynamically determined based on the estimated handover time. An upper bound for the packet loss rate during a handover is derived for a Gaussian shadowing channel. A manner in which this approach can be applied to IEEE 802.21 is shown in media independent handover scenarios. Simulation results of the proposed predictive link triggering mechanism show that it provides a timely proactive handover. The packet loss rate observed in a Gaussian shadowing channel remains low during a handover.

Key words: *seamless handover, link triggers, prediction, WLAN, WiMax, heterogeneous wireless networks*

## I. Introduction

Mobile communication has become more popular due to the increased availability of portable devices and advanced wireless technology. The rapid expansion of mobile communications has spawned a number of different wireless communication systems including the Wireless Local Area Network (WLAN), the Worldwide Interoperability for Microwave Access (WiMAX), and the Universal Mobile Telecommunication System (UMTS). In addition, mobile devices are increasingly incorporating multiple wireless interfaces leading to an increased need for these devices to move freely among different network systems and perform handovers seamlessly across heterogeneous wireless networks. Traditionally, a handover is performed within the same wireless system (horizontal handover); however, in heterogeneous wireless networks and with multiple interface devices, a vertical handover between different wireless networks also should be taken into account.

Handovers typically cause layer 2 (L2) switching and/or layer 3 IP connectivity 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 are 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) layer and communicated either to a handover management functional module such as the Media Independent Handover Function (MIHF) of IEEE 802.21 [1], 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 [2]. 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. A number of methods have been proposed for generating LGD triggers [3-5]. However, most of these methods use pre-defined Received Signal Strength Indication (RSSI) thresholds. With these thresholds, 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.

In this paper, a novel predictive link trigger mechanism using a least mean square (LMS) linear prediction for seamless handover in heterogeneous wireless networks is proposed. With the help of the neighbor network information (including the network type, network topology, and handover policies, e.g., association levels, registration methods, and handover protocol types) provided by the current serving base station (BS), access point (AP) and/or the IEEE 802.21 MIHF information server, the MN (or alternatively the network side BS or AP in the case of network-controlled handover) can determine the type of handover that should occur in addition to the amount of time required to perform it before the current link is broken. The required handover times are derived for different handover types and various neighbor network conditions. In the proposed triggering method, the Link_Going_Down trigger is timely fired prior to the estimated handover time from the time the link is expected to go down. This differs from existing methods that are based on a pre-determined power threshold. The LMS linear prediction technique is used to predict, given the required handover time, the viability of the current link. If a $k_h$ time ahead, which is dynamically determined according to the required handover time, Link_Down event is expected, the predictive LGD trigger is then generated to initiate the required handover procedures. All prediction- and handover-related parameters are self-configurable.

To take into account the wireless channel shadowing effects on handover performance, an analytical upper bound of the packet loss rate during the handover is derived using a Gaussian shadowing model. A simulation study shows that the proposed predictive Link_Going_Down trigger results in a packet loss rate less than the analytical bound derived; moreover, it is fired at the right time the handover should be initiated. This timely triggering performance is evaluated using a new metric termed the "handover time difference", which indicates the time difference between the actual handover finishing time and the Link_Down time. The proposed link triggers are applied to WLAN and WiMAX vertical handover cases using the IEEE 802.21 MIHF framework that provides the link layer intelligence and other related network information to the upper layer in order to optimize handovers.

The remainder of this paper is organized as follows: Section II reviews related work and describes the problem statement. In Section III, estimates for the time it takes to complete a handover are derived for different handover types and various neighbor network conditions. In Section IV, the proposed predictive link triggering method is presented and the analytical bound for packet loss rate during a handover is derived. A demonstration of an example scenario that combines the proposed trigger mechanism and the IEEE 802.21 concept is also shown in Section IV. Section V highlights the simulation results that demonstrate the performance of the proposed method in terms of the prediction accuracy, link triggering time effectiveness, and packet loss rate. We conclude this paper in Section VI.

## II. Related Work

In this section, related work on link trigger algorithms for horizontal and vertical handovers in wireless networks is reviewed. Support for mobile users of IEEE 802.11 WLAN and IEEE 802.16 (and 802.16e) WiMAX systems necessitates a handover process that can be broken down into four stages: i) Link_Going_Down (LGD) triggering, ii) network discovery, iii) network selection, and iv) handover execution. The triggering stage is the first step to correspond to the time point when a wireless MN identifies the need to look for another point of attachment (PoA) [4]. Link trigger events are generally invoked when the received signal level or values of quality of service (QoS) metrics such as the error rate and the throughput become lower than pre-defined thresholds. 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 that level of signal decay that triggers a handover is a very important issue.

Most traditional handover schemes based on the received signal strength can be classified into the following categories [6]: i) simple RSSI comparison, in which a handover takes place if the RSSI of the candidate PoA is larger than the current PoA, ii) RSSI with threshold, in which a handover takes place if the RSSI of the candidate PoA is larger than the current PoA and the RSSI of the current PoA is under the pre-defined threshold $T$, and iii) RSSI with hysteresis, in which a handover takes place if the RSSI of the candidate PoA is larger than the current PoA with a pre-defined hysteresis margin $H$. However, different networks involve an asymmetric nature, thus a simple power comparison is not applicable to vertical handovers. In addition, because the condition of the wireless channel has a dynamic nature, decision and procedure initiations using the pre-defined thresholds ($T$ and $H$) may not be able to finish the required handover procedure before the current link goes down. Some fuzzy logic and neural network-based handover algorithms [7][8] have been proposed to assist in the making of handover decisions. They decrease handover latency and the number of unnecessary handovers by changing the RSSI average window according to the MN's speed. It is worth mentioning that these algorithms are complex and are not easy to implement in practical systems.

[9] describes the role of link indications within the Internet architecture. It also points that several models of link conditions have been used to decide when link triggers should be fired; however, as reported in [9], this results in unreliable L2 triggers. In [10], general link layer triggers are defined to assist upper layer handover procedures that include 'Link_Up', 'Link_Down', 'Link_Going_Up', 'Link_Going_Down', 'Link_Quality_Crosses_Threshold', 'Trigger_Rollback' and 'Better_Signal_Quality_AP_ Available'. As mentioned in [4] and [9], the Link_Down may be detected by MN using consecutive non-acknowledged transmissions, loss of beacon frames, and poor (below the decodable power) signals. The Link_Going_Down trigger is usually generated before the link goes down using a pre-defined marginal $\alpha$ (e.g., in a frame-loss-rate case $\alpha$ <1, signal strength case $\alpha$ >1). [11] proposed general unified layer 2 triggers. To determine when the Link_Quality_Change trigger is fired, it uses the SINR, retransmission ratio, frame error rate, and bit rate. Also utilized is the fixed significance parameter $\alpha$ as in many previous threshold-based decision methods.

[5] proposes an analytical model that estimates the anticipation required (Link_Going_Down triggering) in order to achieve a target handover packet loss performance. From the path loss model, when a target loss rate is given, it can adaptively derive a suitable power threshold for the Link_Going_Down trigger. Although it does not use a predetermined fixed threshold, it requires that the MN discern path-loss model parameters such as the path loss exponent and the moving speed in advance; additionally, it assumes that the parameter values are constant in time. [12] proposes a proactive scan mechanism in WLAN to reduce the channel scan delay. A scan trigger that is a new link trigger earlier than Link_Going_Down trigger is defined to start periodic active scanning of the neighbor APs. In this study, a transmission rate drop to a certain threshold value is utilized as an indication of the scan trigger. According to simulation results using the proactive scan, the scanning time can be reduced to less than 50 ms without the need for neighbor AP information. As described in [2], most link triggers are fired based on predetermined threshold values, and these values impact the handover performance. There are some interesting link-layer triggering approaches in the literature [13][14]. Unlike the previous received-signal or QoS-based handover decisions, geographical information is used to trigger a vertical handover. In [13], handover triggering nodes installed in WLAN/cellular transition regions are used to indicate that a MN is close to the boundary of two networks. [14] uses a handover trigger table at an AP to store data related to location information (black holes), in which the link to the AP breaks in a very short time. However, they require pre-installations or localization functions.

The IEEE 802.21 MIH framework [1] currently under development defines a method to provide link layer intelligence and other related network information to the upper layers in order to optimize handovers between heterogeneous networks. Link triggers are used between layers to communicate specific events. The 802.21 MIH framework also defines a mechanism to acquire and exchange neighbor network information. In the fast mobile IPv6 (FMIPv6) protocol [15], the network layer may use the indication of a handover from the link layer in advance to achieve seamless handovers. Thus, a unified architecture that combines the link-layer trigger mechanism, network layer FMIPv6, and 802.21 MIHF services is required [16].

## III. Required Handover Time Estimation based on Neighbor Network Information

A Link_Down event of the current PoA indicates that no additional data packets can be sent or received over this link. Therefore, the required processes for handover – channel scanning, neighbor discovery, L3 fast handover, and vertical handover execution if required – should be finished before the Link_Down event of the current link. In this section, the motivation of this research is described, and the required handover time estimation methods are then shown for various conditions in WLAN and WiMAX overlay network environments. As the link layer switching of these two networks are typically operated in a “break before make” manner, accurate handover time estimation is more important for seamless handovers.

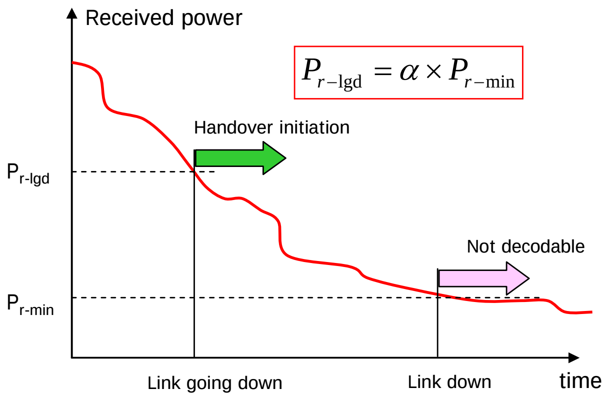
### *A. Motivation*

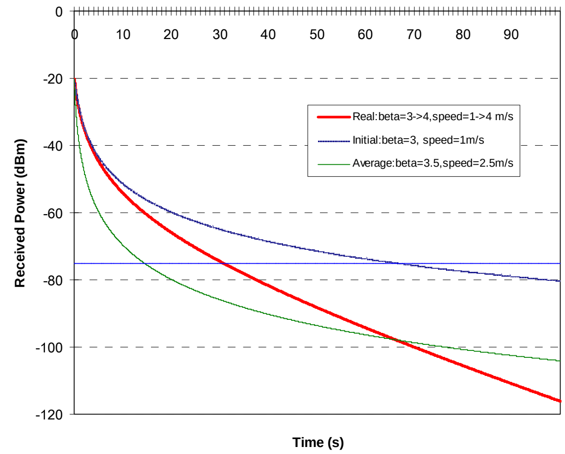
Most previous Link_Going_Down trigger algorithms [5][11][12][17] are based on pre-defined thresholds associated with the received signal strength or QoS metrics. If the measured value crosses threshold $P_{r-\mathrm{lgd}}$, then the Link_Going_Down trigger is generated and the handover process starts, as shown in Fig. 1-(a). However, in real wireless communications, the channel condition is dynamic in time due to such factors as the MN’s movement, shadowing, and shadowing. As an example study, from the Fritz path loss model [18] in (1), the received signal power depends on the path loss exponent and the distance from the transmitter. In addition, these values are time-varying parameters.

$$\left[\frac{P_r(d)}{P_r(d_0)}\right]_{dB} = -10\beta \log\left(\frac{d}{d_0}\right) \qquad (1)$$

where $d$ is the distance between the receiver and the transmitter expressed in meters, $P_r(d)$ denotes the received signal power level in watts at distance $d$, $\beta$ is the path loss exponent, and $P_r(d_0)$ is the received power at the close-in reference distance $d_0$. As shown in Fig. 1-(b), depending on the channel condition and MN’s movement, the received signal is decaying differently. In this example, the real MN’s speed and $\beta$ vary from 1 m/s to 4 m/s and from 3 to 4, respectively, during the simulation time. As can be seen from the estimation, the use of the initial or average parameter values results in different Link_Down times compared to the use of an actual trace. Therefore, when pre-defined thresholds are used for link triggers, there may not be sufficient time in some cases to prepare for the handover, or the link triggers may be generated too early compared to the actual Link_Down. $P_{r-\min}$ is the minimum signal strength to decode data packets so that less than $P_{r-\min}$ indicates a Link_Down event.

An important factor for timely link triggering is the required handover time ($t_h$). 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. This required handover time is different depending on the handover type (horizontal or vertical), the neighbor PoA topology, and the current and neighbor network handover policies.

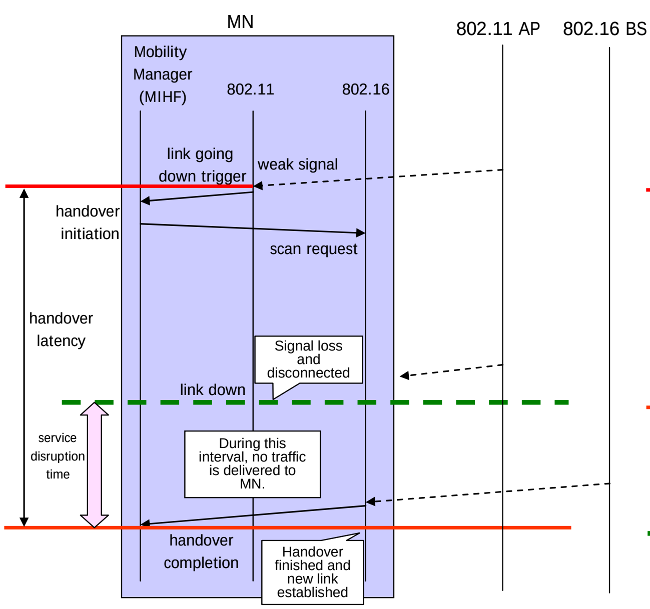


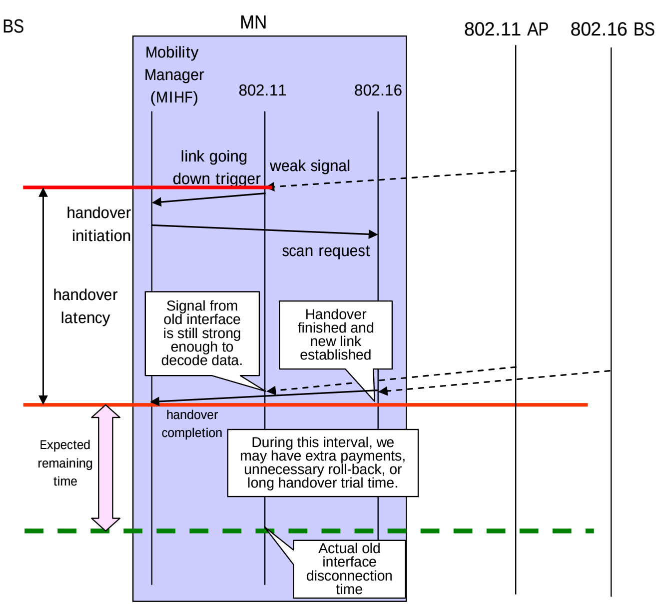




(a) Link trigger operation.

(b) Threshold crossing times for different parameters.

Figure 1. Pre-defined Link_Going _Down threshold operation.




(a) Too late Link_Going_Down trigger.

(b) Too early Link_Going_Down trigger.

Figure 2. Late and early link triggers.

Fig. 2 shows the cost of improper Link_Going_Down triggers. In Fig. 2-(a) the LGD trigger occurs too late to complete the vertical handover from WLAN to WiMAX properly, and before finishing the handover to the WiMAX network, it loses its connection to the WLAN. This can lead to long service disruptions, and some incoming packets can be lost or delayed during the outage. The cost for LGD trigger that are generated too early is also significant. It may force the handover execution to a new interface even when the received signal from 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 Link_Down, frequent event roll-backs or handover cancellations may occur. In this paper, estimation methods for the required handover time under various network conditions are proposed. Based on the estimated handover required time, a forecasted LGD trigger is generated. To estimate the required handover time, a number of beneficial messages and functions that are newly defined in the IEEE 802 standards are used.

### *B. Required handover time estimation*

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 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 $t_h$ should be configurable adaptively.

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 AP (or 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 [15] 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 ($t_{L2p}$). 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 ($t_{FH}$).

$$t_{L3} = \begin{cases} t_{FH} \\ 0, & \text{if the target PoA is on the same subnet.} \end{cases} \tag{2}$$

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

- $t_{L2p-nbr}$ : MAC-level frame exchange time to obtain the neighboring information. The IEEE 802.11k and IEEE 802.16e 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. For the IEEE 802.16e, this includes the scan request /response and the scan report. The IEEE 802.11 defines active and passive scanning procedures.
- $t_{L2p-ind}$ : Handover indication message to the current PoA. For the IEEE 802.16e handover mechanism it includes sending a MOB_HO-IND MAC frame to the old BS. The IEEE 802.21 specification defines message exchanges to indicate the handover execution.

Scanning is required when there are multiple candidate PoAs and/or when the MN needs to check the connectivity or resource availability to the PoAs after obtaining the neighbor information. After scanning, the MN can select a target PoA. $t_{L2p-nbr}$ and $t_{L2p-scn}$ can be performed earlier than the LGD trigger using a periodic message exchange and channel scanning. In this case $t_{L2p}$ includes only $t_{L2p-ind}$.

The maximum and minimum required handover time for horizontal handover is given as (3). Fig. 3 shows the WiMAX horizontal handover scenario combined with FMIPv6.

$$t_h = t_{L2p} + t_{L3}, \quad \begin{cases} t_{h-\max} = t_{L2p-nbr} + t_{L2p-scn} + t_{L2p-ind} + t_{FH} \\ t_{h-\min} = t_{L2p-ind} \end{cases} \tag{3}$$

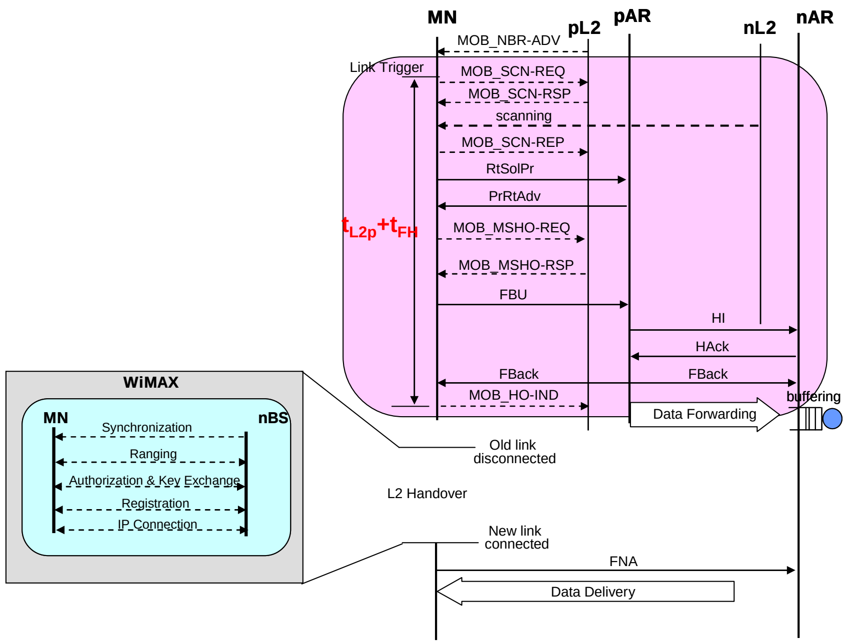



Figure 3. Horizontal handover scenario for WiMAX and the required handover time.

For a vertical handover between WLAN and WiMAX, 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 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 as the previous PoA.

$$t_{hp} = t_{L2p} + t_{FH} = t_{L2p-nbr} + t_{L2p-ind} + t_{FH} \tag{4}$$

- $t_{hn}$: 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.

$$t_{hn} = \begin{cases} t_{L2n-scn} + t_{auth} + t_{assc}, & \text{WLAN} \\ t_{L2n-scn} + t_{rng} + t_{cap} + t_{key} + t_{reg}, & \text{WiMAX} \end{cases} \tag{5}$$

After the neighbor information exchange at the previous interface and scanning the candidate PoAs at the new interface, the MN can select the target PoA. The required procedures at the previous and new interfaces 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 be done using the new interface. Therefore, the total required handover time for a vertical handover is given as (6).

$$t_h = t_{L2p-nbr} + t_{L2n-scn} + \max\left\{ t_{L2p-ind} + t_{FH}, \begin{pmatrix} t_{auth} + t_{assc} : \text{WLAN} \\ t_{rng} + t_{cap} + t_{key} + t_{reg} : \text{WiMAX} \end{pmatrix} \right\} \tag{6}$$

Fig. 4 shows an example of a vertical handover timing relationship from WLAN to WiMAX. It should be noted that IEEE 802.16e registration can be finished before or after the FMIPv6 layer 3 handover using the previous interface.

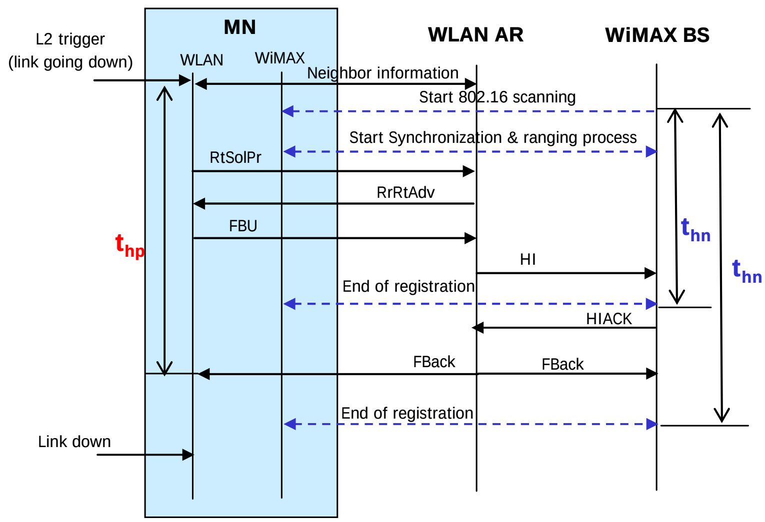



Figure 4. Vertical handover timing relationship from WLAN to WiMAX.

When the MN does not have neighbor information for the handover, the horizontal scanning ($t_{L2p-scn}$) is performed first. If the MN cannot determine the 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 (7).

$$t_h = t_{L2p-nbr} + t_{L2p-scn(\max)} + t_{L2n-scn(\max)} + \max\left\{ \left(t_{L2p-ind} + t_{FH}\right), \begin{pmatrix} t_{auth} + t_{assc} : \text{WLAN} \\ t_{rng} + t_{cap} + t_{key} + t_{reg} : \text{WiMAX} \end{pmatrix} \right\} \tag{7}$$

Fig. 5 shows the overall estimation method of the required handover time for the different handover cases.

There are many information sources to estimate the proper required handover time to the current situation. The IEEE 802.21 specification provides a useful framework in order to estimate the required handover time, including a set of primitives and messages to inform the MN of neighbor network conditions and the handover policies. In addition, the IEEE 802.21 information service provides a framework and corresponding mechanisms by which an MIH functional entity can discover and obtain network information available within a geographical area to facilitate the handover. Once the MN has acquired information about neighbor networks and their availability using the MIHF messages, it can identify whether a horizontal or vertical handover is required and which procedures should be followed. In accordance with the handover association policies between the current and target networks, some handover processes may be skipped or reduced. For example, the WLAN [19][20] and WiMAX [21][22] standards have defined a number of MAC frames to broadcast or to query and reply the neighbor AP (or BS) information. This neighbor information can be obtained by the MN before the handover initiation. In addition there are various proactive or adaptive scanning algorithms [12][23] for WLAN and WiMAX that help the MN locate available APs (or BSs) and the channel information before it is ready to perform a handover. Several approaches have been proposed to reduce the required time for scanning, ranging, and other procedures. In WLAN, the scanning time requires 10 ms – 80 ms [24][25] depending on the number of channels to scan when active scanning is used; for authentication and association it may require less than 10 ms [12]. In [24], it is shown that Mobile IPv6 (MIPv6) layer 3 handover latencies range from 80 ms 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 few seconds [23][26]. 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.

**IF** (MN identifies the target PoA information)

**IF** (handover type = horizontal)

$t_h = t_{L2p} + t_{L3}$, $(t_{h\text{-}max} = t_{L2p\text{-}nbr} + t_{L2p\text{-}scn} + t_{L2p\text{-}ind} + t_{FH},\ t_{h\text{-}min} = t_{L2p\text{-}ind})$

**ELSE** (handover type = vertical handover)

$t_h = t_{L2p\text{-}nbr} + t_{L2n\text{-}scn} + \max[t^*_{hp}, t^*_{hn}]$

$(t^*_{hp} = t_{L2p\text{-}ind} + t_{FH},\ t^*_{hn\text{-}WLAN} = t_{auth} + t_{assc},\ t^*_{hn\text{-}WiMAX} = t_{rng} + t_{cap} + t_{key} + t_{reg})$

**ELSE** (No target PoA information is available)

$t_h = t_{L2p\text{-}nbr} + t_{L2p\text{-}scn(max)} + t_{L2n\text{-}scn(max)} + \max[(t^*_{hp}, t^*_{hn}]$

$(t^*_{hp} = t_{L2p\text{-}ind} + t_{FH},\ t^*_{hn\text{-}WLAN} = t_{auth} + t_{assc},\ t^*_{hn\text{-}WiMAX} = t_{rng} + t_{cap} + t_{key} + t_{reg})$

Figure 5. The required handover time estimation.

## IV. Predictive Link Trigger Mechanism

In Section III, the required handover time was derived. This section addresses the generation of a timely Link_Going_Down trigger within the required handover time before the actual Link_Down event. To achieve this goal, a prediction method is used. This predicts after the required handover time whether the signal strength will cross below the minimum decodable power level ( $P_{r-\min}$ ) or not.

In [4], a prediction-based handover trigger method is proposed in which MN continuously monitors past $L$ signals from the current and target APs. After linear regression using $L$ signals, a line is fitted and the signal in the next time interval is predicted. If the predicted signal of the target AP is greater than that of current AP with a marginal difference, the handover trigger is then generated. In this method, the required handover time is not considered and the linear line fitting does not capture the statistics due to the dynamic changes of mobile node speed and channel conditions so that it may lead to inaccurate prediction results. Additionally continuous signal monitoring of both of the target and current networks for horizontal handover may be impractical in WLAN and WiMAX. In [27] and [28], predictive handover mechanisms for a cellular system were proposed. Among neighboring cells, a target cell is selected based on the historical handover probability. A handover decision is then made with which the current signal level and one next time predicted signal are compared with a predefined priority table.

### *A. Adaptive LMS-based Link_Going_Down triggering*

In order to generate the LGD event based on the required handover time $t_h$, an LMS (Least Mean Square) adaptive prediction technique is applied in this paper. This provides an automatic method for tracking the signal strength continuously. Therefore, the MN does not need to know the path-loss model parameters or its moving speed to determine the trigger threshold and is not required to set a fixed power level for LGD triggering. Instead, depending on the required handover time ( $t_h$ ), the triggering point is adaptively adjusted.

As noted in [29], signal strength data is noisy and is occasionally inconsistent; thus, filtering is needed in order to avoid erratic results. For example, in developing Link_Going_Down and Link_Down indications for use with IEEE 802.21 [1] it is advisable to validate the filtered signal strength measurements with other indications of link loss such as the lack of beacon receptions. In the proposed system, filtered signal samples are used. At each measurement interval $t_m$ the MN measures the received signal strength $m(q)$, and every $N_m$ measurement signals, the prediction sample sequence $x(n)$ is constructed, as shown in Fig. 6. $t_s = t_m \cdot N_m$ is the filtered sample interval. Any filtering technique can be used, such as moving window or the weighted average of (8). The use of filtered samples can also reduce the prediction overhead.

$$x(n) = \sum_{q=0}^{N_m-1} \alpha_q \cdot m(n \cdot N_m - q) \tag{8}$$

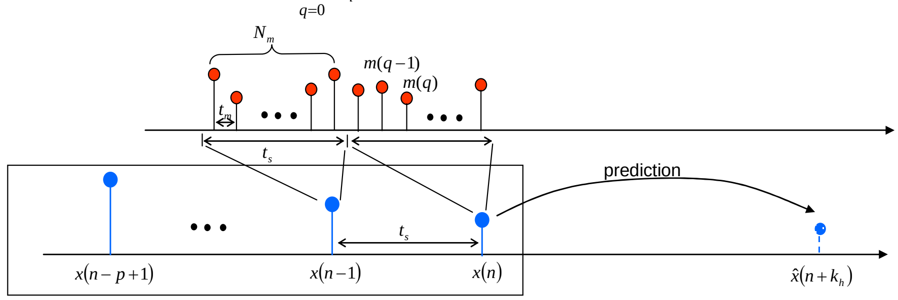



Figure 6. Filtered samples and prediction.

In this paper, the prediction step $k_h$ is determined based on the required handover time. If the $k_h$ ahead predicted power is less than the minimum power level $P_{r-\min}$ to decode data, the Link_Going_Down trigger is then generated.

$$k_h = \left\lceil \frac{t_h + \Delta_h}{t_s} \right\rceil \tag{9}$$

where $\Delta_h$ is the handover marginal time (≥0) to trigger the LGD slightly earlier than the required handover time.

The LMS adaptation algorithm monitors the prediction error $e(n)$ and attempts to minimize the mean squared prediction error, $E\{e(n)^2\}$, by adapting prediction weights, as shown in Fig. 7. The $k_h$-step linear predictor is concerned with the estimation of $x(n+k_h)$ using a linear combination of the current and previous values of $\mathbf{X}(n)$. A $p$th-order predictor has the form of (10). $\mathbf{W}_n$ 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 [30]. The step size $\mu$ is an adaptation parameter that determines convergence speed. In a normalized LMS, if $0 < \mu < 2$, then the LMS will converge to the mean. For the simulation study in this paper, a fixed $\mu$ is used for various conditions.

$$\hat{x}(n+k_h) = \sum_{l=0}^{p-1} w_n(l)x(n-l) = \mathbf{W}_n^T \mathbf{X}(n) \tag{10}$$

$$\begin{aligned} &\mathbf{X}(n) = [x(n), x(n-1), \cdots, x(n-p+1)]^T \\ &\mathbf{W}_n = [w_n(0), w_n(1), \ldots, w_n(p-1)], \mathbf{W}_{n+1} = \mathbf{W}_n + \mu \times e(n)\frac{\mathbf{X}(n)}{\|\mathbf{X}(n)\|^2} \\ &e(n) = x(n+k) - \hat{x}(n+k_h) \approx e(n-k_h) = x(n) - \hat{x}(n) \end{aligned} \tag{11}$$

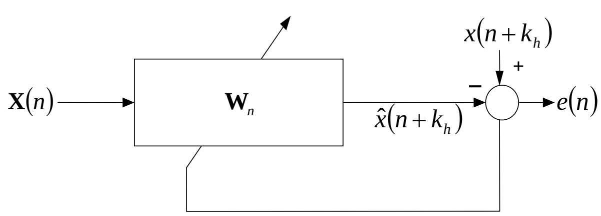



Figure 7. $k_h$-step LMS predictor.

Fig. 8 and Fig. 9 show the proposed predictive LGD triggering mechanism. Let $P_{pred}$ be the prediction start threshold. $P_{pred}$ is adaptively determined based on the required handover time; thus it is not a pre-defined fixed value. $P_{pred}$ is introduced to reduce the prediction overhead. Only when the filtered sample power is less than $P_{pred}$, the prediction process using (10) starts. For each sample prediction, if the $k_h$ ahead prediction value is less than $P_{r-\min}$, then the proper handover procedure of Section III is initiated. $P_{pred}$ should be determined conservatively to guarantee that the time interval from the prediction start to the actual Link_Down event is always greater than the required handover time.

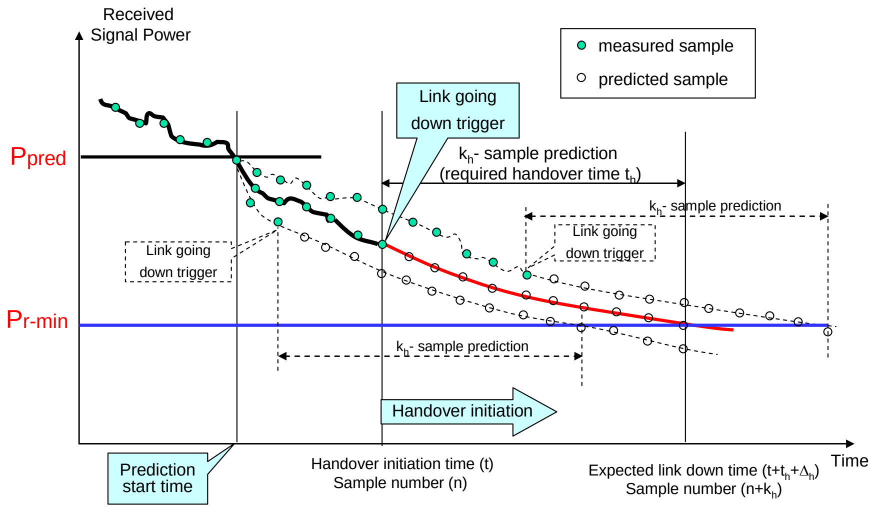



Figure 8. Predictive Link_Going_Down trigger points.

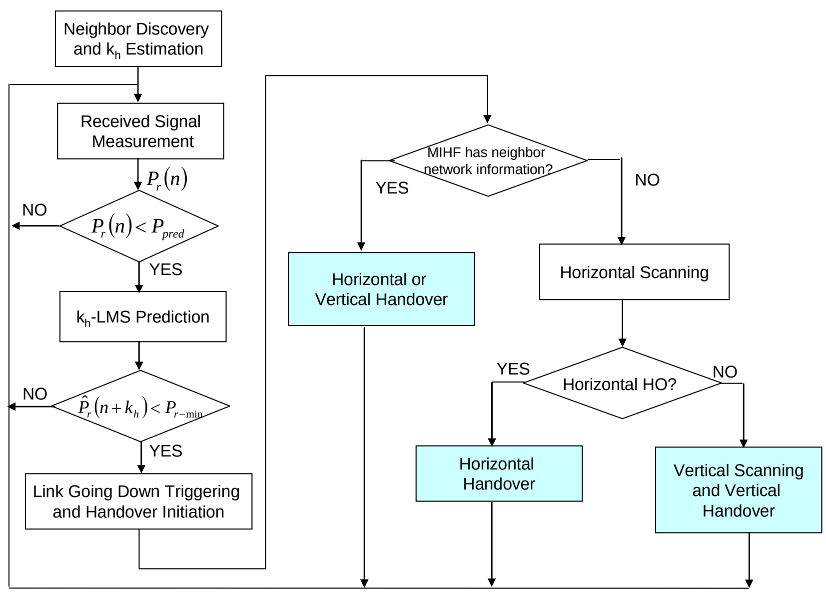



Figure 9. Predictive handover procedure.

Let $t_p$ be the time interval between $P_{pred}$ and $P_{r-\min}$. Then $t_p$ is defined as

$$t_p = t_h + \Delta_p \tag{12}$$

where $\Delta_p$ is the prediction start time margin. From the path loss model of (1), $t_p$ is derived as

$$t_p = \frac{d_0}{v}\left(\frac{P_r(d_0)}{P_{r-\min}}\right)^{\frac{1}{\beta}}\left[1 - 1\Big/\left(\frac{P_{pred}}{P_{r-\min}}\right)^{\frac{1}{\beta}}\right] \tag{13}$$

where $v$ is the MN's moving speed. Given that MN is generally not able to identify the current speed and the path loss exponent value $\beta$, to auto-configure the $P_{pred}$ value from (13), the most conservative parameters are used. Thus,

$$P_{pred} = P_{r-\min}\left[1\Big/\left\{1-t_p\frac{v_{\max}}{d_0}\left(\frac{P_{r-\min}}{P_r(d_0)}\right)^{\frac{1}{\beta_{\max}}}\right\}\right]^{\beta_{\max}} \tag{14}$$

where $v_{\max}$ and $\beta_{\max}$ are the maximum MN's speed and path loss exponent, respectively. These factors can be configured using the history of the MN's movement pattern by the mobility manager or simply can be set using typical initial values. Depending on the current interface type (WLAN or WiMAX), $v_{\max}$ and $\beta_{\max}$ can be different. The typical relationship is as follows:

$$v_{\max}^{WLAN} \le v_{\max}^{WiMAX}, \quad \beta_{\max}^{WLAN} \ge \beta_{\max}^{WiMAX} \tag{15}$$

Using the prediction start time margin and conservative parameters, the prediction procedure can start early enough and before the actual required handover start time.

### *B. Shadowing effect analysis on seamless services during handover*

To study the service disruption time and packet loss rate during a handover for an ideal decaying signal, shadowing effects were investigated. The shadowing effects can be modeled by introducing an additional $X_\sigma$ to the Fritz path loss model of (1).

$$\left[\frac{P_r(d)}{P_r(d_0)}\right]_{dB} = -10\beta\log\left(\frac{d}{d_0}\right) + X_\sigma \tag{16}$$

where $X_\sigma$ is a random variable with Gaussian distribution with a zero mean and a standard deviation of $\sigma$ dB [18].

To accommodate the shadowing noise, the $P_{r-\min}$ threshold value that is used to determine the prediction start power and LGD trigger time should be compensated to reduce the service disruption time and the packet loss rate. Let $C_\sigma$ be the compensation power, *c* be the compensation factor, and $P_{r-\min}^{comp}$ be the compensated minimum power level.

$$\left[\frac{P_{r-\min}^{comp}}{P_{r-\min}}\right]_{dB} = C_\sigma = c\cdot\sigma \tag{17}$$

Therefore, the Link_Going_Down trigger condition in Fig. 9 is changed to

$$\hat{P}_r(n+k_h) < P_{r-\min}^{comp} \tag{18}$$

The service disruption time ($t_{sd}$) during the handover is defined in this paper as the total amount of time during which the actual received power is less than $P_{r-\min}$.

$$t_{sd} = \int_{t_{hs}}^{t_{hf}} g(t)dt, \quad g(t) = \begin{cases} 1, \text{ if } P_r(t) < P_{r-\min} \\ 0, \text{ if } P_r(t) \ge P_{r-\min} \end{cases} \tag{19}$$

where $t_{hs}$ and $t_{hf}$ are the handover start time and handover finish time, respectively; and $P_r(t)$ is the received power level at time *t*.

Given that $X_\sigma$ follows a Gaussian distribution $f(x)$ with a zero mean, only negative $X_\sigma$ random values impact the service disruption. The probability that the received power at the handover finishing time is less than

$P_{r-\min}$ is given as

$$\Pr\left[P_r\left(t_{hf}\right) < P_{r-\min}\right] = F\left(-c\sigma\right) = \int_{-\infty}^{-c\sigma} f\left(x\right)dx$$
$$= \int_{-\infty}^{-c\sigma} \frac{e^{-x^2/2\sigma^2}}{\sigma\sqrt{2\pi}}dx = \begin{cases} 0.15865, & c=1 \\ 0.02275, & c=2 \\ 0.00135, & c=3 \\ \vdots & \vdots \end{cases} \tag{20}$$

Eq. (20) is only valid at the handover finishing time $t_{hf}$, if it is assumed that the received power is monotonically decreasing during the handover. In this case

$$\Pr\left[P_r\left(t\right) \le P_{r-\min}\right] \le F\left(-c\sigma\right), \quad t_{hs} \le t \le t_{hf} \tag{21}$$

If the signal prediction is correct and the packet loss during the handover is caused by an un-decodable received power level, the packet loss rate during a horizontal or vertical handover can then be approximated by (22).

$$PLR_{HO} = \frac{\text{the number of lost packets during the handover}}{\text{the number of transmitted packets during the handover}}$$
$$\approx \frac{\mathrm{sum}\left\{t_k \Big|_{P_r(t_k) < P_{r-\min}}, t_{hs} \le t_k \le t_{hf}\right\}}{t_{hf} - t_{hs}} \le F\left(-c\sigma\right) \tag{22}$$

With Eq. (22), the packet loss ratio is bounded to the desired level so that depending on the user QoS requirement in terms of packet loss ratio the MN is able to determine an appropriate *c* value.

### *C. Implementing the predictive link trigger mechanism using the IEEE 802.21 media independent handover architecture*

For seamless horizontal and vertical handovers, the architecture shown in Fig. 10 that is based on the IEEE 802.21 media independent handover framework [1] is used. The handover decision engine is an MIH user. This user performs appropriate handover actions when the MIH triggers are received. The MIHF is used to exchange information between various network entities for network discovery and network information. It also provides interfaces between the link layer and the MIHF user.

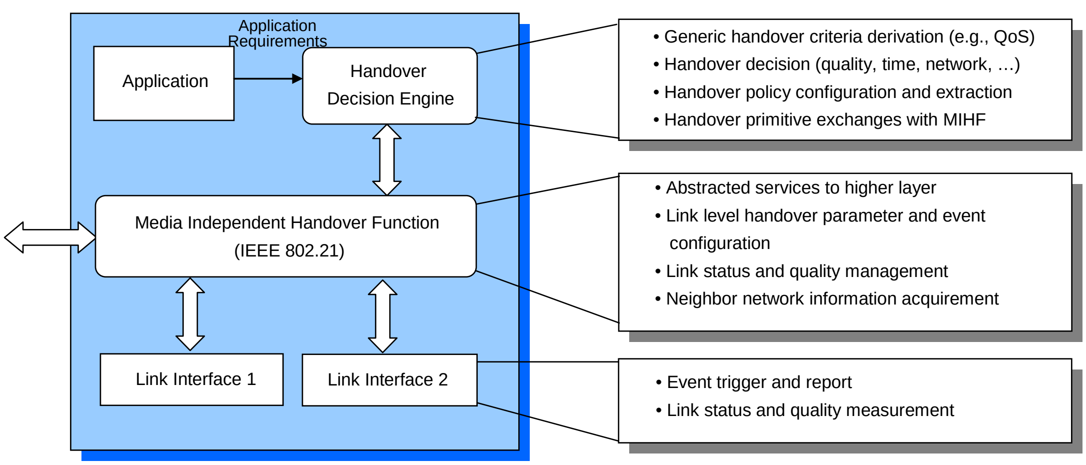



Figure 10. IEEE 802.21 based MIHF architecture.

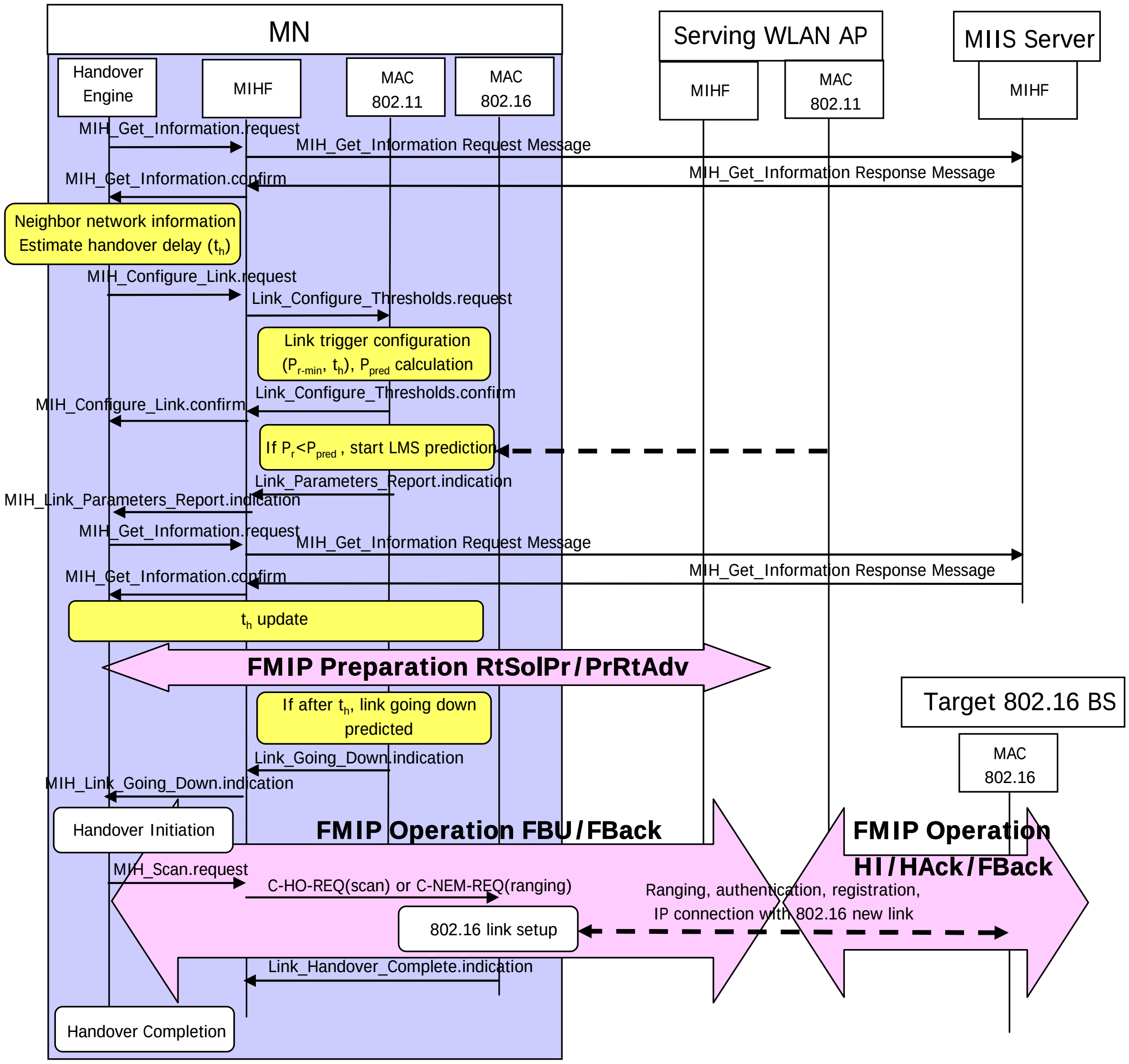



Figure 11. Example scenario of the predictive vertical handover from WLAN to WiMAX based on IEEE 802.21.

IEEE 802.21 defines the following two link configure thresholds.

- *InitiateAction* threshold: threshold value that may cause MIH users to start “setup-type” activities.
- *ExecuteAction* threshold: threshold value that may cause MIH users to take appropriate actions for a handover.

The proposed mechanism can be implemented within the IEEE 802.21 framework as follows. The prediction start point $P_{pred}$ can correspond to the *InitiateAction* threshold. *ExecuteAction* threshold is for the LGD trigger and it is represented as $t_h$ time. Based on the neighbor network information, the MIHF user estimates the required handover time $t_h$ and prediction start power threshold $P_{pred}$. Using the MIH_Configure_Link.request and Link_Configure_ Threshold.request primitives the *InitiateAction* and *ExecuteAction* thresholds are set by the link layer. In the proposed system, if the received signal strength is less than $P_{pred}$, then the *InitiateAction* trigger is generated. The link layer starts the prediction and L2 reports this triggering event to the MIHF with Link_Parmeters_Report.indication primitive. This information is finally delivered to the MIHF user. After the *InitiateAction* trigger, the MHIF user can invoke sending the RtSolPr and will receive the PrRtAdv FMIPv6 messages to prepare the IP address configuration. Therefore it is possible to reduce the actual handover time. If necessary, the MN can also ask for neighbor information and/or perform an active scan of the target network again. The required handover time can be updated if the value is different with the previous estimation. It should be noted that in this approach, the pre-determined power thresholds are not used. Instead, the MIHF user passes the required handover time $t_h$ that was dynamically computed based on the neighbor network information. Fig. 11 shows an example scenario of the proposed predictive vertical handover procedure from WLAN to WiMAX based on the IEEE 802.21 messages and primitives. During the prediction, if after $t_h$ Link_Down is expected, then Link_Going_Down.indication primitives are delivered to the MIHF user and the MIHF user initiates the required handover procedure.

## V. Simulation Results

In this section, the effectiveness of the proposed predictive link-trigger handover mechanism is demonstrated. In Fig. 12, the simulation handover scenario is shown, where vertical handovers between WLAN and WiMAX are considered. A WLAN AP or WiMAX BS can obtain the neighbor network information from a handover information server using the IEEE 802.21 information service function. Here, it is assumed that the actual handover takes the same amount of time as the required handover time that was estimated before the handover execution. The performance is evaluated in terms of i) the signal prediction accuracy using the LMS predictor, ii) the time difference between the handover finishing time and the actual Link_Down time, and iii) the packet loss rates of Gaussian shadowing channels.

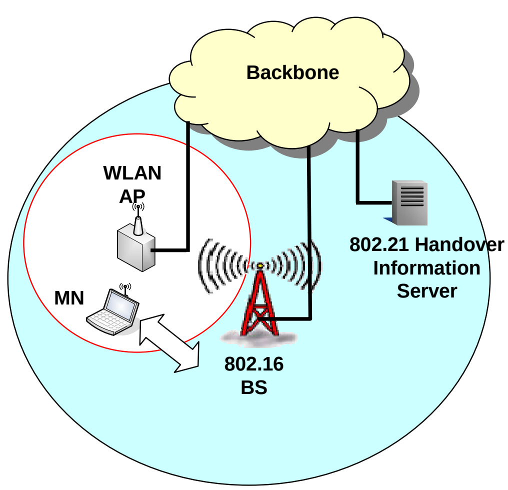



Figure 12. Simulation scenario.

Table I shows the simulation parameters used in this simulation study. $P_r(d_0)$ for (14) is derived as,

$$P_r(d_0) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d_0^2 L} \tag{23}$$

where $P_t$ is the transmitting power, $G_t$ and $G_r$ are the transmitting and receiver antenna gains, respectively, $\lambda$ is the wavelength of the radio signal, and $L$ is the system loss factor.

Table I. Simulation parameters

| | | | |
|---|---|---|---|
| $P_t G_t$ | 100 mW | $\beta_{\max}$ | 5 |
| $G_r$ | 1 | Measurement interval $t_m$ | 1 ms |
| $\lambda$ | 0.124 m | Prediction sample interval $t_s$ | 10 ms |
| $L$ | 1 | Required handover time $t_h$ | 250 ms, 500 ms |
| $d_0$ | 1 m | Marginal time $\Delta_h, \Delta_p$ | 0 |
| $\beta$ | 3– 4 | Standard deviation of Gaussian shadowing | 0 dB – 2 dB |
| MN speed $v$ | 1 m/s – 4 m/s | Compensation factor $c$ | 0–2 |
| Minimum power level $P_{r-\min}$ | $3.162{*}10^{-11}$ W | Prediction order $p$ | 10 |
| $v_{\max}$ | 5 m/s | LMS $\mu$ | 0.01 |

For performance comparisons, we have defined three performance metrics. To verify the prediction accuracy of seamless handovers, the $k_h$-step prediction errors have been evaluated with (24) and (25). $PredError_{ABS}$ is the average absolute prediction error from the prediction start sample point to the actual Link_Down sample point. $PredError_{dB}$ is the average dB scale prediction error. The third metric is *HoTimeDiff*. This metric represents the time difference between the handover finishing time ($t_{hf}$) and the actual link down time ($t_{ld}$) as (26). A negative *HoTimeDiff* value implies that the handover has finished before the actual Link_Down event occurs. In contrast, a positive value indicates that the handover finishing time is after the actual Link_Down event, implying that a handover service disruption and packet loss are likely. For a seamless handover, a small negative value is desired.

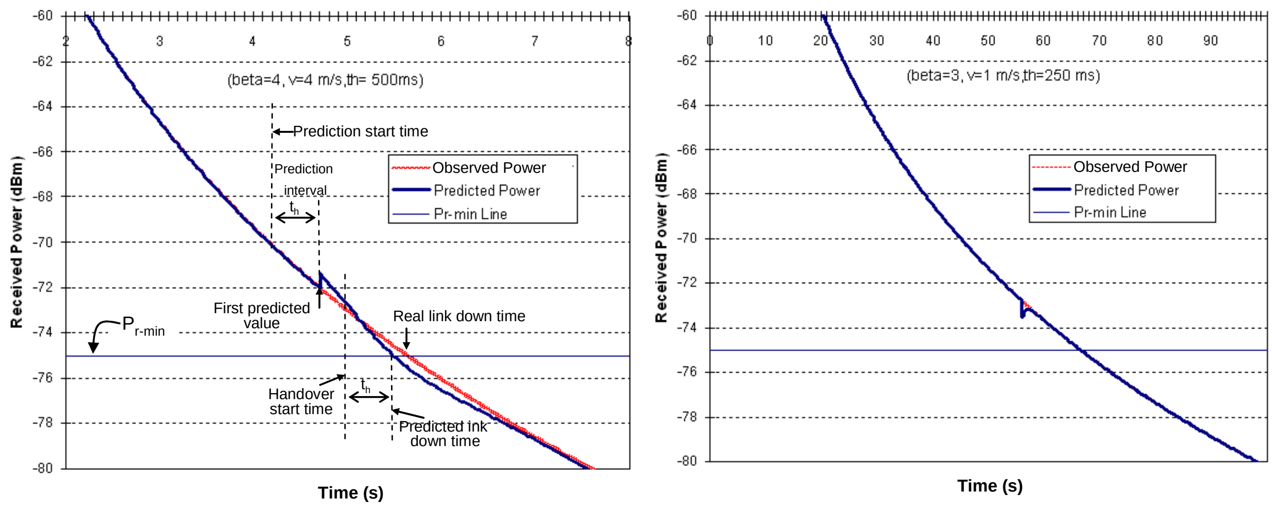
$$PredError_{ABS} = \left( \sum_{i=n_p}^{n_d} \left| P_r(i) - \hat{P}_r(i) \right| \right) \Big/ (n_d - n_p) \tag{24}$$

$$PredError_{dB} = \left( \sum_{i=n_p}^{n_d} \left| \left[ \frac{P_r(i)}{\hat{P}_r(i)} \right]_{dB} \right| \right) \Big/ (n_d - n_p) \tag{25}$$

$$HoTimeDiff = t_{hf} - t_{ld} \tag{26}$$

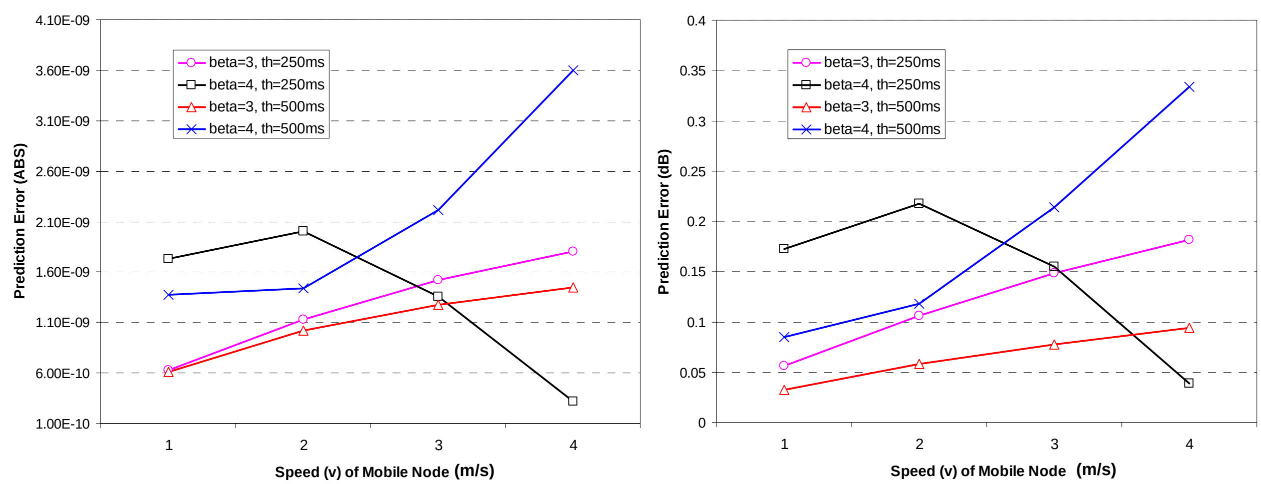
where $P_r(i)$ and $\hat{P}_r(i)$ are the observed signal power and $k_h$-step predicted signal power, respectively; $n_p$ and $n_d$ are the sample sequence number at the prediction start time and at the actual Link_Down time, respectively.

In the following experiment, we show how the LMS predictor can achieve reliable $k_h$-step prediction performance to estimate LGD event. The traces for a predicted and observed signal are shown in Fig. 13. For two different simulation conditions, it is shown that the predicted signal trace estimates the observed decaying signal relatively well. As depicted in Fig. 14, from the prediction start to the actual Link_Down event, the mean power difference between the observed signal and $k_h$-ahead predicted signal is very small at less than 0.35dB. Generally, for higher $\beta$ and $v$ values, a larger average prediction error is observed. As the fixed LMS step size $\mu$ is used here for all simulations, for some channel and movement conditions, this may not be optimal value and may differ somewhat from the general trend.




(a) $\beta$ =4, $v$ =4 m/s, $t_h$ =500 ms (b) $\beta$ =3, $v$ =1 m/s, $t_h$ =250 ms

Figure 13. Comparison of predicted signal and observed signal.




(a) $PredError_{ABS}$ (b) $PredError_{dB}$

Figure 14. $k_h$-step prediction performance.

To evaluate the adaptability of the proposed predictive link trigger mechanism, the path loss exponent $\beta$ and MN speed $v$ are changed over time. In the following simulations, $\beta$ and $v$ increase or decrease linearly during the simulation time (100 seconds). As shown in Table II, the prediction error $PredError_{dB}$ of the proposed method ranges from 0.08 dB to 0.3 dB when $\beta$ and $v$ are time-varying functions. This clearly shows that the LMS predicts the signal power level in time varying network conditions to timely trigger the LGD event.

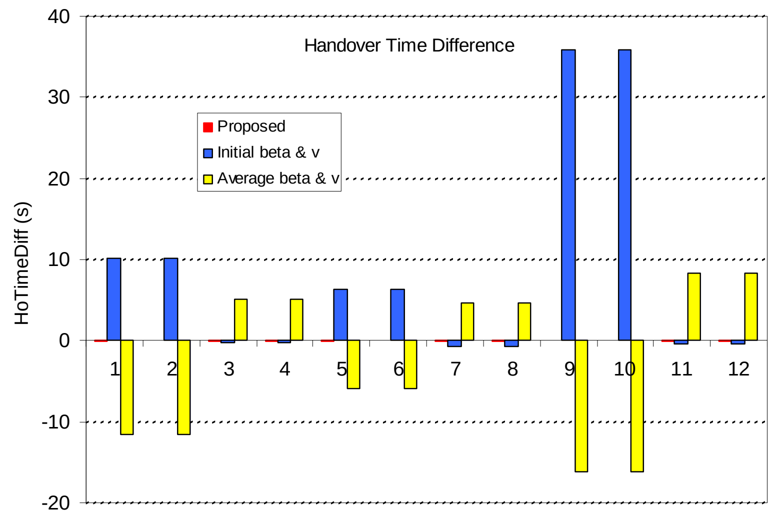
Table II. Prediction error for variable system parameters.

| Initial $\beta$ | Final $\beta$ | Initial $v$ (m/s) | Final $v$ (m/s) | $t_h$ (ms) | $PredError_{dB}$ |
|---|---|---|---|---|---|
| 3 | 4 | 1 | 4 | 250 | **0.1697** |
| 3 | 4 | 1 | 4 | 500 | **0.0808** |
| 4 | 3 | 4 | 1 | 250 | **0.1092** |
| 4 | 3 | 4 | 1 | 500 | **0.3026** |

For comparative analysis' sake, we compare our method to the case where the handover start times (i.e., Link_Going_Down trigger times) are derived with the pre-determined and fixed $\beta$ and $v$ values as in [5]. In this case, the LGD trigger time is analytically derived by assuming that the channel conditions and the MN's movement speed are known in advance and are constant in time, which is not realistic since the MN does not have accurate measurement for the $\beta$ and $v$ values in advance. In Fig. 15, the results using the analytical triggering with the initial and average parameters are compared with the proposed method. The *HoTimeDiff* values of the proposed predictive method are mostly small negatives that are close to the optimal value (zero) for various channels, MN movements, and handover time conditions from Case 1 to Case 12. However, the two compared methods show large variations from +36 seconds to -17 seconds.

Fig. 16 shows the *HoTimeDiff* measurement results when the Link_Going_Down trigger is generated based on the pre-determined threshold as $\alpha * P_{r-\min}$. For various $\alpha$ values from 1.2 to 2.0, it can be observed that a larger $\alpha$ results in the larger negative *HoTimeDiff* values and a smaller $\beta$ and $v$ results in the earlier handover start time. Compared with the performance of the proposed method in Fig. 15 in which the *HoTimeDiff* values vary from -0.01 seconds to -0.17 seconds, the *HoTimeDiff* value of the fixed Link_Going_Down trigger threshold method ranges from +0.25 seconds to -12 seconds.

Finally, the packet loss rate during the handover time is evaluated. Gaussian noise was added to model the shadowing effect. Fig. 17 illustrates the received signal and the predicted signal for Gaussian shadowing channel with a standard deviation of $\sigma = 2$ dB. In Fig. 18, the measured packet loss rates of the proposed method are shown. For CBR traffic, 200 byte packets at 10 ms intervals were generated. The measured packet loss rates for various channel conditions and movement patterns are less than the analytical bounds of (22). This indicates that the proposed predictive link trigger mechanism can timely trigger the Link_Going_Down event to finish the required handover procedure before the actual link goes down. When a larger compensation power $C_\sigma = c \cdot \sigma$ is used, a smaller packet loss rate is observed, as expected. In addition, to achieve less than a $10^{-3}$ packet loss rate, the compensation power for prediction should be greater than three times the standard deviation of the shadowing noise.




| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| β start | 3.5 | 3.5 | 3.5 | 3.5 | 3.0 | 3.0 | 4.0 | 4.0 | 3.0 | 3.0 | 4.0 | 4.0 |
| β final | 3.5 | 3.5 | 3.5 | 3.5 | 4.0 | 4.0 | 3.0 | 3.0 | 4.0 | 4.0 | 3.0 | 3.0 |
| ν start(m/s) | 1 | 1 | 4 | 4 | 2.5 | 2.5 | 2.5 | 2.5 | 1.0 | 1.0 | 4.0 | 4.0 |
| ν final (m/s) | 4 | 4 | 1 | 1 | 2.5 | 2.5 | 2.5 | 2.5 | 4.0 | 4.0 | 1.0 | 1.0 |
| $t_h$ (ms) | 250 | 500 | 250 | 500 | 250 | 500 | 250 | 500 | 250 | 500 | 250 | 500 |

Figure 15. Handover time difference (*HoTimeDiff*) comparisons.

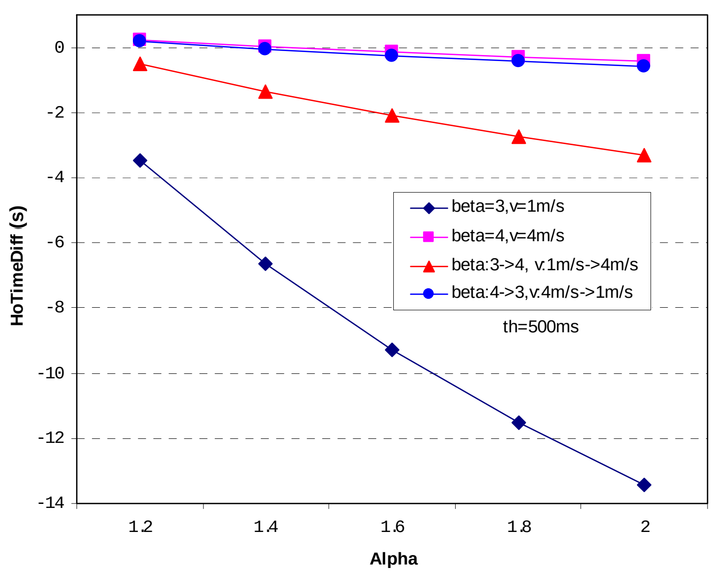



Figure 16. Handover time difference (*HoTimeDiff*) for the fixed Link_Going_Down threshold method.

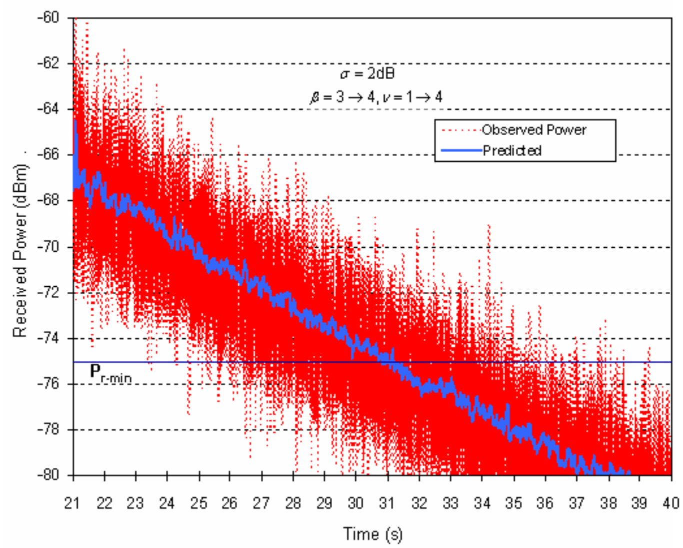
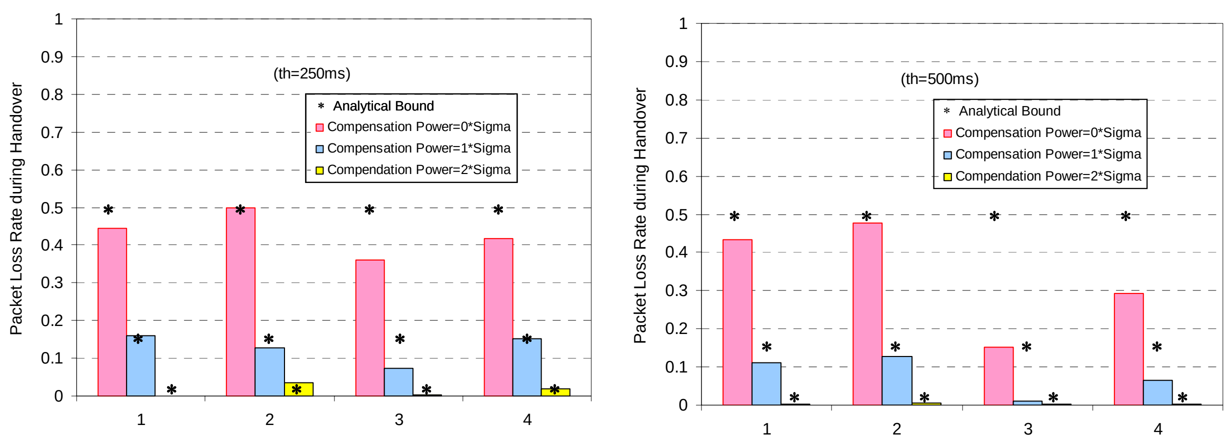



Figure 17. Signal prediction at the Gaussian shadowing channel.




| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| β start | 3 | 3 | 4 | 4 |
| β final | 4 | 4 | 3 | 3 |
| v start(m/s) | 1 | 1 | 4 | 4 |
| v final (m/s) | 4 | 4 | 1 | 1 |
| Sigma | 1 dB | 2 dB | 1 dB | 2 dB |

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| β start | 3 | 3 | 4 | 4 |
| β final | 4 | 4 | 3 | 3 |
| v start(m/s) | 1 | 1 | 4 | 4 |
| v final (m/s) | 4 | 4 | 1 | 1 |
| Sigma | 1 dB | 2 dB | 1 dB | 2 dB |

(a) $t_h$=250ms (b) $t_h$=500ms

Figure 18. Packet loss rates during the handover time.

# VI. Conclusion

In this paper, a predictive link triggering mechanism for seamless handover in heterogeneous wireless networks is proposed. To initiate the timely handover procedure, an auto-configurable triggering method based on the required handover time is presented instead of pre-defined power level thresholds. It was shown that the use of fixed thresholds can cause inappropriate late or early handovers that result in unacceptable service disruptions and/or additional costs.

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. In this paper, a combination of layer 2 and layer 3 handover procedures in horizontal and vertical handovers is considered. For each handover case, the required handover time estimation methods are presented. The *InitiateAction* trigger of the IEEE 802.21 MIHF may correspond to the prediction start time derived from the conservative path loss model, leading to the start of the MN prediction process. The LMS linear prediction technique is used to predict given the required handover time the viability of the current link. If a $k_h$ time-ahead Link_Down event is expected, the predictive Link_Going_Down trigger is then generated to initiate the required handover procedures. Packet loss-rate bounds during the handover time are derived in a Gaussian shadowing condition. For a shadowing wireless channel, to determine the proper Link_Going_Down time to minimize the packet loss rate, it was shown that the minimum power level should be offset for the prediction. The proposed predictive link trigger mechanism can be successively applied to IEEE 802.21 media independent handover architecture.

In the simulation results, the average power difference between the observed signal and the $k_h$ -step predicted signal is very small at less than 0.35dB for various channel and movement conditions. The proposed handover method with the predictive link triggers can timely finish the required handover procedure before the actual link goes down. It was observed that this method can provide effective and seamless handovers when compared to other methods. The proposed link triggering mechanism can be applied to QoS-aware handover. In this case, instead of the received signal strength, QoS metrics such as delay, loss, and throughput can be considered to determine the handover trigger time. LGD trigger is generated based on the predicted QoS value.

## Acknowledgement

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