

Handover Performance in the IEEE 802.16 Mobile Networks

Vesa Hytönen
Telecommunication Laboratory
University of Jyväskylä,
Finland
vesa.a.hytonen@jyu.fi

Alexander Sayenko
Research, Technology &
Platforms,
Nokia Siemens Networks,
Espoo, Finland
alexander.sayenko@nsn.com

Henrik Martikainen
Telecommunication Laboratory
University of Jyväskylä,
Finland
henrik.martikainen@jyu.fi

Olli Alanen
Magister Solutions Ltd
Jyväskylä, Finland
oli.alanen@magister.fi

ABSTRACT

The IEEE 802.16 standard provides a full mobility support for stations moving across cell borders. In addition, the WiMAX Forum Network Working Group defines a set of procedures to support handovers in the mobile access network. One of the main characteristics of mobility support is fully controlled and optimized handover (HO), in which a mobile station (MS) migrates from the air interface of one base station (BS) to another one. It is vital to keep the BS transition phase as short as possible to decrease delays and data loss, which is especially crucial for real-time applications, such as VoIP. In this paper we analyze ASN-anchored mobility performance and provide advisable handover related parameters. The obtained results show that it is reasonable to adapt the handover initiation functionality to the environment where the network is deployed.

Categories and Subject Descriptors

C.2.3 [Computer-Communication Networks]: Network Operations

General Terms

Measurement, Performance

Keywords

ASN-anchored mobility, handover, IEEE 802.16 WiMAX, NS-2, WMF NWG

1. INTRODUCTION

IEEE 802.16 is a standard for the wireless broadband access network [1, 2, 5] which can provide a high-speed wireless access to the Internet to home and business subscribers.

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Providing a reliable connection for subscribers over a wireless channel is a challenging task, which becomes even more difficult when subscribers are allowed to move across cell borders. It leads to situations where they need to change the point-of-attachment (PoA) in the network in order to maintain a desirable level of communication. A basic PoA switching method defined in the IEEE 802.16 standard is called hard handover (HHO), in which the MS drops connections with the old BS or relay station (RS) before associating itself to a new BS or RS. This kind of break-before-make transition always causes some period of unavailability during which the MS is unable to transmit or receive data [11]. To reduce handover interruption times and increase the performance of the network, a number of methods can be performed where the mobile access network plays a major role.

A network re-entry process may be divided into a preparation phase and an action phase. In both stages, the WiMAX network backbone can be exploited to boost the HO operations. During the preparation phase the MS context and handover messages can be transferred between BSs over the access network. When the actual handover takes place, the required MS information is already available at a new BS, and the information exchange at this stage can be partly omitted. As a result, the optimized handover procedures allow usage of real-time services with strict delay constraints [5].

Fluctuations in the received signal strength create challenges in choosing correct HO triggering criteria. Using badly designed criteria results in handovers being performed either too sparsely or too frequently, reducing in both cases the network performance. In this paper we examine the impact of *Time-to-trigger* timer to handover initiation and network statistics. The timer explicitly affects the moment of time when a handover process is started, therefore it provides a simple way to study network performance in different conditions where handovers are executed. The results shown later in this paper may be used for further development of HO initiation methods.

Handover related topics have been studied quite widely by several researchers. In [9], the authors focus on handover initiation algorithms in WCDMA taking into account the effect of hysteresis margin and the Time-to-trigger on handover initiation mechanism. They utilize soft handover and

active set update which are not of interest for our study. Furthermore, the impact of handover initiation on overall HO process is not investigated. Nevertheless, the paper provides a good basis for further study of handover initiation. In [10] hard handover in WiMAX is studied, but the paper does not account for the effect of Time-to-trigger duration to handover initiation. However, it offers a detailed description of the impact of association and optimization methods to handover performance. In [7], the authors consider predominantly theoretical aspects of mobility management in an 802.16 network, but they do not provide statistics or a simulation based outcome.

To the best of our knowledge, only few researches utilize access network implementation for their handover studies. This could be an important factor when considering the reliability of the simulations. In light of this, the results shown later in this paper provide very accurate handover related simulation statistics that can be used as basis for further study.

In this paper we consider the ASN-anchored mobility defined in [4] in which an MS may move within the coverage areas of base stations located in the same Access Service Network (ASN). This type of MS movement is called intra-ASN mobility. From the network element deployment point of view, it is reasonable to determine the areas within which people preferably move. The base stations in these areas are served usually by the same ASN node. Thus, in this paper we simulate intra-ASN mobility, which is the most common mobility type in WiMAX. The ASN-anchored mobility also includes inter-ASN mobility in which stations may move across multiple ASNs. However, this remains outside of the scope of the paper.

The rest of this paper is organized as follows. In Section 2 we introduce the reader to the handover process from wireless link and access network points of view. From there, we continue to introduce our simulations and results in Section 3. Section 4 concludes the paper.

2. BASIC MOBILITY SUPPORT IN WIMAX

This section concentrates on describing optimized hard handover in ASN-anchored mobility events. The handover process is depicted mostly from the IEEE 802.16 standard point of view, focusing on wireless communication. The ASN-anchored mobility is defined by the WiMAX Forum's Network Working Group (NWG), thus the description of this mobility type introduces mostly access network functionality during HOs.

The WiMAX reference model depicted in Fig. 1 shows the logical composition of a WiMAX network. Network entities are connected by reference points designated as mediates for bearer plane or control plane functions. The ASN-anchored mobility exploits intra-ASN R6 reference point for communication between BS and ASN-GW. As shown in Fig. 2 an ASN consists at least of one BS and one ASN gateway (ASN-GW), which are able to control traffic and load balance within one ASN or among multiple ASNs.

2.1 ASN-Anchored Mobility

In the ASN-anchored mobility, the MS is allowed to migrate between BSs located in the same ASN or in different ASNs as long as it does not change the traffic anchor ASN and thus the Connectivity Service Network (CSN) through which the MS is connected to core network. ASN-anchored

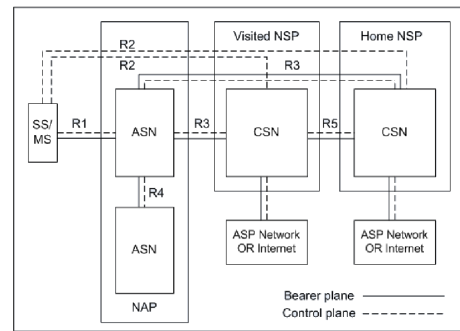


Figure 1: WiMAX network reference model.

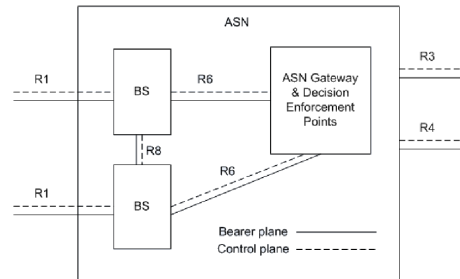


Figure 2: ASN decomposition.

handover procedures include MS's context exchange between ASNs and BSs via the R4 and R6 reference points, packet loss reduction and maintaining packet ordering and latency. Intra-ASN mobility management (MM) and Inter-ASN MM are covered by the ASN-anchored MM category. The ASN-anchored mobility specification defines three functions which are Data Path (Bearer plane) function, Handover function and Context function. These take care of data path setup and packet transmissions, handover decision and signaling procedures and MS related context acquisition, respectively. [4]

The functions above reside at ASNs which can be divided into four groups during a HO process: anchor ASN, serving ASN, target ASN and authenticator ASN (Fig. 3) [4].

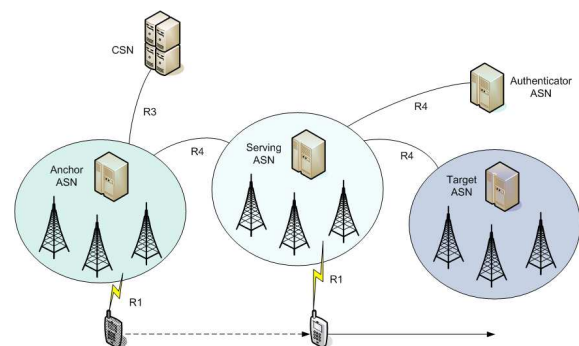


Figure 3: ASN-anchored mobility.

The anchor ASN operates as a connection point to the CSN and network services by hosting the anchor DP function for the MS. The serving ASN serves the MS prior to a HO and manages the serving HO function. The target ASN

hosts the target HO function. It is the network entity the MS will be bound after a successful HO, thus becoming a new serving ASN. Authenticator ASN provides the authenticator/key distributor function for the MS. [4]

2.2 Handover Process

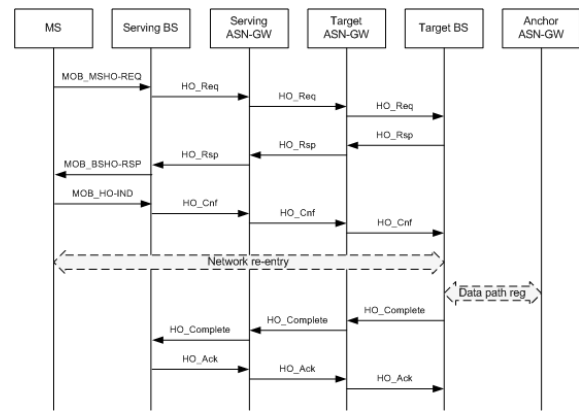
A handover may be triggered by various reasons, each of which is usually aiming to provide the highest level of service available for the MS. In this paper, we hold to the Received Signal Strength Indication (RSSI) measurement as a handover triggering mechanism. With this method there exist at least two distinct variables which determine the handover process commencement, namely hysteresis margin P_{hyst} and *Time-to-trigger* duration T_{trig} . Prior to the handover preparation phase the MS surveys signal strength levels during predetermined scanning intervals from the serving BS as well as from nearby BSs for RSSI comparisons. In a simple handover initiation algorithm, the MS starts a *Time-to-trigger* timer if the signal strength from the neighboring BS P_{nbr} exceeds the sum of P_{hyst} and the signal strength of the serving BS P_{srv} . If such condition remains through the whole T_{trig} duration, the MS considers the neighbor BS in question to be a suitable target for migration. [5, 7, 10]

Once a decision to perform a HO is made, the handover process may be initiated either by the mobile or the network. As seen from Fig. 4(a) the handover preparation phase begins with the transmission of a handover request message that indicates a need for PoA switching; a MOB_MSHO-REQ in mobile initiated handover and a MOB_BSHO-REQ in network initiated handover. A request message contains, for instance, identifiers of the selected target BS candidates. Upon reception of the MOB_MSHO-REQ the serving BS transmits a HO_Req message to target ASN over the backbone network. Particularly, MS's service flow information is stored in this message, which is required for the re-establishment of transport connections after the handover. [4, 5]

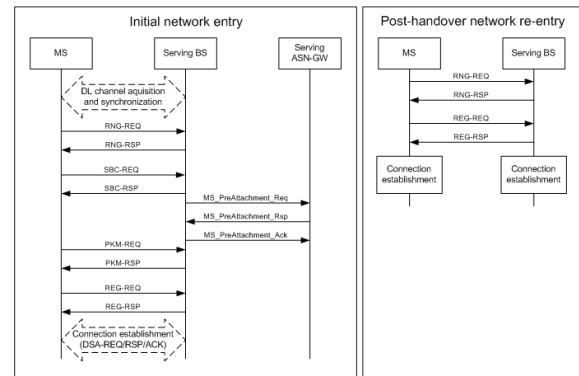
After receiving and processing the handover request, the target ASN replies with a HO_Rsp message. When the serving BS receives the HO_Rsp it transmits a MOB_BSHO-RSP message to the MS over the air interface. The purpose of the MOB_BSHO-RSP is to report the MS about BSs that are ready to take the MS under their control. It may also tell the MS about a pre-allocated fast ranging time interval which can be used to accelerate the network entry after the HO. [4, 5]

The MS decides the eventual target BS and adds its identifiers into a MOB_HO-IND message which the MS transmits to the serving BS. This will be the last message sent to the old BS before the actual HO, after which the MS terminates connections with the serving BS and starts its ranging operation with the target BS. Provided that the MS has accepted the candidate target BS to become its new PoA, upon reception of the MOB_HO-IND the serving BS will transmit a HO_Cnf message to the target ASN. After MS's successful network re-entry to the target BS (which becomes a new serving BS after the HO) a data path registration process is started between the target ASN and the anchor ASN for proper functionality of the bearer plane functions. [4, 5]

During a handover some MS context may already be transferred to the target ASN over the backbone network. Furthermore, the target ASN may request for MS's context from the serving ASN over the backbone network in spite of having received the context earlier. This type of han-



(a) Management messages during handover.



(b) Initial and post-handover network entry messages.

Figure 4: Management message exchanges.

dover is called optimized handover and its task is to keep handover latencies and interruption times small, allowing usage of VoIP and other real-time applications. An MS performing an optimized handover may omit exchanging some information during the network re-entry. This includes, for example, exchange of SBC-REQ/RSP messages, some parts of PKM authentication and service flow encodings. [4, 5]

3. SIMULATIONS

3.1 Simulation Environment

We simulate handover operations with WINSE, which is an 802.16 extension to the NS-2 network simulator [12]. It introduces the 802.16 PHY layer functionality, as well as a very detailed MAC layer implementation.

To create realistic handover simulations, we also expand the simulator functionality with the ASN-GW module that enables access network modeling and ASN-anchored mobility in NS-2. The [4] defines three profiles for the ASN-GW that determine the decomposition of the functions and tasks within the BS and the ASN-GW. Our implementation may be categorized as profile C, as the radio resource and the service flow management reside at the BS. However, since not all the functionality included in the profiles is implemented in the simulator, it is not meaningful to strictly classify our simulator implementation in one specific profile.

Fig. 5 shows the network topology used in our simula-

tions. It contains three sectors from three different BS sites. Each BS sector applies a directional antenna covering 120 degrees, with the antenna angles pointing at 0, 120 and 240 degrees. The inter-site distance is 1000 meters. All the BSs are connected to the same ASN-GW via wired links. We use R4 and R6 reference points for communication between BSs and ASNs, so inter-BS forwarding over R8 is not utilized.

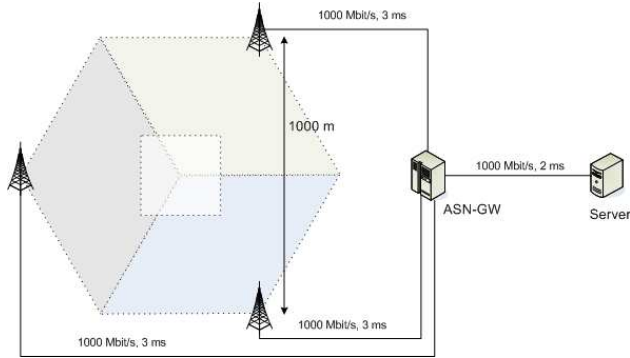


Figure 5: Network topology for the simulations.

In the simulations mobile stations are positioned randomly inside the rectangular area crossing the cell edges. Based on the initial RSSI measurements of all the BSs, each MS selects a BS and performs a network entry. Right from beginning of the simulation all the MSs start to move towards a randomly determined location within the rectangular area, where they might perform handovers between BSs. Although we use a word "random" here, the positions of the MSs and their moving paths depend merely on the seed value of the scenario which can be given as an input parameter. This makes the positions and paths rather "semi-random" since they are reproducible. The 802.16m EMD document [3] defines use cases for the HO performance evaluation. They propose MS trajectories covering movement across border of two cells as well as MS's movement along the border. For the sake of brevity, we do not use separate simulation scenarios designed for different trajectories, but rather utilize a single topology. By introducing random starting and destination points, we simulate various trajectories including the ones specified in the 802.16m EMD document. The distance between the starting coordinates and the final coordinates for the MSs is always at least 300 m. If, while randomly selecting the coordinates, the calculated distance between the points is less than 300 m, a new iteration is performed where new starting and ending coordinates are calculated. By this we make sure that each MS travels long enough for experiencing alteration of the channel quality due to path loss which will increase the probability of handover execution.

We use mobile station velocities of 2 m/s, 5 m/s, 10 m/s and 20 m/s to study whether the movement speed impacts handover procedures. Simulations with different velocities are conducted in a way where the simulation time depends on the MS velocity. The time is calculated with the following equation: $simulation\ time = 300\ s \div MS\ velocity$. As a result, during each simulation run an MS moves the same distance, 300 m, regardless of its velocity. For example, if the velocity is set to 10 m/s, the simulation time is $300 \div 10 = 30\ s$. During this time an MS in question moves $10\ m/s \cdot 30\ s = 300\ m$. This type of approach makes a comparison

Table 1: 802.16 network parameters.

Parameter	Value
Center frequency	2.5 GHz
Reuse factor	1/3
Bandwidth	10 MHz
PHY	OFDMA
Duplexing mode	TDD
Frame duration	5 ms
Cyclic prefix length	1/8 symbol
TTG+RTG	296+168 PS
OFDM symbols	47
DL/UL symbols	28/18
DL/UL subcarrier alloc.	DL PUSC/UL PUSC
Channel report type / interval	CQICH / 20ms
Channel measurements DL/UL	preamble / data burst
Channel measurements filter	EWMA, $\alpha = 0.25$
Link adaptation model	target FEC BLER, 10^{-1}
Antenna technique	SISO
BS / MS Tx power	10 / 0.25 W
BS / MS antenna pattern	3GPP / omni
BS / MS antenna gain	17 / 0 dBi
BS / MS antenna height	32 / 1.5 m
Inter-site distance	1000 m
Path loss	.16m UMA
Fast fading K factor	0 dB
Handover hysteresis margin	3 dB
Time-to-trigger	0.05, 0.1, 0.25, 0.5 s
Max. handover attempts	3
HARQ	Type I (CC)
HARQ channels	16
HARQ buffer size	2048 B (per channel)
HARQ shared buffer	ON
HARQ max. retransmissions	4
HARQ ACK delay	1 frame
PDU SN	ON
PDU SN type	long (2 bytes)
Ranging transm. opport.	2
Ranging backoff start/end	1/15
Request transm. opport.	2
Request backoff start/end	1/15
PDU size	Unlimited
Packing/Fragmentation	ON

of handover functionality in varying velocities simpler when compared to a constant simulation time for all the velocities.

Table 1 shows the parameters we use in the simulations, which correspond to the WiMAX Forum system profile [6]. In addition to the common network parameters, there are a few implementation specific ones. Firstly, we use a constant hysteresis margin of 3 dB that the system broadcasts in conjunction with the time-to-trigger values. We use four T_{trig} values: 50 ms, 100 ms, 250 ms and 500 ms. They affect, explicitly, the point of time when a HO is initiated and, implicitly, network performance statistics. Secondly, the maximum number of handover attempts is limited to 3; if an MS runs out of attempts, then it goes to the scanning mode and performs an initial network entry.

The handover optimization includes a number of practical features. Since both MS capabilities and the authentication context are transferred to the target BS by the network, SBC and PKM messages are omitted. Furthermore, the target BS receives information on MS service flows. It allows the target BS just to assign new CID values without exchanging explicitly DSA messages.

In addition, Table 2 presents the retransmission timeout values that we use in our simulations; they are very crucial for understanding the handover performance. If a certain management message is lost, the timeout value will trigger a message retransmission process. The values are chosen

Table 2: Management retransmission timeouts.

Management message	Timeout [ms]
RNG-REQ	10
SBC-REQ	50
PKM-REQ	50
REG-REQ	10
DSA-REQ	200
DSA-RSP	100
MOB_MSHO-REQ	30

based on recommendations given in [5, 6].¹

We use twelve simulation runs with different seed values for each combination of velocity and T_{trig} for gathering enough information on the network behavior. In total, 20 stations are deployed in the simulations. Best effort UDP traffic is created in UL and DL for each user with the traffic transfer rate of 100 000 bit/s.

3.2 Simulation Results

First, we present information on how much time a typical network entry process takes. The obtained results are useful for understanding the performance of the initial network entry process during a mobile equipment startup. Fig. 6 shows CDF graphs for network entry times, including the first network entry that the MS performs and also the network entries that are done after failed HOs. The steps in the graphs come from management message retransmissions and processing time. The T_{trig} (*TTT* in the figure legend) does not affect the entry process itself, but rather affects the handover initiation moment and consequently the post-handover network entry. As the figure does not show separately statistics on network entries after successful HOs, here the T_{trig} creates variance to the graphs only in case of a failed handover.

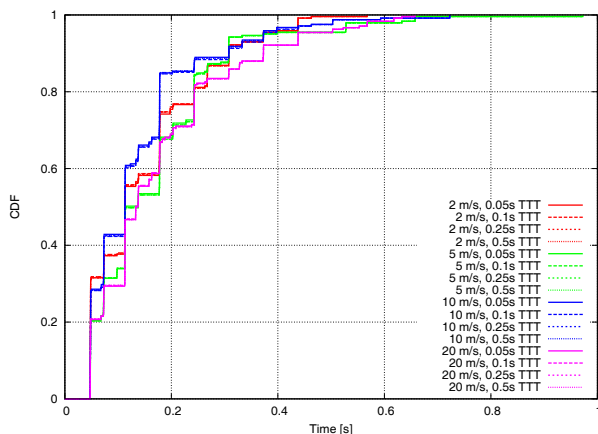


Figure 6: Initial network entry durations.

It is understandable that such delays taking place during normal operation after failed handovers would cause significant performance degradation, being perceivable particularly with real-time traffic.² For instance, according to

¹The WiMAX Forum defines an optional possibility to support HARQ on the management connection. It eliminates a need to specify any management retransmission timers or keep them to much smaller values. This feature is not present yet in our simulator.

²It is anticipated that the initial network entry time will

[8], end-to-end VoIP delays should preferably be kept below 150 ms in order not to experience interruptions in transmissions. With the delays shown in Fig. 6, at least half of the users would not achieve this recommendation.

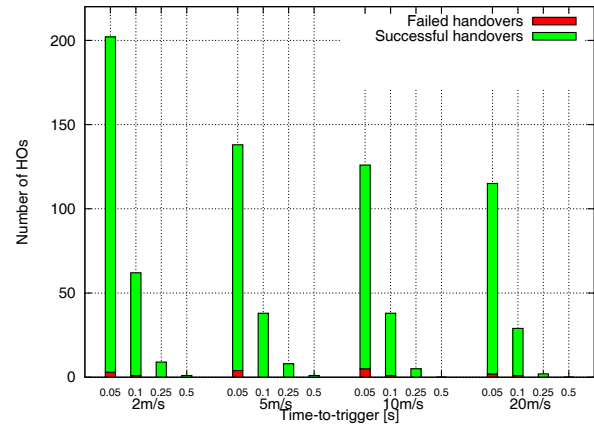


Figure 7: Total number of handovers.

Fig. 7 shows the number of handovers performed during the simulations. As expected, the total number of HOs decreases with a longer T_{trig} value. An explanation for a larger number of HOs with 0.05 s T_{trig} and especially 2 m/s velocity arises partly from the fast fading behavior. The fast fading phenomenon on RSSI level is caused by signal's multipath propagation, and the velocity of the receiver impacts fast fading, for instance, due to doppler spread and the angle of arrival of the signal [13]. Fig. 8 shows RSSI levels from two BSs measured by an MS moving at the speed of 2 m/s. In our simulations MSs measure signal quality in every frame, that is, every 5 ms, which means that the Time-to-trigger timer may be started or stopped in 5 ms cycles. In spite of a short measurement cycle, it can be observed that occasionally the fast fading does not change the RSSI levels enough for the smallest T_{trig} value, 0.05 s. In other words, despite the impact from fast fading, the RSSI level might remain quite stable for a longer period of time than 0.05 s. If the *Time-to-trigger* time is started, during the 50 ms time the difference between compared channels might not change enough to prevent a possibly unnecessary handover triggering.

As an example, let us assume that in Fig. 8 an MS makes a handover to BS 2 at approximately 14.65 s. Then, due to strong influence from fast fading, or due to lack of it, the signal strength from the BS 2 drops and the MS is forced to make a new handover back to BS 1 at around 14.82 s. This example scenario starts to recur in a situation where channels from two or more BSs are somewhat equal. In reality, in slow velocity scenarios this is very common since slow fading and path loss only slightly impact the channel in short distances thus the signals may stay at similar level for prolonged time. From the figure it is obvious that a very small T_{trig} might not be suitable for small subscriber velocities which is usually the case, for instance, in city centurms or shopping malls. The unsuitability comes from a high num-

ber even larger because we did not simulate the process of a subscriber authentication by the mobile access network. Only the exchange of the PKM messages was modelled.

ber of connection drops caused by handovers. With higher velocities path loss and fast fading alter more rapidly and the channel measurement process follows more the average signal level. Therefore, HOs do not occur so often even with a small T_{trig} .

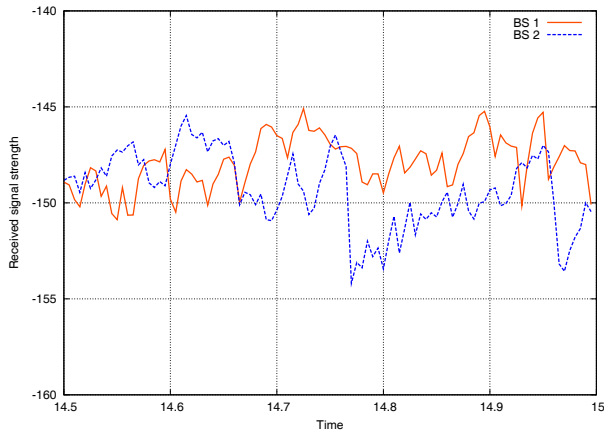


Figure 8: Impact of fast fading on RSSI levels.

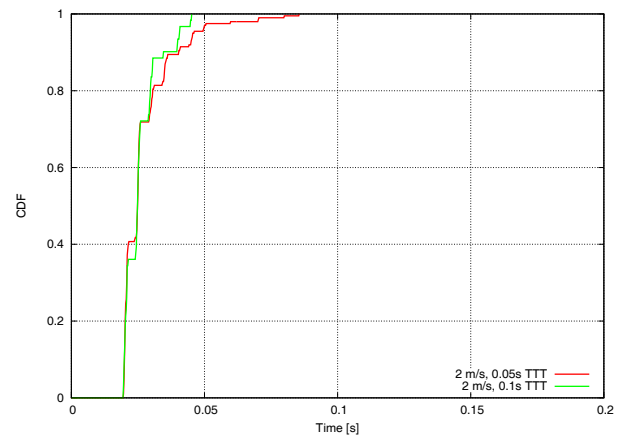
Fig. 7 presents that there is a number of failed handovers. A closer inspection revealed that they are due to the exceeded number of handover attempts caused by dropped MOB_MSHO-REQ or MOB_BSHO-RSP messages. Thus, a practical system may consider transmitting these messages with a more robust MCS or apply HARQ to the management connection.

A BS switching is preceded by a handover preparation phase starting from transmission of the MOB_MSHO-REQ message. The preparation is concluded with a MOB_HO-IND transmission, after which the MS deletes old connections. New connections are established after the network re-entry and registration to the target BS. Therefore the time gap between the MOB_HO-IND and the REG-RSP messages (handover interruption time) has a direct impact on packet delays and throughput. Durations of HO preparation³ and interruption⁴ times are depicted in Fig. 9 and Fig. 10, respectively. In these figures only the extreme scenarios are included for keeping the figures readable, so curves showing 2 m/s and 20 m/s velocity with 0.05 s and 0.1 s T_{trig} are visible. Results for longer T_{trig} , 0.25 s and 0.5 s, are left outside the figures due to small number of samples.

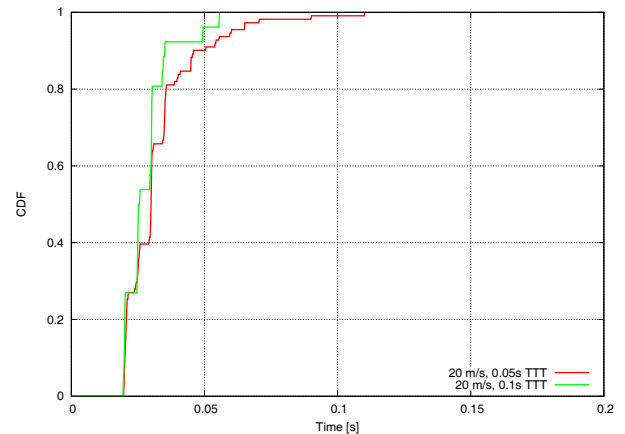
It can be seen from Fig. 9(a) and Fig. 9(b) that there is no strong correlation between a particular T_{trig} value and handover preparation time, but we may observe that it is rather the MS's velocity that impacts the rapidness of the handover process. In general, with 20 m/s velocity the handover preparations take longer than with 2 m/s. Indeed, the time needed for the handover handshake process depends merely on a fact that the handover messages are transmitted successfully, which, in turn, depends on the MS speed and other mechanisms, such as channel measurements, link adaptation, scheduling etc. Although the preparation times

³Handover preparation time is measured from transmission of the MOB_MSHO-REQ to transmission of the MOB_HO-IND message.

⁴Handover interruption duration is measured from transmission of the MOB_HO-IND to transmission of the REG-RSP.



(a) 2 m/s.



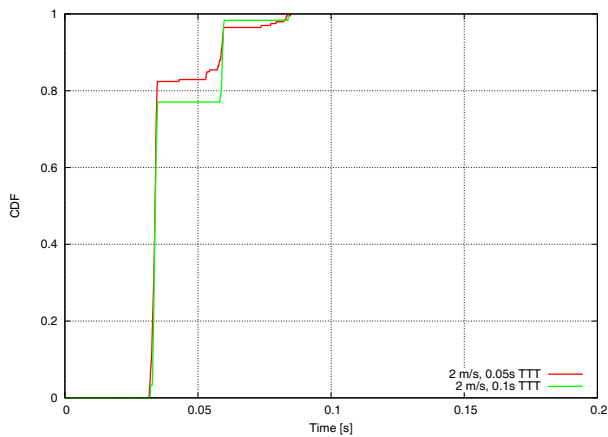
(b) 20 m/s.

Figure 9: Handover preparation times.

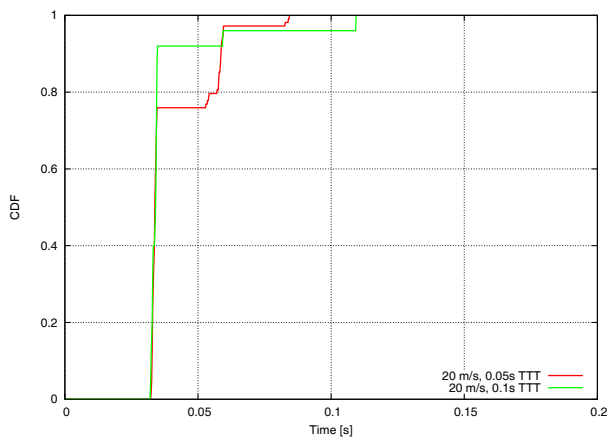
are quite small and do not interrupt a data transmission process, there seems to be lots of message retransmissions triggered by the retransmission timers. This will increase overhead that, at the cell edge, will consume a large portion of the available bandwidth even without handovers. At least UDP traffic with even moderate data rate demand will suffer at this stage from excessive signaling.

The handover interruption times in Fig. 10 correlate neither with different T_{trig} values nor with MS velocity. The interruption times do not exceed 0.11 s and at least 75% of the post-handover network entries can be performed approximately within 30 ms. With VoIP, such a disruption time should not decrease the quality of the connection excessively.

For an explanation of the durations in the figures Fig. 10(a) and Fig. 10(b) mere knowledge of retransmission timeout values is not enough, but also a detailed inspection of the network entry signaling is needed. Fig. 11 shows two examples of network entry related message exchanges after a handover. The procedure in the upper figure shows an optimal interruption time, that is, the entry process without message drops. From this figure it is clear that the interruption time is always at least 30 ms. In the lower figure the RNG-REQ message is retransmitted once, increasing the network entry and interruption times by approximately 20 ms. This is applicable also to subsequent retransmissions.



(a) 2 m/s.



(b) 20 m/s.

Figure 10: Handover interruption times.

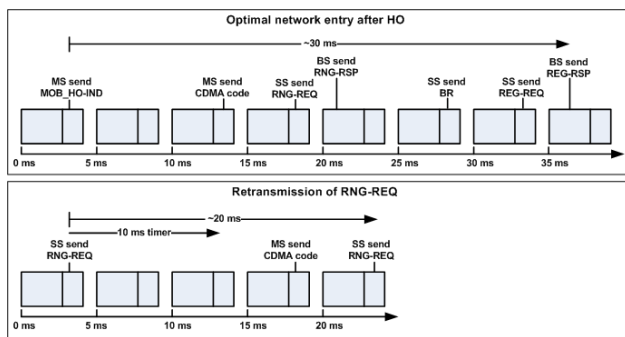


Figure 11: Network entry signaling during handover.

Total handover time, which is the sum of durations shown in Fig. 9 and Fig. 10, could be reduced by utilizing bandwidth pre-allocation mechanisms for HO messages. In addition, interruption times could be decreased with fast ranging, which was not applied in the simulations. With fast ranging, it is possible to hasten the re-entry process at least by 5 ms by pre-allocating bandwidth for the ranging request. Another handover optimization is that a new serving BS can send the REG-RSP message in an unsolicited way without

waiting for an explicit REG-REQ request from an MS. Nevertheless, a clear advantage of the optimized handover to network entry durations can be seen when comparing initial network entry durations in Fig. 6 to re-entry times after handovers in Fig. 10. Durations in both figures are quite comparable since the measurements for Fig. 6 begin from the transmission of RNG-REQ and for Fig. 10 from the transmission of MOB_HO-IND, which is immediately followed by a transmission of the RNG-REQ message.

So far the findings have been focusing on the handover process itself. The impact of different T_{trig} values to overall network activity may also vary considerably. In Fig. 12 we see a distribution of the Modulation and Coding Schemes (MCS) used for transmitted bursts when stations move at 20 m/s velocity. The figure contains statistics from all the simulation runs (where only the seed value changes) for each T_{trig} . For lower speeds similar behavior occurs, thus they are not shown here for the sake of brevity. The most efficient MCS, 64QAM5/6, is located to the leftmost side of the figure and the robustness of the MCSs grow towards the right side, where QPSK1/2 with the repetition factor of 6 is the most robust one.

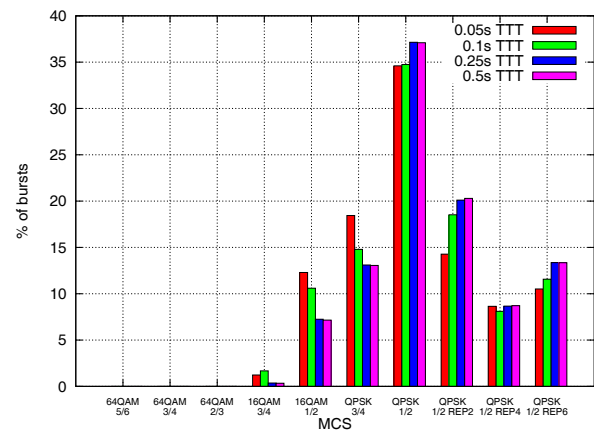


Figure 12: Distribution of MCSs at 20 m/s MS velocity.

The T_{trig} value of 0.05 s provides highest proportion of bursts that are able to use more efficient MCSs. Better results for the smaller T_{trig} values can be explained partly when we take into account the time the handover is performed. With long T_{trig} an MS may need to be connected to the old BS even a few seconds longer than with 0.05 s T_{trig} before being able to make a handover to the new BS that provides a better channel. It is obvious that during this time an MS, which uses a small T_{trig} and migrates quickly to a better channel, is able to benefit from more efficient MCSs. Meanwhile, an MS with a longer T_{trig} has to communicate through the old BS over a worse channel, thus being forced to use more robust MCSs.

The HO initiation time is not the only reason for such MCS distribution. As mentioned before, with a short T_{trig} the MS's RSSI measurement is occasionally able to follow the channel fluctuation caused by fast fading. In such a situation the MS may migrate between BSs multiple times to acquire a better channel. On the other hand, one needs to remember the amount of connection drops with a small T_{trig} due to numerous handovers. This inevitably reduces

the overall network performance even though it is possible to transmit more data by using more efficient MCSs. In light of these obtained pieces of information, when aiming for a better network performance a small T_{trig} could be preferable if an excessive amount of handovers can be avoided or if heavy signaling over the air interface can be sustained in case of small MS velocity. Otherwise a longer T_{trig} would be more suitable. Of course, when designing network behavior it is reasonable to also take into account and inspect other detailed network statistics regarding, for instance, packet drops and load division among BSs.

4. CONCLUSION

In this paper, we have analyzed the hard handover performance in the WiMAX network and the impact of the *Time-to-trigger* duration to the handover process. The results show that there are significant differences in network behavior depending on the handover initiation criteria. This might affect not only the handover process, but also the overall network performance.

Based on the obtained results, the handover triggering criteria selection should depend on the environment where the network is deployed. It is reasonable to use larger *Time-to-trigger* values to cater for slow user velocity environments in order to decrease the number of ping-pong effects. Furthermore, a slow speed will not result in drastic changes in shadow fading, which allows a user to stay for a longer period of time in its serving cell. In a high velocity environment, a smaller *Time-to-trigger* value would be more suitable. In this case, channel measurements and reporting follow variation of path loss rather than the slow and fast fading. As a result, the amount of redundant handovers remains acceptable while the migration between BSs can be performed at an early stage of movement from one sector to another. Such a condition would be desirable, for instance, when moving with a car or train. In any case, a smaller *Time-to-trigger* value can be a valid choice for all the environments if the core network can accommodate a larger signaling load for the handover events.

Even though we did not study it thoroughly, there may exist a tradeoff between the *Time-to-trigger* value, and as a result the core network load, and the wireless network capacity. Smaller triggering values allow MSs to move faster to another cell with a better channel thus increasing the overall system spectral efficiency. On the other hand, constant ping-pong handovers may impact negatively both VoIP and TCP performance.

There exist many interesting fields of research related to mobility management. Handovers in relay networks, in particular, have not been studied extensively. The research topic of this paper could be extended to cover inter-ASN mobility and CSN-anchored mobility. In light of all these concerns, one intriguing future topic would be development of adaptive handover initiation algorithm that can be applicable for various environments and channel conditions and can work in a coordinated way with the mobile access network.

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