Numbat – extensible simulation environment for mobile, IPv6 capable IEEE 802.16 stations

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***Abstract*— Numbat is a new simulation environment, developed with IPv6 mobile stations supporting WiMAX in mind. To provide near real-time capabilities (required for VoIP or video streaming) in a mobile environment, full handover procedure has to be as fast as possible. Both investigated components – IEEE 802.16 based networks and IPv6 capable nodes – are rapidly gaining acceptance. Therefore it appears essential to perform full scale analysis of the handover procedure in such an environment. Numbat allows simulation and analysis of various mobility related issues. It offers support for multiple base stations with groups of subscribers, both fixed and mobile. Also support for tight integration with higher layers (IPv6, DHCPv6, Mobile IPv6) is usable, but still under development.**

This paper presents the purpose, functional requirements and architecture of the simulation environment. The current state of implementation, validation, future areas of improvement and an example simulation results are also discussed in detail. Obtained results clearly show that most significant delays are caused by the IPv6 layer. Some of the possible areas of improvement in several autoconfiguration mechanisms are identified. Some optimization proposals are also discussed.

I. Introduction

As digital data processing solutions are becoming ubiquitous, the growing attractiveness of various kinds of digital data processing technologies is observed. The amount of digital information created, stored, retrieved and transmitted is increasing rapidly, thus stimulating interest of both end users and network operators.

At the same time, portable and different handheld devices are becoming smaller and more powerful. As with all electronic equipment, also mobile devices are affected by Moore's law, which states that the computing power of devices doubles every 18 months. With wireless technologies reaching their maturity, more users expect to use mobile devices.

As a direct result of both trends, users demand for transmission and reception of digital data is constantly increasing. This in turn results in growing popularity of various mobile oriented multimedia applications, like video on demand or VoIP services.

From the network point of view, two requirements – delivering large amounts of data and providing mobility at the same time – are very hard to achieve. That is because changing a point of attachment to the network by a mobile station is usually complicated.

Since the handover procedure is fundamentally different in various networks, detailed analysis can cover only subset of selected technologies. It is important to analyze handover procedure as a whole process, not just network or data-link layer operation. Researchers usually focus on one specific technology, e.g. IEEE 802.11 (WiFi), IEEE 802.16 (WiMAX) or UMTS ([13], [14], [15]). However, the full handover procedure is much more complex. After achieving network or data-link layer handover, upper layers also have to be reconfigured.

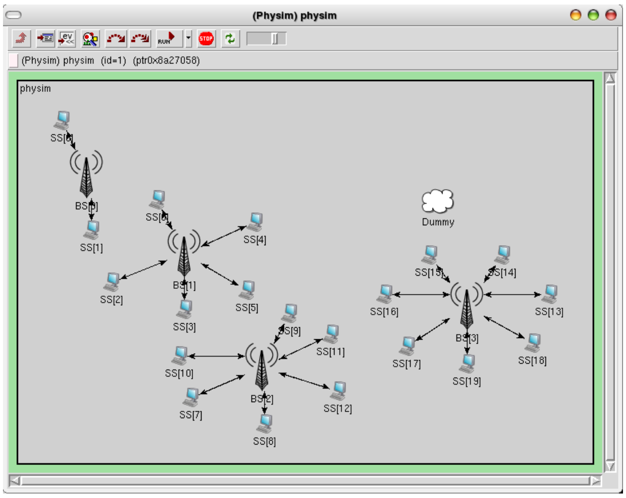

Fig. 1. Example network with four base stations and 20 subscribers, simulated in Numbat

In this paper we develop a novel approach to handover procedure analysis. Instead of examining each layer separately, drawing conclusions from partial results and possibly proposing some improvements, we are not distinguishing between layers. Every component, regardless of its layer, is simulated along with other modules, possibly from other layers. Although combined analysis of several layers is more complicated than separate analysis of each layer, it is very useful for locating inter-layer dependent delays. Also, due to different timescales (e.g. WiMAX radio frame lasts usually 5ms, DHCPv6 server discovery takes one second), simulation is time consuming.

In the following section (Section 2), a mobile WiMAX overview is presented. Mobility delays and lack of communication capability is defined in Section 3. To analyze related mobility related topics in IPv6 over WiMAX, a new simulation environment has been developed. It provides support for multiple base stations with multiple subscribers, both fixed and mobile. Also support for close integration with higher layers (IPv6, DHCPv6, Mobile IPv6) is usable, but still under development. In Section 4 a developed environment with its purpose, functional requirements and architecture is presented. Current state of implementation, testing, as well as future improvement areas and example simulation results are also thoroughly discussed in Section 5. Although the environment itself is not complete, results obtained using the latest version strongly suggest possible areas of improvement in several autoconfiguration mechanisms. Some of the proposals are explained in Section 6.

II. Mobile WiMAX and IPv6

WiMAX is the commercial name of network solutions based on the IEEE 802.16 standard. Defined by the IEEE 802.16 working group in 2004 [1], this specification is constantly assessed, tested improved. Considered as a wireless replacement for DSL lines, WiMAX meets expectations. Offering a range of up to 50km, with throughput up to 70Mbps and good handling of NLOS (non line of sight) scenarios, it seems to be the perfect network solution for suburban and rural areas. One major flaw that was been quickly identified, however, is the the original WiMAX spec did not support mobility, and hence the most significant improvement make to the specification is support for mobile stations. An example WiMAX network is presented in Fig. 1.

Since fixed, IEEE 802.16 based network solutions started to appear in 2004, intensive work has been undertaken to provide mobility support. As a result in late 2005, a mobility-supporting specification was released [2]. Currently IEEE 802.16 based network solutions are rapidly gaining acceptance, both in academic and telecommunication sectors. Most of the already deployed solutions are fixed, but road-maps of major telco corporations indicate that mobile versions will be commercially available in a very near future [12], [11].

Large scale deployment of mobile WiMAX solutions is expected to occur within 2 years. In a similar time range, a new version of the currently omnipresent IPv4 protocol, designated next generation IP (or IPv6) will also gain acceptance. Although defined in 1996 ([3]), its rate of adoption has been somewhat slower than initially anticipated. However, there are strong indicators suggesting that massive migration to dual-stack (i.e. supporting both IPv4 and IPv6) or IPv6-only will occur within 2 years. The most important driving force behind this is the United States' Department of Defense (DOD). According to a DOD Memorandum dated June 9th, 2003 [10], DOD is obliged to switch its internal IT structures and all their contractors must provide all services using IPv6 by the year 2008. Another, and perhaps more fundamental cause of accelerating migration is uneven distribution of IPv4 addresses. Because the internet began in the USA, most of the IPv4 user space is allocated for the USA and, to some lesser extent, Europe. From the pool distribution, the poorest region of the world is Asia[1]. Rapidly developing large countries such as India or China require vast amounts of addresses, a desire that cannot be satisfied with depleting IPv4 pool. Therefore, the rates of adoption of IPv6 technology in several Asian countries are among the highest in the world. According to some sources, exhaustion of the unallocated IPv4 address pool will happen in March 2010 ([16]).

It appears reasonable to assume that a significant part of all mobile WiMAX stations will be dual-stack or even IPv6 only. Therefore authors chose IEEE 802.16-2005 as a PHY/MAC layer and IPv6 as a network layer. The mode to IPv6 has an interesting aspect, in that IPv6 provides extensive automatic configuration mechanisms, including stateless (i.e. router advertisements, [5]) and stateful (dynamic host configuration protocol (DHCPv6, [6]) autoconfiguration, Duplicate Address Detection ([5]), and Mobile IPv6 ([7]).

[1]IPv4 allocations are similarly scarce in Africa, but due to a minimal demand, that is considered smaller issue.

III. Problem definition

Different network layers will produce dramatically different delays during handover. The network and MAC layer in WiMAX has been developed with mobility support and fast processing in mind. Therefore delays introduced are considered small (reaching a few hundred milliseconds, usually below 100ms). Unfortunately, IPv6 protocol was not designed in this manner. Several steps introduce delays that are very large from the mobility point of view (one second or more). For example, the DHCPv6 server discovery phase takes exactly one second as clients are required to wait for possible responses from other servers, even when one or more servers have already responded (according to DHCPv6 spec,[6]).

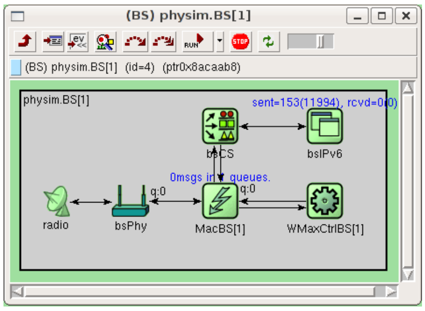

Fig. 2. Base station model

Even the handover procedure on the PHY and MAC layers alone is rather complicated. It consists of the following steps:

- **Neighbour Discovery (WiMAX)** – The base station periodically transmits Neighbour Advertisement messages containing information related to other base stations nearby.
- **Scanning (WiMAX)** – A subscriber station, after obtaining information about potential handover targets, performs scanning. This is a temporary detachment from the current base station. During the scanning phase, the subscriber tries to adjust its radio to receive information from other base stations and assess its signal strength and quality. After scanning is complete, the subscriber gains knowledge about the target base station. Using various metrics (signal strength, signal to noise ratio, etc.), the subscriber sorts the base station list.

- **Handover (WiMAX)** – A subscriber sends a list of desired target base stations to its serving base station. The serving base station can modify this list and send it back. The actual detachment is signalled by an HO-IND message transmission performed by the subscriber. After this transmission, all connections to the serving base station are removed and the subscriber loses its communication capability.
- **Network Re-entry (WiMAX)** – After adjusting the radio to the target base station's frequency and modulation, subscriber initiates network re-entry. Depending on network configuration and management, this can be a highly optimized re-entry involving the exchange of just four messages. When the target base station has no a priori information about this particular subscriber, full network entry must be performed.

In the optimistic case, when intradomain handover takes place (i.e. handover between two base stations governed by the same operator), the network operator contains information about the current subscriber location. It is possible to adjust routing strategies, so the subscriber will be able to send and receive IP datagrams without changing its IP address. This is only an option and even during handover between the same operators' base stations it is not always reasonable (e.g. due to large number of subscribers and thus complicated routing table may degrade routing efficiency and manageability. Therefore operators may want to limit excessive routing modifications.)

Interdomain handover, which is more difficult than intradomain handover, must be analyzed, due to the reasons stated above. When a subscriber completes network reentry, the higher layer (i.e. IPv6), must be reconfigured. According to IPv6 standards ([4], [5], [6], [7]), the following steps are necessary:

- **Stateless autoconfiguration (IPv6)** – The station must wait for a Router Advertisement (RA), a message announced periodically by routers. It is possible to request for such a message by sending SOLICIT message. RA will contain information about locally available prefixes and further autoconfiguration instructions [5]. It also allows subscriber routing to be configured properly.
- **Stateful configuration (DHCPv6)** – Only some basic parameters can be configured using stateless configuration, so stateful configuration is required to obtain such parameters as IPv6 addresses, DNS configuration, SIP domains and server. Stateful configuration is performed according to the DHCP for IPv6 protocol (often abbreviated as DHCPv6).
- **Location update (Mobile IPv6)** – After mobile station receives a new IPv6 address and configuration parameters, it must inform its home agent and corresponding nodes of its new point of attachment, and thus of its new address. After this step is complete, mobile station is finally able to resume communication.

It is essential to realize that not all handover steps are causing handover delays. Goal of this work is to **identify reasons of major delays during full handover in an IPv6 capable mobile WiMAX stations.** To assess impact of every part of the handover procedure on lack of communication capability, an advanced simulation environment is required.

IV. Simulation Environment

In order to reliably measure and analyse delays introduced by handover procedures and their impact on a lack of communication capabilities, an advanced simulation environment is necessary.

Currently there are no applicable solutions available, so the authors chose to implement a new one. To encourage open discussion and contributions to this, the authors have released this simulation environment as open source. Source code is available at the project website [9]. Since several IPv6 simulation environments are already available and WiMAX simulations are anticipated in the near future, the present environment has been assigned a name, Numbat, to differentiate if from other implementations.

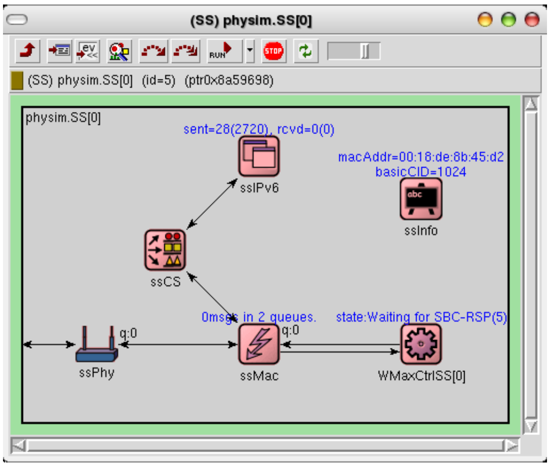

Fig. 3. Subscriber station model

Numbat is a simulation environment designed and implemented in order to fulfill specific goals and requirements. Most important principles are:

- **Coverage** – Provide environment for simulation of the IPv6 capable 802.16 stations. That includes fixed subscriber stations, mobile subscriber stations and base stations.
- **Handover Oriented** – Simulate essential 802.16 mechanisms (e.g. network entry and handover procedure), but omit unnecessary mechanisms, not important from the mobility point of view (e.g. dummy implementation of the cryptographic protection, simple radio channel implementation)
- **IPv6 stack implementation** – Stateless autoconfiguration, Router Advertisements, DHCPv6 and Mobile IPv6. No full implementation is necessary, only aspects related to or affecting mobility.
- **Modular approach** – The Numbat environment is and will be under constant development. Instead of simulating one complex system, it has been split into numerous small modules, each interacting with its

neighbours or parent only. To simulate complex entities easily, several simple modules may be grouped into larger complex modules.

- **Composite approach** – Although authors' interests focus on mobility and IPv6, other users may find different aspects more interesting. It must be very easy to modify or extend some parts of the environment without comprehending every detail of the whole simulation.
- **Flexibility** – Definition of the simulation parameters must be flexible and easy to modify. Therefore most of the parameters must be easily configurable.
- **Visual and text versions** – During development, debugging and presentations it is more convenient to use a graphical interface that allows visual inspection of all network elements. When simulation parameters are prepared, however, complicated simulations can take a long time to produce results. During such runs, visualisation only slows down the simulation processm so a command line interface is necessary. As an added benefit, a CLI allows remote execution on powerful servers.
- **Parallel approach** – Since Gdansk University of Technology provides multiprocessor clusters with up to 256 processors, it seems reasonable to take advantage of parallel processing.

After thorough evaluation of several environments, Omnet++ was chosen as a simulation engine. Compared to other (NS-2, ANVL) possible choices, Omnet++ has clear and well defined architecture, is fast (all modules are coded in C++), provides command-line and graphical interfaces, is modular, is well documented and is free for non-commercial use. Unfortunately, Omnet++ does not provide IPv6 or WiMAX simulation modules, so they have had to be implemented.[2]

A. *Subscriber and Base Station Architecture*

IEEE 802.16 is an asymmetric protocol: a station acts differently depending on if whether it is a subscriber or a base station. However, there are some functional similarities. For example both stations have schedulers that coordinate transmission and reception of data messages. Therefore both station models have been split into similar modules.

A complicated network environment usually deals with large number of data packets and a much smaller amount of controlling packets. For performance benefits, data packets are often processed using a "fast path" that is referred to as the "data plane". Control messages usually require additional processing, so their transmission and reception takes longer. This "slow path" message processing is called "control plane". In the Numbat design, control plane and data plane have been split and implemented separately. The following modules have been implemented:

- **IPv6 module** – Sends and receives IPv6 messages. This is a composite module that represent full IPv6 stack. Consists of several submodules: IPv6Gen (an IPv6 traffic generator and analyzer), DHCPv6Cli (a DHCPv6 client), DHCPv6Srv (a DHCPv6 server), RaSrv (Router Advertisement server/router), RaCli (Router Advertisement client), MobIPv6Mn (Mobile IPv6 mobile node) and MobIPv6Ha (Mobile IPv6 Home Agent).
- **WMaxCS** – Convergence Sublayer. Classifies received data to corresponding connections and dispatches to destination modules.
- **WMaxCtrl** – Represents control plane, i.e. logic of the base or subscriber stations. All decisions are made here. This is an instantiation of the Finite State Machine described in the next subsection.
- **WMaxMAC** – Represents the main part of the data plane. That is mainly scheduler (transmission) and dispatcher (reception).
- **WMaxPHY** – Simulation of the 802.16 PHY layer. Since PHY operation is outside the scope of discussed topics, this implementation is trivial.
- **WMaxRadio** – Present in the base station only. That is a simple simulation of the radio channel. It supports two transmission types: broadcast (one sender transmitting to many receivers, i.e. downlink: one base station to multiple subscribers) and unicast (one sender transmitting to one receiver, i.e. uplink: one subscriber transmitting to one base station).

Since base stations act as a relays and do not generate any data traffic on their own, additional subscribers have to be added to simulate "background" traffic. A fixed subscriber can be configured very easily to act as a traffic generator/analyzer.

The Omnet++ environment includes FSM implementation, but the provided interface does not offer the required flexibility. the largest flaw in the Omnet's FSM is that staying in the same state is not supported (state exit and entry must be performed). Therefore new state machine framework has been developed.

V. Example simulation results

Although the environment is not yet complete, it is suitable for simulating significant parts of the mobile stations. In this section an example of a such simulation is presented and obtained results are discussed.

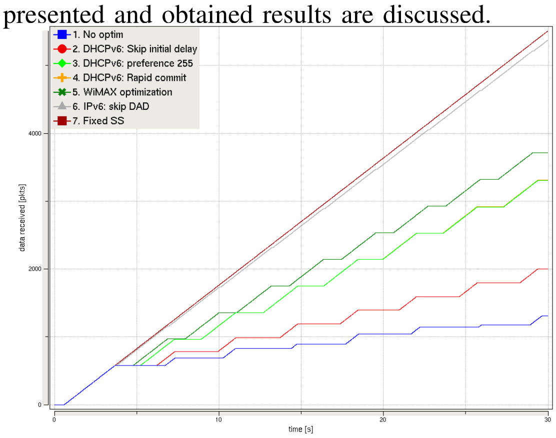

Fig. 4. Number of packets received by subscriber station

The IEEE 802.16 standard defines two handover types:

[2]There is a separate project based on Omnet++ environment called INET, which provides IPv6 implementation. However, its complicated nature and fragmentation made it unusable for the author's purposes.

initiated by the base station or by a subscriber. The later was chosen because it is more complicated. In a real network, the decision when handover should be initiated may be a quite complicated algorithm. Luckily, since the main object of this research is to optimize the handover procedure itself and not the decision to start the procedure, this part may be greatly simplified. In presented results, handover started 3000ms after successful association with a base station was completed.

A. Optimization scenarios

Several scenarios were investigated. Each scenario, except the last, contains all optimisations introduced in previous ones.

1) **No optimization** – All possible (provided by standards and proposed by authors as well) optimizations are disabled. During each handover, mobile station must perform full network entry, recreate all service flows, obtain and verify its IPv6 address. No optimizations on the IPv6 layer. This scenario is considered the worst possible case.
2) **DHCPv6: Skip initial delay** – DHCPv6 spec [6] states that initial transmission "must be delayed by a random amount of time between 0 and 1 second". This feature is intended to prevent congestion following a power outage. Unfortunately, it introduces unacceptable delays if stateful (DHCPv6) autoconfiguration is required in mobile devices. Therefore this intended random delay is removed in this scenario.
3) **DHCPv6: Preference 255** – As DHCPv6 offers redundancy, it is possible for more than one server to exist on the same link. Therefore DHCPv6 offers a mechanism to discover all servers. After transmitting a SOLICIT message, the server replies with an ADVERTISE message. This discovery phase takes exactly one second because clients are required to wait for possible responses from other servers, even when one or more servers have already responded. To omit this waiting phase, a server may send responses with the maximum preference set, causing the client to abort its discovery phase.
4) **DHCPv6: Rapid-commit** – After discovering a DHCPv6 server (two messages), the client requests an address (two messages), so in total four messages are exchanged. It is possible to shorten this to only two messages, with an actual assigned address may be sent in the reply to the initial SOLICIT message. This fast approach is called rapid-commit.
5) **WiMAX optimization** – IEEE 802.16 provides extensive set of possible optimizations. This includes context sharing between base stations, so target base stations knows in advance about incoming subscriber. If such a priori knowledge is available, significant number of steps may be omitted: basic capability negotiation (SBC-REQ/SBC-RSP), registration (REG-REQ/REG-RSP) and key exchange (multiple PKM-REQ/PKM-RSP) and service flow creation (DSA-REQ/DSA-RSP/DSA-ACK). This results in significant decrease in amount of time required to perform 802.16 handover (i.e. phy and MAC switch).
6) **IPv6: Skip DAD** – After obtaining an IPv6 address, according to [4], a node is required to perform Duplicate Address Detection – a mechanism intended to detect cases when about to configured address is already used. Again, this feature was not designed with mobility in mind, so it takes one second to wait for possible responses from other nodes using the same address.
7) **Fixed SS** – This scenario assumes that the subscriber station is fixed, i.e. it does not perform any handovers. It is used as a reference or as a theoretical perfect, no-loss scenario.

B. Mobility model

There are several possible approaches to mobility modelling in Numbat:

- Location based – A mobile subscriber can change its physical location and periodically perform scanning. When it detects that there is a better base station than the one currently associated, it initiates handover. This model is more "realistic", but it requires planning base station locations and defining subscriber station path. Both problems are not trivial and can blur simulation results easily.
- Time based – It is possible to define that, regardless of its location, subscriber initiates handover after a certain amount of time. This model is a simplification, but it is very useful for scenarios focused on the handover procedure itself.

The example results presented in this paper are based on the latter approach. Handover is executed exactly three seconds after previous handover of the 802.16 layers has been completed. Delay values related to DHCPv6 protocol simulation are a real values, measured on real hardware. The precise logging mode, which uses microseconds instead of the usual y:m:d h:m:s format has been implemented in Dibbler [8] – a DHCPv6 implementation. During simulation data packets were sent with random sizes between 64 and 128 bytes. Packet sizes are not significant as they are used mainly as indicators if SS is able to communicate or not. Each scenario was run 10 times and the results averaged.

C. Conclusions

Each scenario has been simulated for the same time (30 seconds). The choice of this particular time period was a compromise: it is long enough to perform several handovers, yet it is short enough to observe single handover disturbance. The number of packets received in the downlink direction is presented in Fig. 4.

Handover time intervals are clearly visible in the graph. Handover events occur at times, when (otherwise constantly increasing) curves representing carried out traffic are horizontal (no transmission is possible during handover). To better analyze it, a zoomed area of the graph depicting the first handover is presented in Fig. 5.

In every case data transmission begins after initial network entry. Differences start to appear during the first handover. In the worst case (scenario 1), full handover procedure takes almost as long as handover intervals, so time "spent" on data exchange is minimal. Skipping initial DHCPv6 delay considerably decreases handover time vs. transmission time ratio (scenario 2). It appears that the biggest advantage is to further optimize DHCPv6 exchange by using rapid-commit or using maximum preference value. Both scenarios 3 and 4 appear almost identical on the graph (using rapid-commit decreases handover time by about 15ms, so lines almost completely overlap).

Another significant improvement is gained by using 802.16 handover optimizations. Most of them assume that target base station has *a priori* knowledge about the incoming subscriber. To gain such knowledge, some off-the-network communication framework between base stations is required. It appears that in real life solutions, operators will deploy such operation, administration and maintenance (OAM) entities that also serve several other purposes, such as accounting and network management. Deploying such entities, called ASN Gateways, seems inevitable for networks more complicated than a single base station. With such information about an expected subscriber station, a base station is able to skip most of the otherwise required steps. This in turn shortens the reentry procedure, which results in a greater number of received packets.

The last optimization analyzed is related to the Duplicate Address Detection mechanism in IPv6. Since there are 2^{128} addresses available in the IPv6 address space, it seems highly unlikely that duplicates will ever occur, except during malicious attacks. A prevention mechanism, designed by IPv6 spec authors [4], allows protection against such cases. Unfortunately it introduces one second delay between address assignment and its actual exploitation. Authors of the current paper have designed a way to circumvent this delay and obey IPv6 specs at the same time, but this is not complete yet, so this scenario must be considered theoretical for the time being.

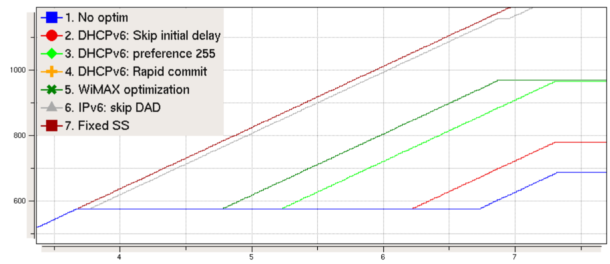

Fig. 5. Number of packets received (handover close up)

The seventh scenario investigates a fixed (or a standing still mobile) subscriber. This scenario is used as a reference or theoretical goal of a perfect, no loss handover.

Comparing all scenarios together it is clearly visible that the most useful optimizations are possible in the IPv6 related areas (DHCPv6 and DAD). However, to obtain the best results it is strongly recommended to combine DHCPv6, IPv6 and 802.16 optimizations.

VI. Future work

The completed work focused on IEEE 802.16 and DHCPv6 implementation. All major elements of the WiMAX stack were implemented and are working properly. Advanced work is being concentrated on the remaining IPv6 stack implementation, Mobile IPv6 and stateless autoconfiguration (using Router Advertisements). Estimates and simulation results obtained with the use of Numbat strongly suggest that the largest delays are caused by the DHCPv6 protocol and Duplicate Address Detection. After finishing design of the DAD+DHCPv6 optimizations and more thorough assessment, proposed optimizations in DHCPv6 will be implemented in the simulation environment and evaluated. If proven useful, enhancements will be implemented in Dibbler [8] – an actual implementation of the DHCPv6 protocol, developed at Gdansk University of Technology since 2003[3]. Since that is widely used software, users' feedback will eventually test the usefulness of proposed features in a real life environment.

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References

[1] IEEE working group, "IEEE 802.16-2004: IEEE Standard for Local and Metropolitan Area Networks – Part 16: Air Inter- face for Fixed Broadband Wireless Access Systems", IEEE, Oct.2004
[2] IEEE working group, "IEEE 802.16-2004: IEEE Standard for Local and Metropolitan Area Networks – Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems", IEEE, Dec.2005
[3] S. Deering, R. Hinden, "Internet Protocol, Version 6 (IPv6) Specification", IEEE, Dec.1998
[4] T. Narten, E. Nordmark, W. Simpson "Neighbor Discovery for IP Version 6 (IPv6)", IETF, Dec.1998
[5] S. Thomson, and T. Narten "IPv6 Stateless Address Autoconfiguration", RFC2462, IETF, Dec.1998
[6] R. Droms, Ed. "Dynamic Host Configuration Protocol for IPv6 (DHCPv6)", RFC3315, IETF, Jul.2003
[7] D. Johnson, C. Perkins, J. Arkko "Mobility support in IPv6", IETF, Jun.2004
[8] T. Mrugalski, "Dibber – a portable DHCPv6", project homepage, http://klub.com.pl/dhcpv6/, Aug.2007
[9] T. Mrugalski, "Numbat – mobile IPv6 in WiMax environment", project homepage, http://klub.com.pl/projects/numbat/, Aug.2007
[10] M. Kraus, "DOD: Transition to IPv6", http://www.usipv6.com/2003arlington/presents/Marilyn_Kraus.pdf, Dec.2003
[11] WiMAX Forum, "Mobile WiMAX – Part II: A Comparative Analysis", http://www.intel.com/netcomms/technologies/wimax/mobile_wimax_p2.pdf, Apr.2006
[12] K. Tae Lee, "Create the future with Mobile WiMAX", Communications Magazine, May 2007
[13] J. Wozniak, K. Nowicki, T. Mrugalski, "Mobile users issues, in micro and macro scale, in IP networks", SIS2004, Lodz, Sep.2004
[14] A. Conceiao, J. Li, D. Florencio F. Kon, "Is IEEE 802.11 Ready for VoIP?", Microsoft Research, IEEE International Workshop on Multimedia Signal Processing, 2006
[15] P. Matusz, P.Machan, J.Wozniak, "Analysis of profitability of inter-system handovers between IEEE 802.11b and UMTS", LCN'03, IEEE International Conference, Oct.2003
[16] Wikipedia "IPv4 address exhaustion, http://en.wikipedia.org/wiki/IPv4_address_exhaustion, Aug.2007

[3] Available for Windows and Linux, accepted in 5 linux distributions, confirmed use in 27 countries.