# Wireless Experimental Metropolitan Area Network Using IPv6 in Norway (WEMAN)

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## Abstract

*We report from experiments with wireless and mobile computing at the University of Oslo, NORWAY. We have established a wireless Experimental Metropolitan Area Network (WEMAN), based on Mobile IPv6 for mobility and IEEE 802.11 technology for wireless links and access.. WEMAN is a wireless extension of the IPv6 based Internet 2 in Norway, and enables flexible access for nomadic and mobile users. Using Low Noise Amplifiers and antenna diversity, we obtain reliable performance on links longer than 15 km. We have experimented with four alternatives for automatic network configuration for mobile clients and report on initial feasibility and performance results.*

## 1. Introduction

The recent de-regulation of telecommunications allows organizations and network providers to extend private IP networks over a Metropolitan Area (MAN). The advent of Spread Spectrum technologies for use in the ISM (unlicensed industrial, scientific, and medical) bands makes it possible to establish such networks at low cost compared to leased lines. To find how an organization such as the University could leverage this development to provide a seamless work environment for their employees, we have established an experimental MAN network, interconnecting small wired and wireless subnetworks installed at home. This network is provided with advanced mobility support to simplify access to computer facilities at the university. With this infrastructure, the same computer (typically a Laptop or Personal Digital Assistant - PDA) can access resources at work or at home without need for reconfiguration. Use of this technology gives us access to a high performance wide area mobile network, far outperforming the commercial cellular data services and avoiding toll charges completely.

We want to be able to move (small) computers from one workplace to the other, without having to reconfigure protocol parameters. Such roaming is taken for granted when a cellular phone is moved, but the current version of the Internet protocol (IPv4) was designed when computers where statically attached to the network. Thus, it is a great challenge to migrate from fixed locations to nomadic and even wireless connections without the need for manual protocol reconfiguration. The network technology we use is based on the IEEE standard IEEE 802.11 Wireless LAN[5], using the 2.4 GHz ISM band. Even though this is a LAN technology, we are able to cover large areas of the Oslo metropolitan area and have established a backbone network by Wireless LAN point to point links. According to the manufacturer [7], the point to point links should only work up to 3 km, and then only when there is a clear sight between the two points. We report that it is indeed possible to use this wireless technology even beyond these limits and have demonstrated successful operation over more than 15km with stable connectivity with up to 3Mbit/s link speed. We discuss our observations that latency and maximum achievable link speed is changing during the course of the day, possibly with some changes in weather conditions.

The IEEE 802.11 protocol is suited for our use primarilly because it is a high-throughput wireless network standard which can be used without any special licence for the end-users. It is based on an advanced CSMA/CA MAC protocol (Carrier Sense Multiple Access with Colision Avoidance), which helps in providing access to a high number of concurrent users without heavy investments in network infrastructure. The IEEE 802.11 standard supports three different physical layer protocols, Direct Sequence Spread Spectrum, Frequency Hopping Spread Spectrum, and Infrared transmission. In our network, we only use Frequency Hopping.

On top of our LAN and MAN network infrastructure, a next generation IP network (IPv6)[1] is built to gain operational experience with mobility support with IPv6 in a seamless network environment. Terminals shall stay in touch with the network without user reconfiguration across a heterogeneous network environment, supporting both wired and wireless attachment. As an example, the audio stream requested from our multimedia server should maintain service while a terminal roams between different access networks. We describe our findings related to seamless network operation between home and office. We report our experience with various ways of providing seamless mobility in our network. The solutions range from simple Dynamic Host Configuration Protocol (DHCP)[22] address change when a new node appears on the network, to Mobile IP solutions using IPv6.

The IPv6 protocol has some important improvements over IPv4 provided by the flexible IPv6 packet extension header. Some of these properties are very well suited for mobile networking. These properties include

- Address Autoconfiguration[24] and Neighbor Discovery[25] - makes the switching of networks transparent to the user. Hosts use Neighbor Discovery to find neighboring routers that are willing to forward packets on their behalf, use the protocol to actively keep track of which neighbors are reachable and which are not, and to detect changed link-layer addresses. When a router or the path to a router fails, a host actively searches for functioning alternativeses.
- A Source Routing header where any reply packet will follow the same source routed path. This is important, as IP packets back to the mobile node will have to be source routed through the nearest care-of router.
- An Autentication extension header on each packet which ensures that the packet has not been changed and is from the correct sender, for instance when the sender is mobile in the network. In IPv4, source routing is normally disabled because of the severe security problems present when the source of the packet can not be reliably verified.

The rest of this paper is organized as follows: In section 2 we list some related work and in section 3 we detail the architecture of WEMAN, our experimental wireless network. Section 4 discuss our experience with various levels of mobile network support, and section 5 presents the measured performance in WEMAN. Section 6 concludes the paper and discusses areas of further work.

## 2. Related work

The Mobile Multimedia Computing group at University of Lancaster is very active in the field of Mobile IPv6 and Wireless MAN[2]. University of Tromsø provides IPv6 over IrDA links[3] used for a desk area network, and is also working closely with Lancaster on Mobile IPv6.

University of California at Berkeley is active in the field of mobile networking. The Bay Area Radio WAN [14] proposes a wireless overlay networks above the various radio based access technologies (satellite, metropolitan and campus networks). Seamless service access is discussed in [15], and describes how mobile computers can attach to the local services they move to, eg. that a print command will print on the printer that is the present local printer. This group also gives contributions related to protocol performance [16]. This paper demonstrates how TCP can be improved for Wireless operation.

Adaptive Wireless communication is explored in [17], focusing on seamless switching between different types of networks, while maintaining the task that was in progress. Mobile computers should ideally be able to visit foreign networks, even when the foreign network does not support foreign computers. The Monarch project at the Carnegie Mellon University [18] is active in the field of wireless and mobile computing, and is developing Mobile IPv6 support for BSD-Unix derived systems. At the University of Pitsburgh the “Wireless Andrew” infrastructure [19] spans Pitsburg with a low bandwidth wireless network and a Wireless LAN in the CMU Campus area. Scalability concerns in mobile networking are discussed in [20], where protocol enhancements for IPv6 allows transparent routing of IP packets to mobile computers. A good overview of fundamental challenges in mobile computing is given in [21] which also discuss scalability of mobile computers in the Internet.

## 3. WEMAN Network architecture

Our MAN network currently spans 4 home installations (`bryhni-gw`, `stein-gw`, `odd-gw` and `ryan-gw`) and use multi-hop routing to reach the farthest nodes as shown in Figure 1.. The recently standardized IEEE 802.11 Frequency Hopping Spread Spectrum (FHSS) technology[5] is used for the Wireless access networks and for the MAN links. We have achieved high-speed (3 Mbit/s) interconnection over a distance up to 15 kilometers. This is much further than specified by the manufacturer of the FHSS equipment[7]. The long distance is achieved with very low power and relatively small antennas giving Equivalent Isotropic Radiated Power (EIRP) of less than 100mW in Europe (for comparison, US regulations allows 1W EIRP). We further use Low Noise Amplifiers and antenna diversity to improve sensitivity and demonstrate high reliability on the long distance wireless links. This physical range makes it relatively easy to span a metropolitan area with few base stations. To reach stations beyond line-of-sight required by the microwave links, we have established a repeater station located at Holmenkollen. This station is equipped with two sets of antennas, one set pointing at the University, the other set pointing at the farthest nodes (`odd-gw` and `ryan-gw` in the figure). Shorter distances (up to 1km) is supported with small patch antennas simply installed in a window or even integrated into the laptop or PDA for mobile operation. The network fully supports IPv6 and is a part of the IPv6-based Internet 2 network in Norway[8]. WEMAN is assigned a separate 6BONE subnet for experimental purposes[9].

### 3.1. Components of the test network

The routers used in WEMAN consist of Pentium and 486 Linux machines, 16-32 MB RAM and up to three network adapters. We use Linux kernel 2.1.90 with built in IPv6 support[10].

The IEEE 802.11 Wireless LAN adapters are manufactured by BreezeCom and support regular 10baseT connections to the routers. We have installed the radio units in weatherproof containers supplied with regulated DC power supply. This is done to keep the antenna connections as short as possible to avoid attenuation in antenna feeding cables. One exception is the installation at repeater installation `stein-gw`, where 10 and 5 meters Heliax microwave feeders are used to connect to antennas in the radio tower. IP parameters, Frequency Hopping pattern, Spread Spectrum spreading code and other radio parameters of the Wireless LAN units are configured through a serial port. We use single and dual near-parabolic antennas. For the 3km link between `stein-gw` and `tunnel-gw2`, trees and a ridge is half-blocking the sight, but connectivity is stable.

In the home networks, both fixed attachment through 10baseT networks, and wireless attachment through a Wireless LAN at home is used to access the network. Clients are using both Linux with IPv6 support and Windows NT with the IPv6 implementation from Microsoft Research[11]. We use Dell laptop and Toshiba clients with both operating systems.

Static IPv6 routing is used with exception of Mobile IPv6 as we will discuss in section 5.1. IPv4 tunneling is used to export a subnet from the Department of Informatics to the main MAN access point located below a radio tower in a high university building. This subnet is partitioned and used for IPv4 routing in WEMAN.

### 3.2. Tools

An automated network surveilance tool[12] is developed to keep track of operational status of the network. A web interface to the tool is provided, indicating faulty nodes and lost connections, and a simplified example of the user interface is shown in Figure 2..

Another tool is an interactive web-based IPv6 Domain tracer[13] developed in the project, useful for nameserver lookups in a given namespace. Sample output from this tool is shown in Figure 3.

### 3.3. Operational problems

The main base station is located at the roof of one of the highest university buildings, and at the highest point in the area. We were troubled with a very high breakdown rate on the network adapter connected to the radio access point in the main IPv6 router (`tunnel-gw2`). Three theories were put forward: 1) Electrostatic discharges caused by micro lightning, 2) Electrostatic charge build-up in the long feeding UTP-5 Ethernet cable discharged as network connectors were inserted and removed. 3) Ground potential mismatch between the antenna tower and the main computer room. After a long period with frequent network card replacement, we first installed a simple surge arrestor device on the Ethernet cable. However, this modification had no effect and network cards were still damaged. After advice from Odd Bryhni, our WEMAN radio and antenna expert, we decided to connect the antenna tower with 4 spare copper cables in the UTP-5 cable to the chassis of the router. We measured more than 50 volts difference

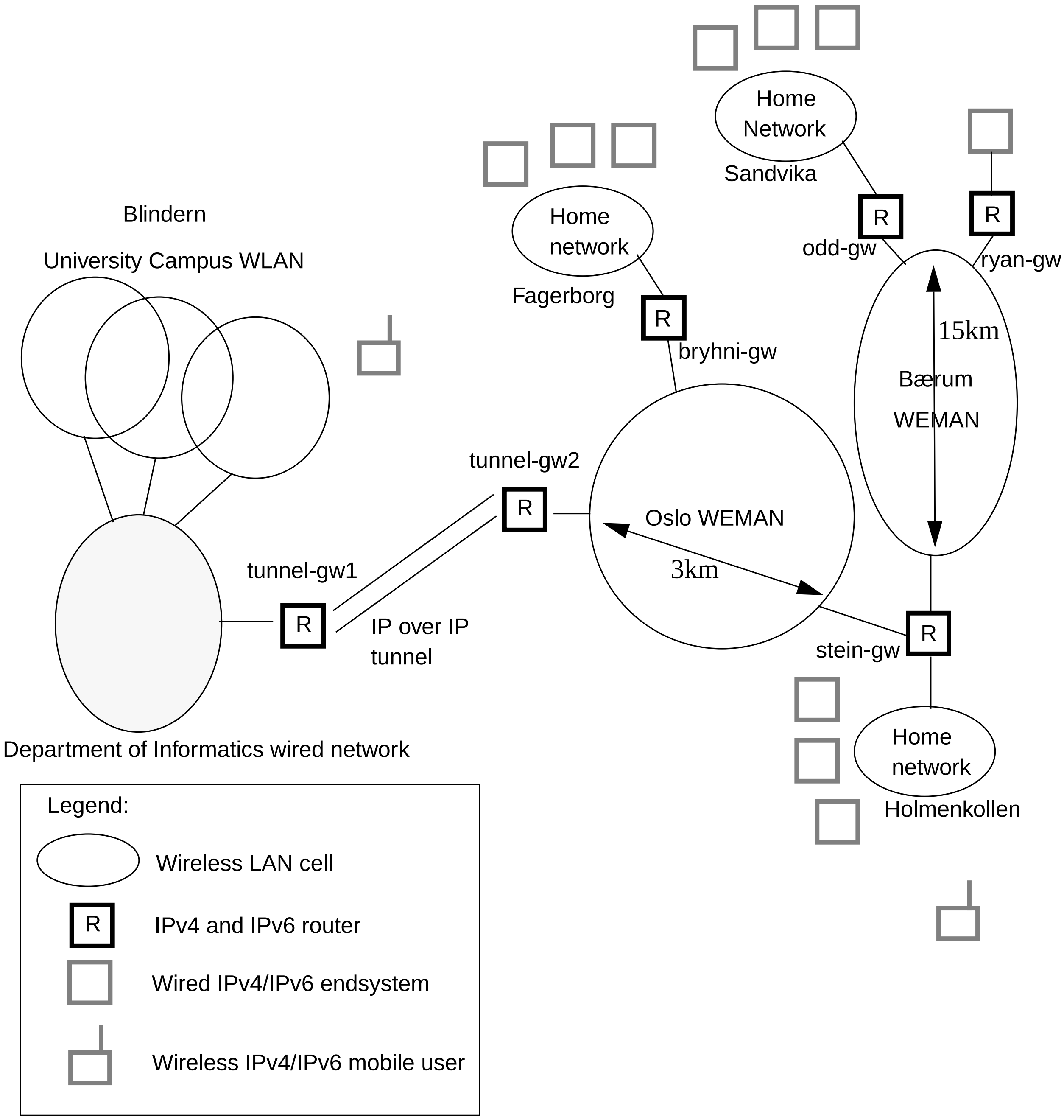


**Figure 1. WEMAN Network architecture**

```
UiO WEMAN network surveilance tool 01:53:04 01.Jun.1998

ifi-gw
 |
tunnel-gw1
 |                    |             |-bryhni1
 |                    |             |-bryhni2
 |      la1ad         |--bryhni-gw--|-bryhni3
 |      /             |             |-bryhni4
 |-fys-gw             |             |-bryhni5
       \              |
        \             |
       tunnel-gw2-----|
         |            |
         |-nazgul     |
         |-la1ad-4    |                                             |-odd1
         |-la1ad-5    |                                             |-odd2
         |-eks        |---stein-gw--|---------------------odd-gw--|-odd3
         |                 stein1-|          |                      |-odd4
                           stein2-|          |- ryan-gw---sjr-pc
```

**Figure 2. Network surveilance tool**

```
kameralus.ipv6          1D IN AAAA      3ffe:2a00:100:1001:2cd:4fff:fea9:1cb0
bildeus.ipv6            1D IN AAAA      3ffe:2a00:100:1001:2c0:4fff:fea3:cd0
laudanum.ipv6           1D IN AAAA      3ffe:2a00:100:1001:2a0:c9ff:fe44:995a
la1ad-4.ipv6             1D IN AAAA       3ffe:2a00:100:6001:2c0:f0ff:fe25:f2ea
deveus.ipv6             1D IN AAAA      3ffe:2a00:100:1001:2c0:4fff:fea3:cd3
symfonius.ipv6          1D IN AAAA      3ffe:2a00:100:1001:2c0:4fff:fea9:1384
mobilus.ipv6              1D IN AAAA       3ffe:2a00:100:1001:2c0:4fff:fea9:1cb3
mmcl2-gw.ipv6           1D IN AAAA      3ffe:2a00:100:1001:0:10:2fff:fe8c:3400
fixus.ipv6                1D IN AAAA       3ffe:2a00:100:1001:2c0:4fff:fea9:141a
```

**Figure 3. IPv6 Nslookup tool**

between mains and the ground potential, possibly caused by large current drains by scientific equipment (e.g. a betatrone and a cyclotrone) in the bulding or poor electric planning in the building. After this modification, we have not had any problems with network card failures.

Another source of connectivity problems has been collection of snow on the microwave antenna feeders. This problem was removed as the spring emerged and disappeared without a trace.

## 4. Supporting mobile clients

Traditionally, the Internet is such that one needs a new IP-address whenever one connect to the network from a new physical location. If you move your computer in the network, you must configure the IP protocol stack such as setting a new IP addresses, the address of the local router and the network mask of the subnet you are connecting to. This usually requires a network administrator, and is highly impractical for most users. Various methods exist to solve this problem, each relying on different support protocols in the fixed network infrastructure. We have identified four ways to provide mobility to the users of WEMAN.

1. IPv4 DHCP method: The first approach has been use of the Dynamic Host Configuration Protocol (DHCP) [22] that handles out IPv4 addresses dynamically as the computers connect to the network. We have successfully been using DHCP both at home and at the University, and we can avoid reconfiguring and rebooting the system every time we change location. In this scenario, a pull aproach is used. The client always request an IPv4 address

and the DHCP server assigns addresses with a certain time to live. When this time expires, the client automatically send a renew IP address request. The shortest time we can set is 1 second, thus a new address can be assigned very quickly. However, the IPv4 address always change as we move in the network topology, and network applications must be restarted.

2. IPv6 Route Advertisement method: As we move to IPv6 applications, we use a push model where IPv6 route advertisements[24][25] are used in addition to the interface MAC address to obtain our IPv6 address automatically when we move in the network. Thus, the operating system can provide us with the correct IPv6 address without user intervention. However, the address is dependent on the physical location, and when we move location all network connections are lost (such as TCP transfers) since we get a new IPv6 address. As with IPv4 DHCP, we still need to restart applications when we have moved. Experience from the IPv4 DHCP and the IPv6 Neighbor Discovery[25] approach has shown that this method is fine as long as the frequency of moves is low and when few applications require continous network connectivity. Another disadvantage with these methods is that clients connecting to a roaming computer do not know which address to connect to since it is always changing.
3. Dynamic IPv6 tunneling method: To support applications which require continous network connectivity we want a fixed IPv6 address, even when we connect to the network from different locations. This can be obtained by IPv6 tunneling, first described in [10]. We adopted a similar scheme in the WEMAN network, and access to the IPv6 network is now done through tunneling in the IPv4 network. Using this method, we can maintain IPv6 connectivity from our fixed IPv6 address, as long as an IPv4 route is established. IPv4 addresses are assigned using regular DHCP[22]. In this configuration, our IPv6 applications maintain connectivity, as network connectivity change. However, as the IPv4 address change, we have to manually update the IPv6 tunnel to point to the correct IPv4 tunnel endpoint. This can be done automatically by a service daemon, but a protocol based solution is still to be preferred. Another disadvantage is that packets must always be sent through the IPv4 tunnel endpoint in your home network, thus degrading performance compared to a more direct path to your current location.
4. Mobile IPv6 method: The preferred method to support mobile IPv6 clients is to adopt the Mobile IPv6 scheme[1] proposed by IETF[6]. Evaluation of this approach were carried out using the university of Lancaster Mobile IPv6 implementation[23] installed in the WEMAN IPv6 test network. Mobile IPv6 is a concept where a mobile node can maintain its home address even when it is roaming to a different IPv6 subnet. In a good implementation, a node should also maintain all TCP connections even when roaming. The Lancaster implementation includes kernel modules for the home agent, which takes care of incomming connections and redirects them when the mobile node is not on the home network. A connecting node does not need to have any special configuration, because the Mobile IPv6 node will use the routing extension header in the IPv6 packets to indicate the address of the nearest gateway. In this way, the connecting node will send all packets directly to the Mobile IPv6 node without going through the home network.

It should be noted that IPv4 DHCP and the IPv6 Route Advertisement methods are easily supported by all IPv4 and IPv6 implementations, while the IPv6 tunneling method requires access to the server in the remote end of the tunnel. The Mobile IPv6 method is the preferred method for mobility, but is still in the process of standardization within IETF. However, we have been fortunate to experiment with an early implementation, discussed in detail in section 5.1.

## 5. Measurements

This section describe a series of measurements carried out in our experimental wireless network. First, we report on the Mobile IPv6 evaluation and go on to discuss latency and throughput of IPv4 and IPv6.

### 5.1. Mobile IPv6

The Mobile IPv6 approach has been evaluated using the testbed shown in Figure 4.. A connecting node wants to send data to the mobile IPv6 node. The first packet is routed to the Home agent, which will tunnel

1. Mobile IPv4 is not preferred due to problems with triangular routing as in the IPv6 tunneling method. In Mobile IPv4, the connecting node has to send all packets to the home agent which tunnels these to the mobile node. This is because source routing is a security hole in IPv4, and we do not want to modify the connecting node.

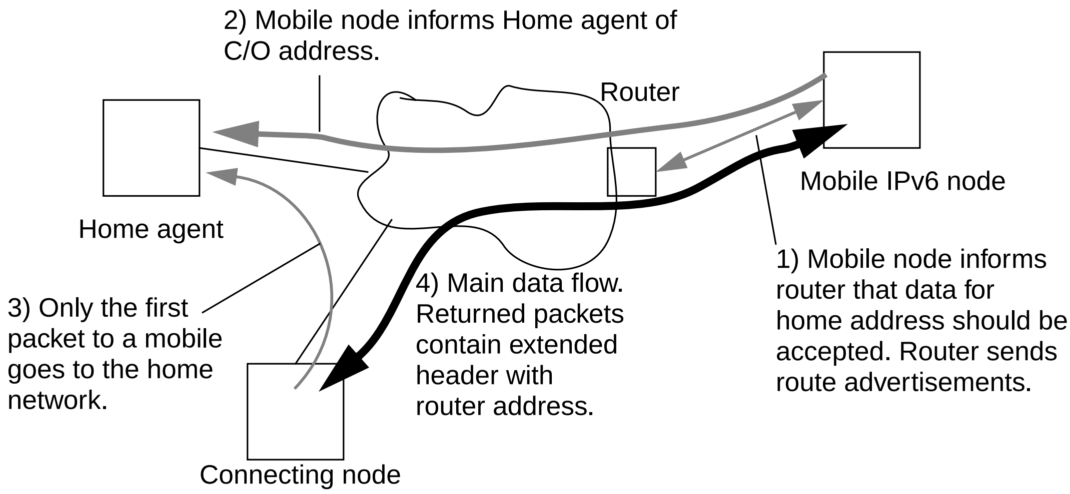


**Figure 4. Mobile IPv6 testbed**

the packet to the Mobile IPv6 node. The reply to the connecting node contains the address of the nearest router, and subsequent packets use the direct path.

Our Mobile IPv6 node was equipped with two interfaces, one 100baseT and one IEEE 802.11 Wireless LAN interface. Initially, the connecting node was accessing the Mobile IPv6 node while it was connected to the home network using 100baseT. The observed ping latency was in the order of 1 ms. Then the Mobile IPv6 node was disconnected from the home network, and was moved into the Wireless LAN coverage area. After a short delay, the Connecting node was informed about the nearest router to the Mobile IPv6 node, and communication *using the same IPv6 address* could continue. Here, latency is about 10ms, typical for a Wireless LAN. Figure 5. shows a plot of the latency of a continous ping to the mobile node when it is roaming between the Home network and the Wireless LAN.

The time for switching between the networks seem to be longer for roaming from the remote network (wireless) to the home network (about one minute) than when roaming from the home network to the remote network (a few seconds). The implementors at Lancaster report the handover time for the Mobile IPv6 node to be about 500 ms. We later learned that the implementors have used a switch of PCMCIA network cards to trigger the (quick) hand-over [27]. This will be corrected in future versions of the Linux mobile IPv6 implementation. However, the important point of automatic address configuration and direct connection between the connecting node and the Mobile IPv6 node has been demonstrated in our wireless experimental IPv6 network. This approach is the most elegant solution to mobile nodes using IPv6 and will be implemented throughout the Internet 2 network in Norway[8] for further evaluation.

### 5.2. Latency

Latency performance evaluation was carried out using standard 56byte ICMP ping-packets. The measurements were performed over a week, with a train of IPv4 ping packets to each participating node every 10 minutes. In addition, one IPv6 station was pinged. Figure 6. shows a plot of the median ping-latency each hour for the test period. Note that some of the machines involved in the test were temporary down.

This plots shows a quite steady average latency for all stations. The shortest latency is as expected to the nearest node (600m). The next higher is to the router 3 km away, at Holmenkollen. The difference in latency here is because the nearest node (about 1 km) can sustain a 3Mbit/s rate whereas the nodes farther away (3-15 km) can only sustain 1Mbit/s due to the increased distance. However, in good conditions we can achieve 3Mbit/s also for the longest distance links, but this requires absolutely unobstructed path and the correct meteorological conditions, which we will discuss in section 5.4. The higher two graphs are the two nodes in Bærum, 15 km away. The difference in latency between these two is because of end system speed. There are two “spikes” in the diagram, the first outage is caused by high winds moving the antenna out of position and the preceeding spike is when .the antenna is aligned again. The the other spike is caused by an intentionally large (~500MB) file transmitton between `tunnel-gw2` and `bryhni-gw`. This file transfer caused the radio link to

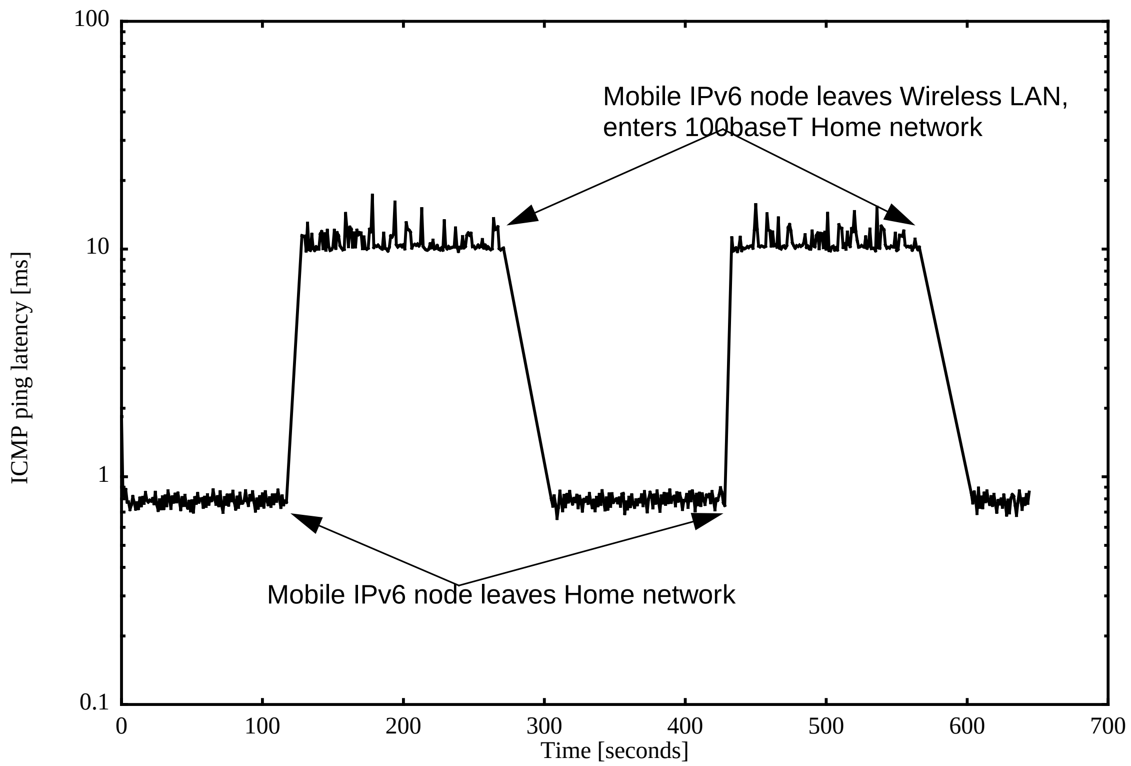


**Figure 5. Reconfiguration between fixed and mobile network**

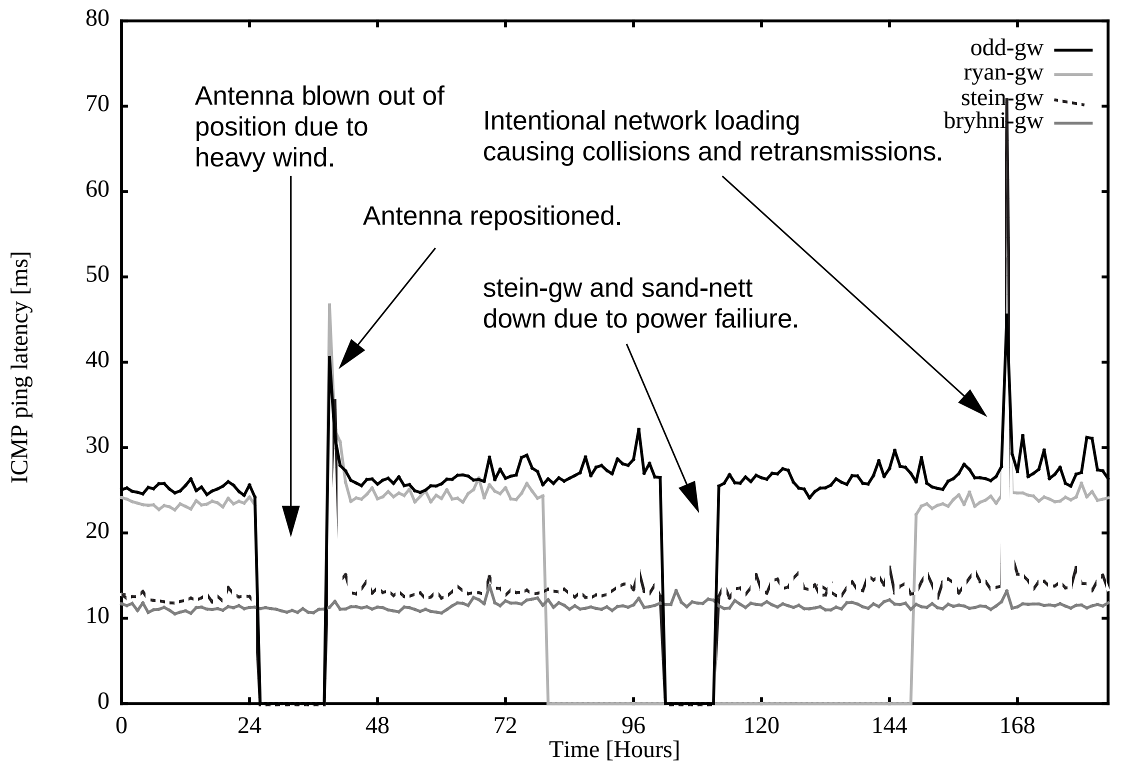


**Figure 6. Median ping latency for IPv4 in WEMAN**

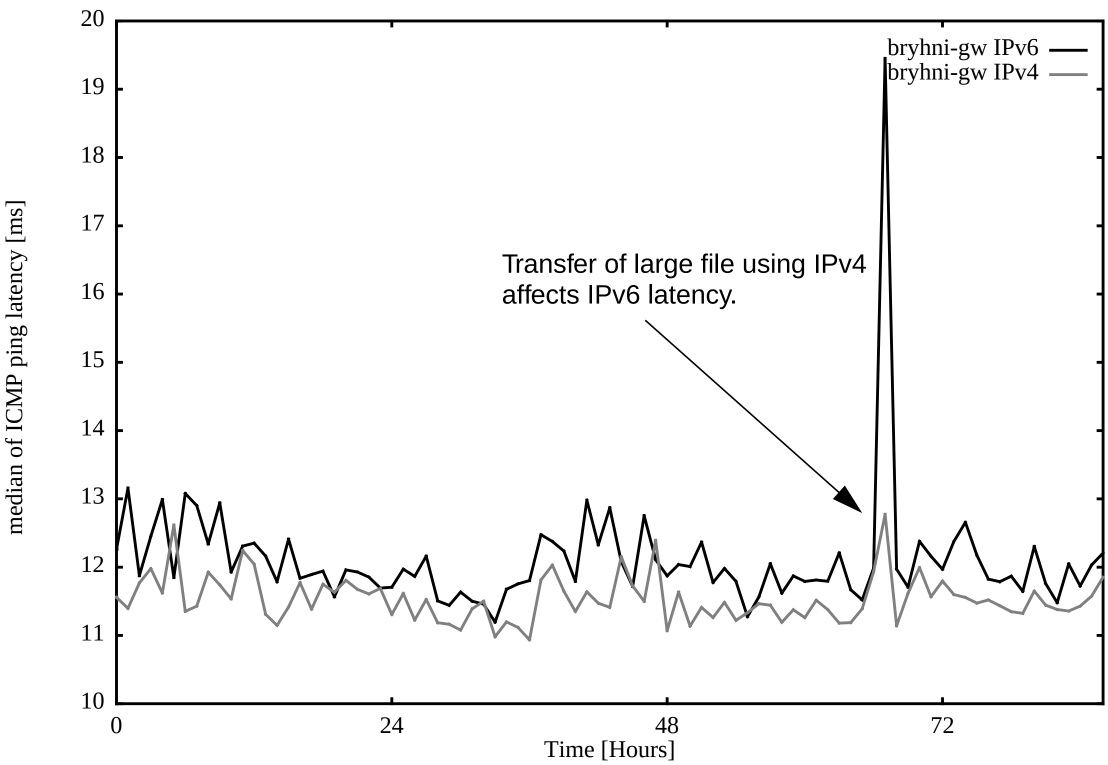


**Figure 7. ICMP ping latency comparison IPv4 and IPv6**

retransmit colliding IEEE 802.11 packets, thus giving higher measured latency.

### 5.3. IPv6 versus IPv4 ICMP latency

Figure 7. shows a plot of the latency for IPv6 vs. IPv4. It is apparent that the IPv6 latency in general is higher than the IPv4 latency. This is probably an effect of the early implementation of IPv6. The IPv4 implementation is rather mature, and has been optimized over a long time, whereas the IPv6 implementation is very new, and the code needs time to mature such that optimizations can be included. We can also see that IPv6 performs worse than IPv4 when the net is loaded (with IPv4 traffic). IPv6 packets are currently not prioritized in the routers, but this may be done by reservation protocols at a later stage when we want QoS support for IPv6 connections

### 5.4. IPv4 Throughput

Figure 8. shows a plot of the IPv4 throughput measurements between tunnel-gw2 and stein-gw, for a period of about 3 days. The `ttcp` program from the US Army Ballistics Research Lab (BRL) were used for the throughput test, transmiting 512 buffers of 8K each, every 10 minutes. It is obvious from the graph that the throughput varies with the time of day, giving up to 20% higher throughput at night. We also see a falling tendency in the graph. The periodical nature of the throughput tests made us curious to know wether the performance had any relation to meteorological conditions.

Empirical studies of the link quality indicators and weather observations by Odd Bryhni, our radio and antenna expert, made us suspect that meteorological conditions could influence link quality. Meteorological data (temperature, humidity and pressure) was then aquired from the Norwegian Meteorological Institute[26]. It has not been observed rain during the period. Correllating throughput with weather data in Figure 9., we can see that the average temperature through the period has increased. This may correspond to the falling tendency in our throughput measurements. Further correlation can be observed between the daily fluctuation in throughput and temperature. We note that the highest throughput is obtained at the lowest temperature. Note also that the decrease in throughput occurs a few hours after the peak temperature. This observation support our theory that radiation from the sun heats the ground and causes disturbances in the air, creating tem-

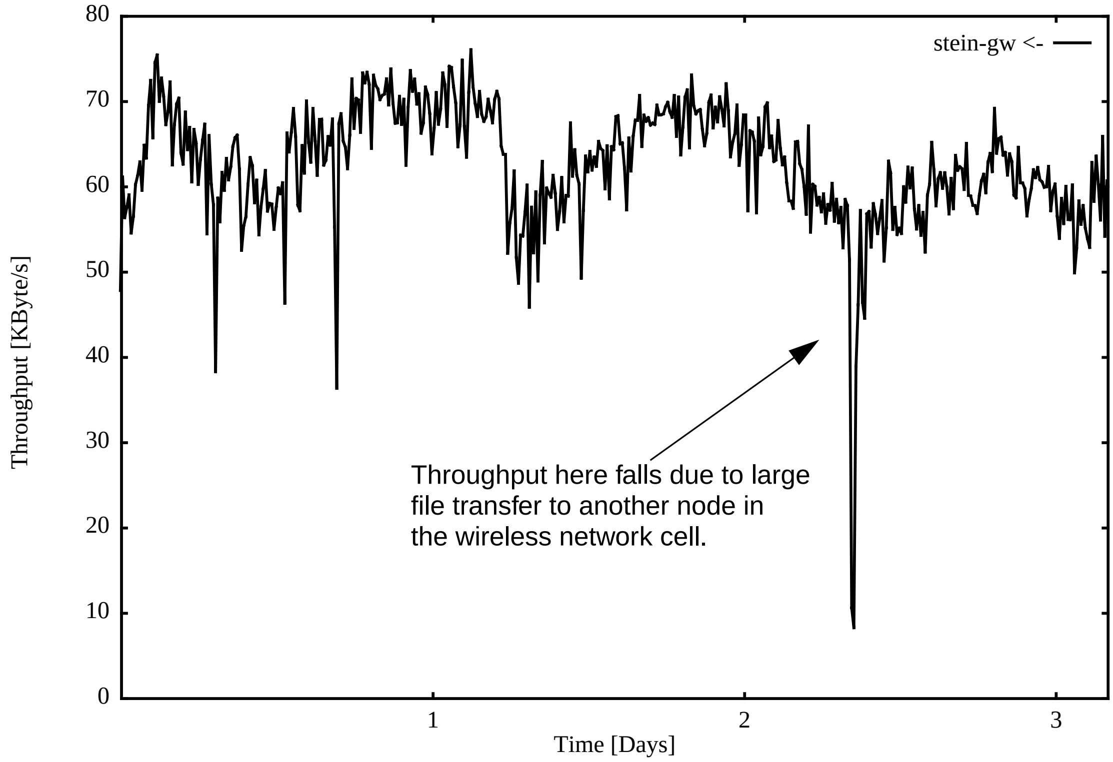


**Figure 8. IPv4 thoughput measurements over 3km link using IEEE 802.11 in WEMAN**

perature boundaries where the microwaves may be refracted or change polarity with subsequent reduced link quality. The plot of the humidity does not indicate any direct correlation, probably indirect since humidity is linked to temperature.

### 5.5. IPv6 Throughput

Figure 10. shows the throughput for a wireless link using different packet sizes. We have used the `ttcp6` program provided with the current Microsoft NT IPv6 distribution, transmitting 2MBytes for each measurement. We can see that there are peaks at regular intervals (1408, 2880, 4224, 6912). This corresponds aproximately to the Maximum Transmission Unit (MTU) of the Ethernet links, where packets are fragmented before leaving the first server. The throughput generally increases with increased packet size, until a new packet is needed by the fragmentation process, and this decreases throughput. Maximum throughput is reached for the largest packet sizes, peaking at about 150Kbyte/s which is the expected maximum for a 802.11 wireless link.

We suspect that the Microsoft NT IPv6 protocol implementation is at a very early stage, and performed a comparison between TCP/IPv6 throughput over Wireless LAN and 100baseT networks. The results were very disappointing as shown in Figure 11.. We can still see the dependency on Ethernet MTU size, but the system seems to be saturated as packet size increase beyond 4Kbytes.

### 5.6. Stability

We do not have measurements for any period with rain or snow, but user reports from before the measurements started indicate that they have little impact on the throughput as long as snow does not settle on the microwave antenna feeders.

We have observed very little packet loss on operational links. This is due to the IEEE 802.11 retransmission scheme at the radio link. However, the effect of such retransmissions can be observed in the latency measurements.

Since our test period has covered the spring in Oslo, we were very curious to see the effect of spring leaves that potentially could degrade link quality. Our observations have not shown any problems related to spring leaves. However, during our mobile sessions we have observed high vulnerability when trees block the direct radio link path. In particular, this is important when the

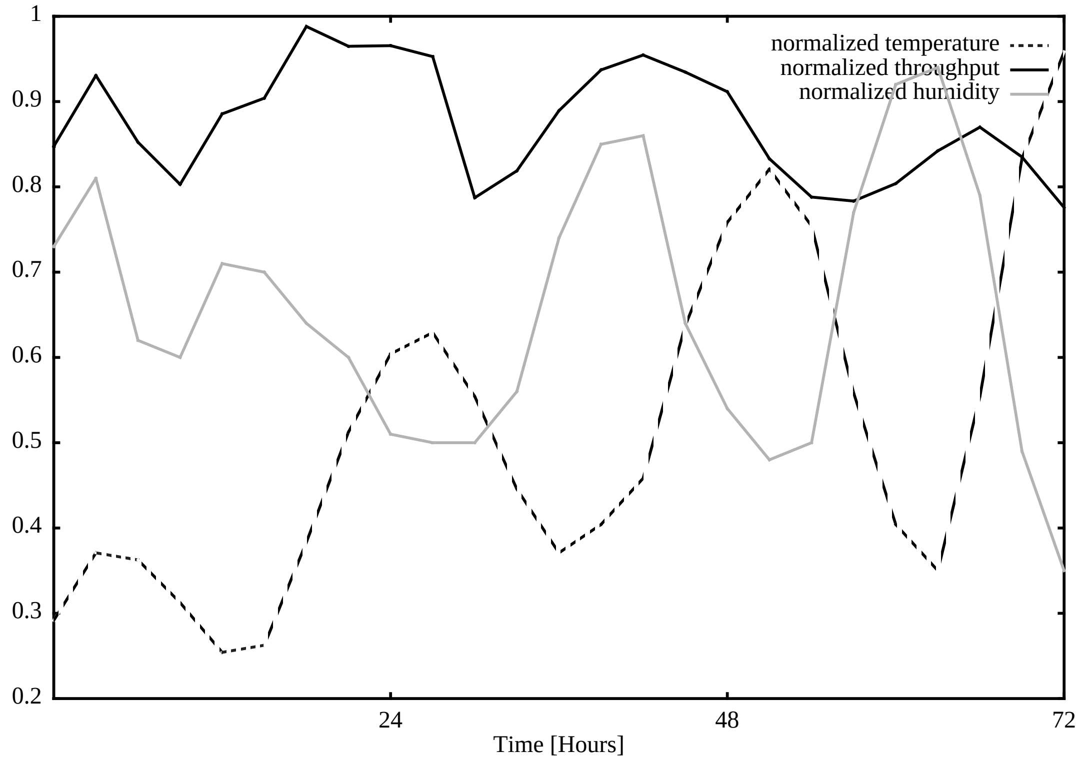


**Figure 9. IPv4 throughput measurements and Meteorological data**

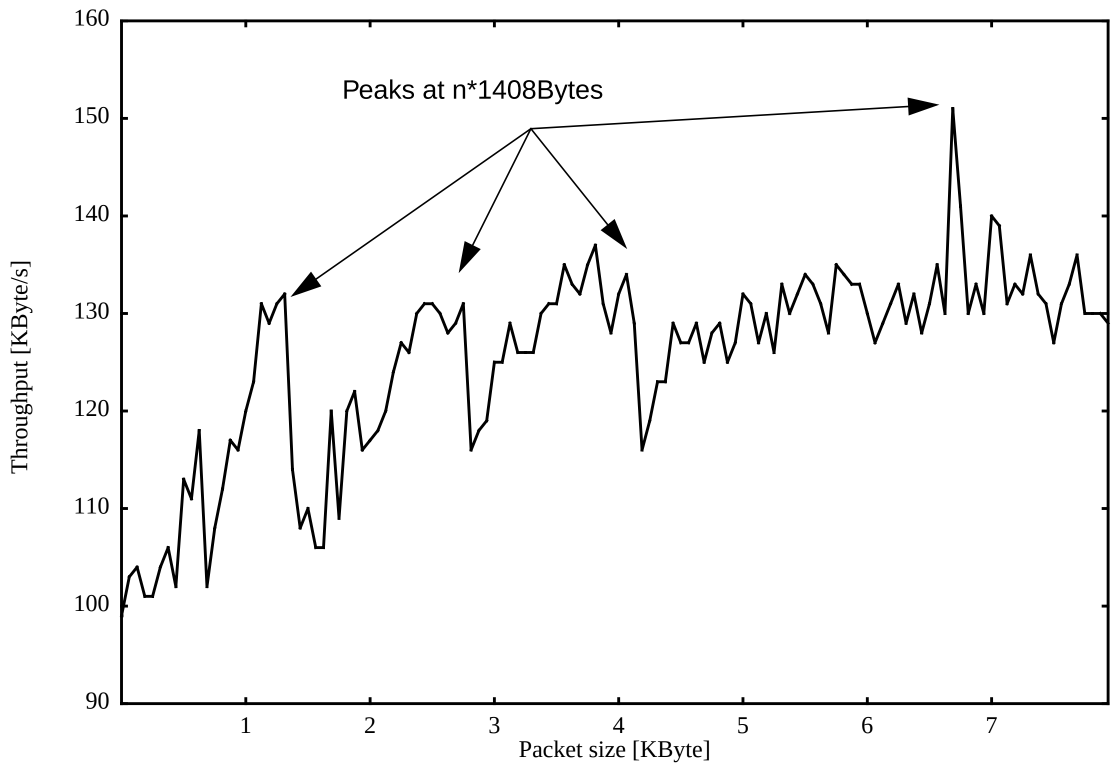


**Figure 10. IPv6 throughput measurements for different packet sizes.**

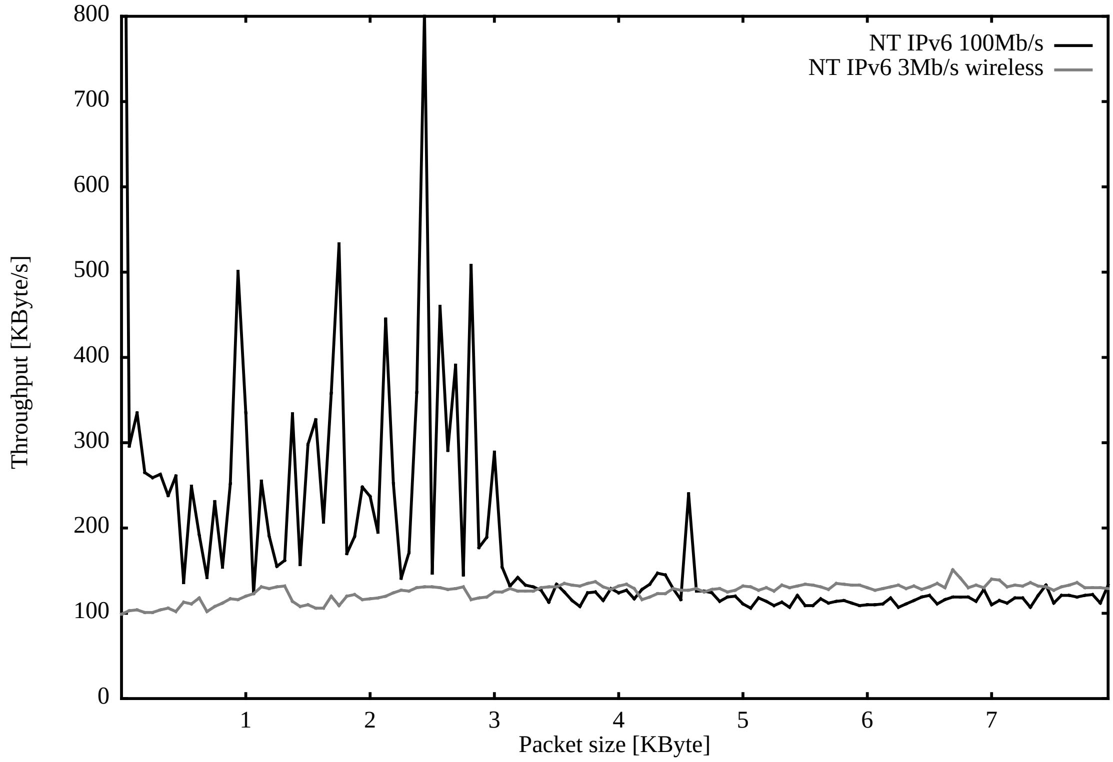


**Figure 11. IPv6 throughput for different packet sizes, comparing Wireless LAN and 100baseT**

objects are close to the antenna. Obstackles further away (>10m) in line of sight is of less importance.

## 6. Conclusion and further work

We have sucessfully demonstrated full IPv6 mobility in a high speed Metropolitan Area Network built using Wireless LAN technology. Wireless LANs are previously limited to building or campus operation. However, using directive antennas and Low Noise Amplifiers, metropolitan range can be achieved. Proof of concept is our demonstration of physically moving a portable computer with a Mobile IPv6 client between a wired and a wireless connection in WEMAN. In the following we list the individual contributions and give our suggestions for further work in this area.

### 6.1. Contributions

We have presented a feasibility study of Metropolitan Area Network using Wireless LAN technology. Our conclusion is that IEEE 802.11 technology is well suited for high speed network access. Antennas are small for mid-range distance (up to 1km) and moderately large for long distance (up to 15 km). The large antenna reflectors are perforated and can withstand strong wind. We have had one link failiure due to wind, but this was resolved by better mechanical mount procedures.

We have explored four options of protocol support for mobile clients, ranging from simple DHCP solutions and IPv6 Route Advertisements through Dynamic IPv6 tunneling and finally Mobile IPv6 support. All options are verified by experiments in WEMAN.

We have presented an evaluation of Mobile IPv6[6] which is the most promising approach for mobile access to IPv6 networks. We conclude that the Mobile IPv6 implementation from Lancaster performs very well, when the problem with the long hand-over time is solved.

A performance evaluation of IPv4 throughput and latency in WEMAN is presented. We achieve throghput in the order of 70-150 Kbyte/s and roundtrip latency in the order of 10ms in the MAN.

We have observed interesting variations in throughput during the course of the day, and have investigated possible correlation with meteorological conditions. We have shown a clear correlation with the average air temperature and propose that this is due to radiation related to the sun heating the ground and causing disturbances in the air. This creates temperature boundaries where the microwaves may be refracted or change polarity with subsequent reduced link quality.

We have measured the roundtrip latency of IPv4 versus IPv6 and found that IPv6 latency is affected by high IPv4 traffic. In general, IPv6 roundtrip latencies are slightly higher than IPv4, probably due to immature protocol implementations.

Finally, we have presented an evaluation of throughput of IPv6 over Wireless LAN with 3Mbit/s maximum link speed. Memory to memory TCP/IPv6 throughput reaches about 150 KByte/s, approximately the same peak as observed using IPv4. However, if we measure performance of TCP/IPv6 transfers using 100baseT networks, we get a peak performance of 1.6 MByte/s. For comparison, IPv4 peaks at about 10 MByte/s. This is believed to be related to a protocol implementation optimized for functionality and not performance at this stage. Subsequent implementations are believed to perform much better.

### 6.2. Further work

We plan to follow and take part in development of Mobile IPv6 in the future. We will introduce Mobile IPv6 in the IPv6 Internet 2 research network infrastructure in Norway, and experiment with new applications using IPv6. We are currently porting a number of such applications.

We would like to improve our understanding of the correlations between network performance and meteorological conditions. To improve accuracy of meteorological data, we would like to establish weather station at remote nodes and continue our collaboration with the Norwegian Meteorological Institute. In particular, we are interested in variations over longer time.

Since throughput in a mobile network is limited, we would like to extend our experiments with resource reservation protocols such as RSVP into WEMAN. In this way, we may be able to handle scarce resources in a better way, and even provide guaranteed Quality of Service guarantees for mobile clients.

We believe that Spread Spectrum communication has good scalablity properties, and would like to investigate this issue futher. If the technology scales well, use of the ISM band is a low cost and flexible network access solution, both in the private and commercial sector.

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