Broadband Wireless Access in Disaster Emergency Response

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KTH Information and Communication Technology

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Abstract

The “WLAN in Disaster Emergency Response” (WIDER) project has developed and implemented an emergency communication system. It provides network and communication services to relief organizations. In order to guarantee the stable and efficient connectivity with a high quality of service (QoS) for the end user, and to make the WIDER system more adaptive to the disaster area, the IEEE 802.16 specification based broadband wireless access solution is adopted. This thesis work aims at evaluating and testing the WIDER system integrated with WiMAX. By learning and analyzing the technology, the benefits and perspective for WIDER using WiMAX are described. A WiMAX solution was configured and integrated into the WIDER system. A series of tests and measurements provide us the performance of the WiMAX solution in throughput, QoS, and reality. The tests helped us to learn and verify the improvements for WIDER due to WiMAX.

Keywords: Disaster Response, WIDER, IEEE 802.16, IEEE 802.11, WiMAX, WiFi, BWA, Point-to-Multipoint

Abstract in Swedish

"WLAN in Disaster Emergency Response" (WIDER) projektet har utvecklat och implementerat ett kommunikationssystem för katastrof situationer. Systemet tillhandahåller nätverk- och kommunikationstjänster för hjälporganisationer. För att garantera en stabil och effektiv anslutning med hög Quality of Service för användarna samt göra WIDER systemet mer anpassbart för katastrofområden, kommer Broadband wireless access som är baserade på IEEE 802.16 specifikationen att användas. Det här examensarbetet har som målsättning att utvärdera och testa WIDER med WiMax tekniken, vi beskriver olika fördelar och synvinklar med att använda WiMax genom att lära oss och analysera tekniken. En WiMax lösning konfigurerades och integrerades i WIDER systemet. En rad tester och mätningar visar WiMax-lösningens prestanda i form av throughput, Quality of Service och realitet. Testerna lärde oss och hjälpte oss att verifiera förbättringarna i WIDER i och med användningen av WiMax.

Nyckelord: Disaster Response, WIDER, IEEE 802.16, IEEE 802.11, WiMAX, WiFi, BWA, Point-to-Multipoint

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Abbreviations

Table 1: Abbreviations

BE	Best Effort
BPSK	Binary Phase Shift Keying
BS	Base Station
CPE	Customer Premises Equipment
DL	Down Link
FDD	Frequency Division Duplexing
HW	Hard Ware
IDU	Indoor Unit
IEEE	Institute of Electrical and Electronics Engineers
LAN	Local Area Network
LOS	Line Of Sight
MAC	Media Access Control
NLOS	Non Line Of Sight
MAN	Metropolitan Area Network
ODU	Outdoor Unit
OFDM	Orthogonal Frequency Division Multiplexing
PPP	Point-to-Point Protocol
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RADIUS	Remote Authentication Dial-In User Service
RF	Radio Frequency
SF	Service Flow
SNMP	Simple Network Management Protocol
SME	Small Medium Enterprise
SOHO	Small Office / Home Office
SS	Subscriber Station
SW	Soft Ware
TDD	Time Division Duplexing
UL	Up Link
VLAN	Virtual LAN
VoIP	Voice over IP
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless LAN
WMAN	Wireless MAN

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1. Introduction

1.1 Ericsson Response Program

The Ericsson Response Program, the sponsor of this project, is a global initiative aimed at developing a better and faster response to human suffering caused by disaster [1]. The initiative formalizes Ericsson's commitment to this issue. It builds upon Ericsson's previous involvement and experience in various disaster response efforts throughout the world. Ericsson in partnership with the United Nations High Commissioner for Refugees (UNHCR), the Office for the Coordination of Humanitarian Affairs (OCHA) and the International Federation of Red Cross and Red Crescent Societies (IFRC) is developing disaster preparedness programs around the world. When an international request for help is sent out from the UN or IFRC to Ericsson, then the Ericsson Response Program will provide rapid deployment of communications solutions encompassing Ericsson technologies and skills to support and respond to the unique communication challenges of each disaster. [1]

1.2 WIDER

A fast and effective response to disaster is desirable. Communication plays a pivotal role in an efficient response to relief organizations. In order to help provide the data communications required for one or more relief organizations in the field, Ericsson Response started a project called WLAN in Disaster and Emergency Response (WIDER) in September 2002. The main aim of this project is to facilitate relief organizations operating in a disaster area to share their communication infrastructure while limiting the cost, and to increase both efficiency and security. [2]

WIDER has been carried out in corporation between the Ericsson Response Program and Royal Institution of Technology (KTH). It has lasted for three years. The basic network topology and services have been established. With the continuing development of wireless technology, the latest wireless solutions and standards should be investigated and incorporated with the WIDER project. This thesis project continues this work by considering the addition of WiMAX technology (See section 3.3).

1.3 Vision

Wireless connectivity is provided by the WIDER system. Until the second phase of the WIDER project (2004), Wireless LAN was used to offer connectivity for end users in a local area network, and a point-to-point wireless connection was setup between this local area network and the WIDER central system. In the third phase (2005), point-to-multipoint wireless connectivity is to be added. In order to provide efficient wireless connectivity with high flexibility and greater capacity, WiMAX [3] is to be introduced. It is defined by IEEE standard 802.16 [4].

As an emerging wireless technology, we needed deeply investigate WiMAX technology concerning its flexibility, capacity, QoS, the ability to transport different types of traffic, such as data and voice, and its reliability. Together with the utilization of WiFi [5] in the client network, the impact of adding WiMAX to the WIDER project and the advantages and disadvantages for end users should be evaluated.

The WiMAX solution should be tested as part of WIDER. The tests should include different types of traffic, VLAN support, internetworking connections, and the QoS WiMAX.

2. Background

2.1 Broadband Wireless Access (BWA)

Broadband wireless access is a technology aimed at providing wireless access to data networks, at high data rates. From the point of view of connectivity, broadband wireless access is equivalent to broadband wired access, such as via ADSL or cable modems.

Broadband wireless access (BWA) has become the best way to meet escalating business demand for rapid Internet connection and integrated data, voice, and video services. BWA can extend fiber optic networks and provide greater capacity than cable networks or digital subscriber lines (DSL). For the broadband network operators, one of the most compelling aspects of BWA technology is that networks can be created in just weeks by deploying a small number of base stations on buildings or poles to create high-capacity wireless access systems. [6] In the WIDER project, it only takes several hours to deploy the system with one base station. The measurement in live test which can be found in section 7.3 proves this.

2.2 Relevant IEEE 802 Wireless Standards

The following IEEE 802 wireless standards were considered to be potentially relevant to this thesis.

- **IEEE 802.11™ Working Group for Wireless Local Area Networks**

The IEEE 802.11 wireless standards specify an "over-the-air" interface between a wireless client and a base station or access point, as well as among wireless clients. The IEEE 802.11 specifications address both the Physical (PHY) and Media Access Control (MAC) layers and are tailored to resolve compatibility issues between manufacturers of Wireless LAN equipment. [7]

- **802.16™ Working Group for Broadband Wireless Access Standards**

The IEEE 802.16 standard specifies the Wireless MAN Air Interface for wireless metropolitan area networks. It addresses the “first-mile/last-mile” connection in wireless metropolitan area networks. It focuses on the efficient use of bandwidth between 10 and 66 GHz, and was extended to include the 2 to 11 GHz region with point-to-multipoint and optional Mesh topologies. In addition, it defines a medium access control (MAC) layer that supports multiple physical layer specifications customized for the frequency band of use. [6]

- **IEEE 802.20 Mobile Broadband Wireless Access (MBWA)**

The mission of the IEEE 802.20 working group is to develop the specification of an efficient packet based air interface that is optimized for the transport of IP based services. The goal is to enable worldwide deployment of affordable, ubiquitous, always-on and interoperable multi-vendor mobile broadband wireless access networks that meet the needs of business and residential end uses. [8] Since there is no specification available and no compliant products yet exist, it is not further examined in this thesis. In the future, it will be interesting to investigate the use of IEEE 802.20 in the WIDER project

2.3 IEEE802.16 and WiMAX

Broadband Wireless Access (BWA) has its own limitation, because of the need for a universal standard to increase the market and the benefit. Otherwise it is difficult to define the market and products. The Institute of Electrical and Electronics Engineers Standards Association (IEEE-SA) sought to make BWA more widely available by developing IEEE Standard 802.16, which specifies the WirelessMAN Air Interface for wireless metropolitan area networks. [6] The first version of the 802.16 standard released addressed Line-of-Sight (LOS) environments using high frequency bands operating in the 10-66 GHz range, whereas the recently adopted amendment, the 802.16a standard, is designed for systems operating in bands between 2 GHz and 11 GHz.

The major difference between these two frequency bands is the ability to support Non-Line-of-Sight (NLOS) operation in the lower frequencies, something that is not possible in higher bands. Consequently, the 802.16a amendment to the standard opened up the opportunity for major changes to the PHY layer specifications specifically to address the needs of the 2-11 GHz bands. This is achieved through the introduction of three new PHY-layer specifications (a new Single Carrier PHY, a 256 point FFT OFDM PHY, and a 2048 point FFT OFDMA PHY); major changes to the PHY layer specification as compared to higher frequency operation, as well as significant MAC-layer enhancements. [9]

Although the IEEE 802.16 working group specifies much of how a BWA system should operate at a system-level, a great amount of flexibility also exists within the specification for parameters such as frequency band, modulation, and channel bandwidth. In addition, there is no uniform test or verification for different vendors' equipment. To solve these issues, in April 2003 a non-profit BWA industry association was launched called Worldwide Microwave Interoperability (WiMAX) Forum. It is a non-profit industry trade organization that develops conformance and interoperability test plans, selects certification labs, and hosts interoperability events for IEEE 802.16 equipment vendors. [9]

3. WiMAX (802.16) and WIDER

3.1 Why use WiMAX in WIDER

As an emergency communication system to be used in a disaster area, flexibility and reliability are the two most important features required. Because of the unpredictable situation in a disaster area, due to weather, environment, or human needs, a means of providing adaptive and efficient connectivity with sufficient QoS between relief organizations should be provided. That's the basic motivation behind introducing WiMAX into WIDER.

WIDER requires three major features for this wireless connectivity.

1. **Full non-line-of-sight (NLOS) coverage** [10]

There are often a great number of relief organizations' offices and camps surrounding the disaster area. It is impossible to ask the relief organizations to select their location based on the availability of wireless access. As a result, a means of providing full wireless coverage is required. Thus, because of the unpredictable and complicated environment in the disaster area, WIDER should provide non-line-of-sight wireless coverage.

2. **Point-to-Multipoint wireless connections**

The main aim of the WIDER project is to provide a shared communication infrastructure to relief organizations. This means that any relief organization in the disaster area should be able to access the WIDER system in order to utilize the services provided remotely. Hence a Point-to-Multipoint mode is necessary.

3. **High throughput and sufficient QoS**

As more and more services are integrated into the WIDER project, greater and greater capacity is required for some bandwidth consuming services, such as video. In addition, sufficient QoS of the wireless connectivity is needed to guarantee stable connections between different relief organizations.

Currently, the WIDER solution [2] (see Figure 1) provides point-to-point wireless connectivity between the central system and the relief organization by using an 802.11b wireless bridge. Although it could be configured to support point-to-multipoint wireless connectivity, the coverage is still very limited because of some restrictions of the WiFi products (which use IEEE 802.11), such as the range it supports and capacity. Thus, WiFi alone can't satisfy the requirements of the WIDER project. As a result, WiMAX is being considered.

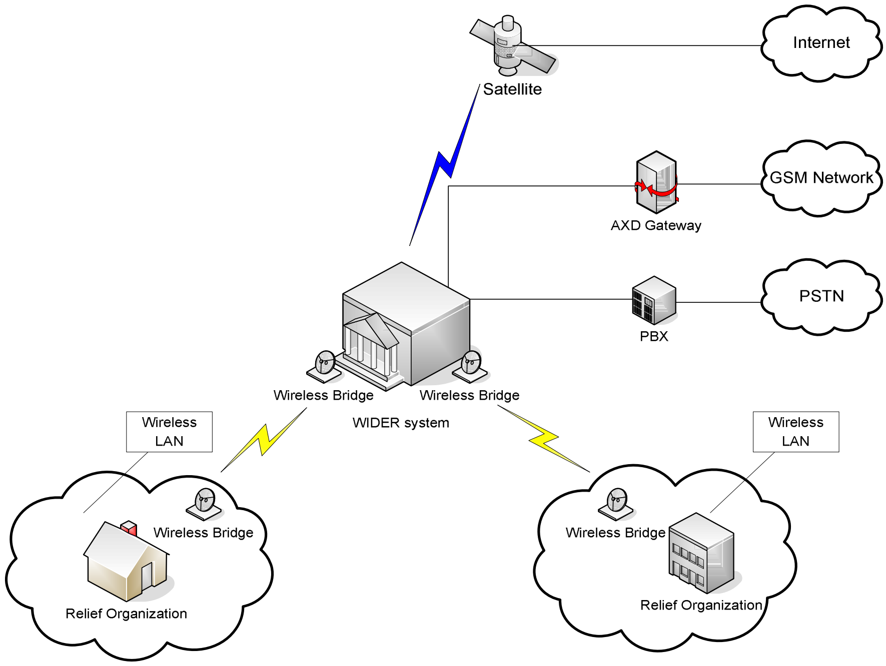

Figure 1: WIDER with WiFi wireless bridge

3.2 Comparison between WiMAX and WiFi in WIDER

As described in section 3.2, several wireless access standards have been developed by the Institution of Electrical and Electronics Engineers (IEEE). Currently, both IEEE 802.11 and IEEE 802.16 have been driven forward by the industry. In the case of the IEEE 802.11, this role was and is fulfilled by the WiFi Alliance. For the Broadband Wireless Access (BWA) market and its IEEE 802.16 standard, this role is played by WiMAX Forum. All the solutions currently being considered for the terrestrial portion of WIDER are related to either WiFi or WiMAX. The following comparison between them will emphasize the advantage of WiMAX to provide the longer range and greater capacity which WiFi does not provide.

Note that logically, the WIDER network topology need not be changed when replacing the current IEEE 802.11 bridges with an IEEE 802.16 based solution. However, due to the differences in the properties of the links, the system characteristics do change as described in the following sub-sections.

3.2.1 Range

Since WiMAX was designed for out-door use, it has a range of up to 50 kilometers with full coverage of a typical cell having a radius of 8 kilometers. [11]

Normally, the relief organizations' offices and camps are located within a radius of approximate 2 km around the disaster area. Thus, WIDER could provide sufficient coverage of wireless access for such relief efforts.

A WiFi hotspot typically covers a radius of 20-300 meters (only a fraction of a kilometre). A number of range estimates can be found in table 1.

Table 2: WiFi Range Estimates [12]

	Maximum Range	Range At 11 Mbps
Outdoors / open space with standard antenna	250-330 m	50-150 m
Office / light industrial setting	80-120 m	33-50 m
Residential setting	30-65 m	20-30 m

There are two problems with WiFi products. First, the speed decreases quickly as the range increases. Thus organizations can not get an 11 Mbps data rate if they are too far away from the base station. Although it is possible to increase the range and performance of WiFi products by using different kinds of antennas, you would then need to change the antenna deployment in WIDER depending on the different disaster situations.

3.2.2 Rates and Services

WiMAX-based networks have the flexibility to support a variety of data transmission rates such as T1 (1.5Mbps) and higher data transmitting rates of up to 70Mbps on a single channel, thus it can support thousands of users. [13] Additionally, adaptive modulation increases the link reliability. WiMAX products can extend the full capacity over a longer distance.

This greater capacity enables WIDER to support many kinds of services, including video. The throughput and capacity of WIDER are sufficient for disaster emergency response.

WiFi certificated products can provide two data rates, 11Mbps and 54Mbps, depending on different version of the IEEE 802.11 standard. IEEE 802.11b's maximum data rate is 11Mbps [14], while both the IEEE 802.11a and IEEE 802.11g can achieve 54Mbps [15]. The disadvantage of the WiFi products is the decrease in capacity with the increment of range. (See first item in section 4.2) As a result, it is not suitable for WIDER to use the WiFi based solution to provide the radio link between the central WIDER system and the relief organizations' sites. However, WiFi is a good solution to provide wireless LAN for the relief organizations' local network. [2]

3.2.3 Both WiMAX and WiFi support the same IEEE 802.2 logical link layers. [13]

Because of this features, the WiMAX and the WiFi solutions support all the same higher layer services, such as IPv4, IPv6, Ethernet, and VLAN services. Additionally, they can simply be connected to LAN bridges and the link frames will be forwarded as necessary.

3.2.4 Point-to-multipoint wireless connections

A WiMAX-based solution can be set up and deployed like other cellular systems using base stations. The IEEE 802.16 wireless link operates with a central base station and a sectorized antenna that is capable of handling multiple independent sectors simultaneously. Within a given frequency channel and antenna sector, all the subscriber stations (SSs) receive the same transmission, or parts thereof. The SSs check the Connection Identifiers (CIDs) in the received protocol data units (PDUs) and retain only those PDUs addressed to them. [16]

WiFi also provides point-to-multipoint wireless connections, but because of the limited coverage, this kind of point-to-multipoint wireless connection is focused on end users close to the base station (for example, at the relief organization's site). Therefore, it is most useful as a wireless local network rather than between the WIDER central system and the relief organizations' sites.

3.2.5 QoS levels

The 802.16 Media Access Control (MAC) protocol allows effective allocation of channel resources to meet the demands of the active connections with their granted QoS properties. It provides a connection-oriented service to upper layers of the protocol stack. The bandwidth request and grant mechanism has been designed to be scalable, efficient, and self-correcting. Through the use of flexible PHY modulation and coding options, flexible frame and slot allocations, flexible QoS mechanisms, the WiMAX-based solution enable WIDER to operate over a wider range of population densities and in a wide range of propagation environment. [17]

Because of the limited coverage and QoS mechanisms, the WiFi-based solution can not provide the same QoS as WiMAX for the wireless links between the WIDER central system and the relief organizations' sites.

3.2.6 NLOS (non-line-of-sight) coverage

WiMAX technology solves or mitigates the problems resulting from NLOS condition. Hence it can provide non-line-of-sight coverage.

NLOS coverage is one of the major requirements of WIDER. This feature of WiMAX offers optimised wireless connectivity. Relief organizations can more flexible access WIDER over a wider range of types of disaster areas. Whereas, WiFi can only provide up to approximate 150m NLOS wireless coverage, thus limiting the location of the relief organizations' sites.

WiMAX has some advantages in providing long distance wireless link. Thus, it can be used between WIDER's central system and the relief organizations' sites. On the other hand, WiFi is a good solution to provide WLAN for the end uses in the relief organizations within a short coverage. WiMAX serves as a backhaul for WiFi hotspots or WLAN enabling flexibility in WiFi deployment. Because WiMAX and WiFi use different channels, there is no radio interference problem.

3.3 The disadvantages of WiMAX

So far, WiMAX certified products lack support for mobility of the subscriber units between the different base stations. The base station can not handle the handoff of the subscriber units. This limits the mobility of the client networks. IEEE 802.16's Task Group e [18] is developing Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands as an amendment to IEEE standard 802.16 to support mobility.

3.4 Mesh network mode in WiMAX

A mesh network employs one of two connection arrangements, full mesh topology or partial mesh topology. In a full mesh topology, each node (workstation or other device) is connected directly to each of the other nodes. In a partial mesh topology, only some nodes are connected to all the others, and some of the nodes are connected only to those other nodes with which they exchange the most data. (See Figure 2)

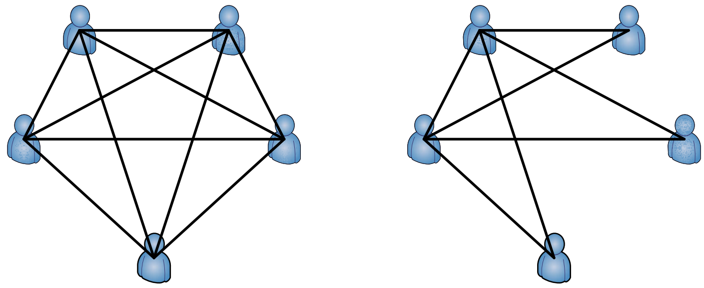

Figure 2: Full Mesh mode and Partial Mesh mode

A mesh network offers redundancy and hence increases reliability. As a result, it could be a good topology for the WIDER project. If WIDER was to utilize a mesh network, it could provide a better guarantee of the reliable connections for end users.

Because WiMAX is based on the IEEE 802.16a standard and this standard defines two modes of operations: (1) Point-to-Multi-Point (PMP), where the traffic is directed from the base station (BS) to the Subscriber Station (SS), or vice versa. (2) Mesh mode, where traffic flows directly among SSs, without being routed through the BS. [11] The integration between mesh networks and WiMAX will be investigated.

3.5 Mesh mode in WIDER

During disasters and emergency response, time saved often means lives saved. The mater of life and death is directly affected by whether communication or information transmission is prompt. Therefore, reliable communication and data transfer is compulsory in disaster response. Because of the unpredictable situation in the disaster area(s), WIDER should exploit redundancy. In addition, although WiMAX can offer near NLOS coverage, the complicated disaster environment may contain some obstacles preventing wireless coverage by a base station. Thus a simple point-to-multipoint solution can not provide both connectivity and extended coverage. Therefore, a mesh mode is a good choice for WIDER.

Integrating WiMAX with a mesh extension, WIDER can provide wireless access for the relief organization which can not access the base station directly either temporarily or permanently. Other relief organizations which can access the base station can be used to provide redundant routes in WIDER, thus enabling wireless access even for sites out of coverage of a given base station (See Figure 4 in section 3.7). This solution can improve WIDER's performance provided that a suitable routing policy is used. Mesh mode is another important benefit for WIDER using WiMAX.

3.6 Summary of the motivation for the use of WiMAX

Currently, there are a lot of point-to-multipoint wireless access solutions available on the market. Most of them are based on the IEEE 802.11 standard. By utilizing different antennas configurations, these solutions are optimised with regard to some performance metrics and features. However, because of the technology they use, some features, such as a NLOS coverage over long distances, are difficult to achieve. For instance, there are some wireless solutions based on the WiFi technology which can support a range as far of several kilometres. But NOLS coverage can't be achieved. Meanwhile, such optimisation will increase the cost of the solution.

As a wireless technology standard, the IEEE 802.16 offers the features WIDER requires. In addition, it can improve the WIDER solution by offering a number of QoS levels and increasing flexibility. The mesh mode supported by WiMAX can solve some problems which other point to multipoint solutions can not. Based on the analysis in the former sections, WiMAX is a good candidate for the WIDER project to provide wireless link between central system and the relief organizations' sites. Therefore, it is worth evaluating the integration of WiMAX with WIDER.

3.7 Topology of WIDER with WiMAX

Utilizing the point-to-multipoint (PMP) wireless connection provided by WiMAX, the basic topology of WIDER project is as Figure 3.

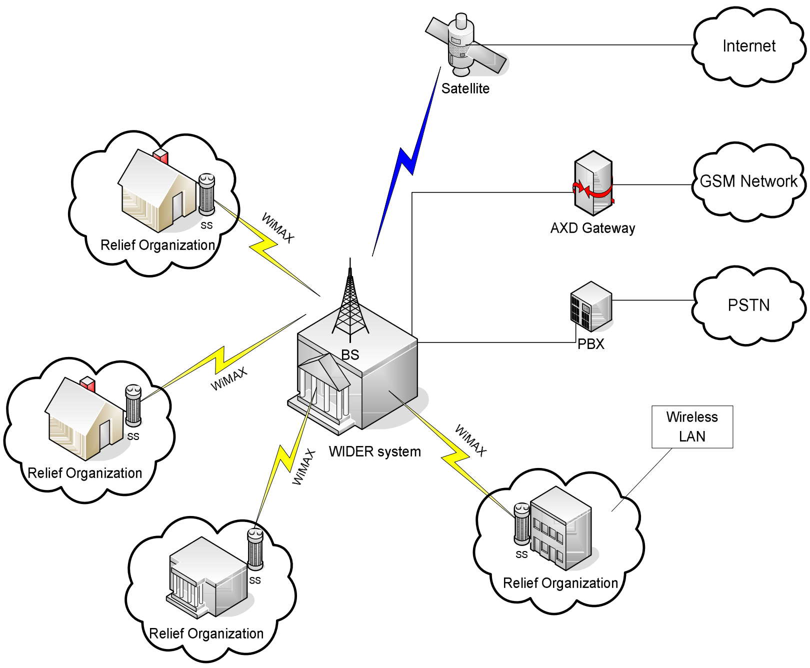

Figure 3: WIDER with WiMAX

Using mesh mode in the WiMAX solution, the WIDER project could be optimised as shown in Figure 4.

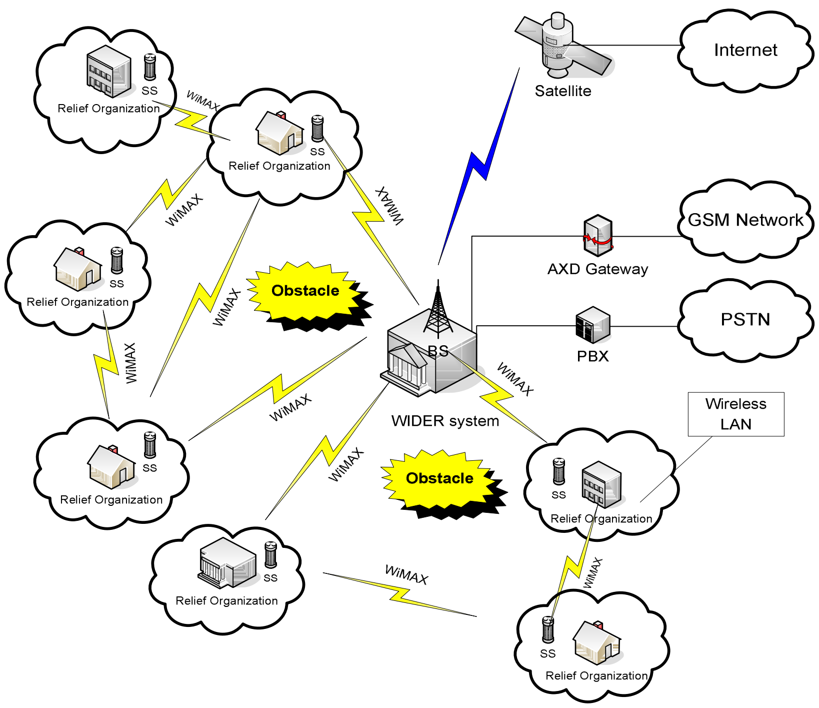

Figure 4: WIDER with WiMAX mesh mode

4. Interworking of WiFi and WiMAX

4.1 The motivation for integrating WiFi and WiMAX

WiFi certification addresses interoperability across IEEE Std 802.11 based products. IEEE 802.11 was designed to address wireless local area coverage. WiFi technology provides portable and stable wireless access using IEEE 802.11 standards with data rates ranging from 11 Mbps to 54 Mbps to the end users in a limited area. Both the good performance within hundred meters and cost effective deployment provided by WiFi have driven WiFi technology’s continuous development and wide deployment.

WiMAX was designed to provide Broadband Wireless Access following the IEEE 802.16 standards. Its advantages in range, scalability, capacity, and QoS make this emerging wireless technology attractive for situations requiring longer ranges than provided by WiFi. Intel has been working within the wireless industry to drive the deployment of both WiFi and WiMAX networks. Today, there is a perception by some, that WiFi is driving the demand for WiMAX by increasing the proliferation of wireless access, increasing the need for cost-effective backhaul solutions, and necessitating faster last-mile performance.

Currently, WiFi offers mobility, while WiMAX offers simply a long-distance point to multipoint last-mile solution. Thus, a combination of WiFi and WiMAX looks very suitable to take place of traditional cable. Since, WIDER acts as an ISP in terms of providing basic services in a disaster area, there is a need for both local and wide area connections. As described in previous sections, WiMAX is an excellent solution to provide wireless interconnections between the WIDER system and various relief organizations. While a WiFi solution is deployed inside of the relief organization’s network to provide end users with both wireless connectivity and local mobility.

4.2 Challenges

4.2.1 Quality of Service (QoS)

WiFi QoS is exclusively based on priorities. Eight different priorities can be assigned to a Data Link Control (DLC) user connection (DUC). The behavior of the MAC scheduler is based on these priorities.

WiMAX, which is based on IEEE Std 802.16, on the other hand uses service flows each containing traffic with specific QoS parameters. A service flow is a MAC transport service that provides unidirectional transport of packets either to uplink packets transmitted by the SS or to downlink packets transmitted by the BS. The service flow defines the scheduling service type to be used by the MAC layer. Four scheduling services are supported:

- Unsolicited Grant Service (UGS)

The UGS is designed to support real-time service flows that generate fixed-size data packets on a periodic basis, such as T1/E1 and VoIP without silence suppression. The service offers fixed-size grants of the channel on a real-time periodic basis, which eliminates the overhead and latency of SS requests and assure that sufficient grants are available to meet the flow's real-time needs, subject to sufficient bandwidth being available to allocation the necessary resource.

- Real-time Polling Service (rtPS)

The rtPS is designed to support real-time service flows that generate variable size data packets on a periodic basis, such as moving pictures experts group (MPEG) video. The service offers real-time, periodic, unicast request opportunities, which meet the flow's real-time needs and allow the SS to specify the size of the desired grant. This service requires more request overhead than UGS, but supports variable grant sizes for optimum data transport efficiency.

- Non Real-time Polling Service (nrtPS)

The nrtPS offers unicast polls on a regular basis, which assures that the service flow receives request opportunities even during network congestion. The BS typically polls nrtPS CIDs at an interval on the order of one second or less.

- Best Effort (BE) service

The intent of the BE service is to provide sufficient service for best effort traffic. In order for this service to work correctly, the Request/Transmission Policy setting should be set such that the SS is allowed to use contention request opportunities.

4.2.2 Congestion Control

By utilizing the interworking mechanism of WiMAX and WiFi which are proposed in the following section (Section 3), the negotiated QoS requirements can be achieved by both the WiMAX solution and the WiFi solution during the creation of new interworking connections. During the setup of a WiMAX logical link, a service flow can be created by an exchange of the dynamic service addition request (DSA-REQ) and dynamic service addition response (DSA-RSP) between the base station and the subscriber station. The creation of a specific local link is based on the QoS parameters specified in either the IP or the MAC frame. For the WiFi link, the QoS of traffic is based on the priorities assigned during the initiation of connection.

However, while packets are transported via the interworking connections, there is no mechanism adapt to the QoS parameters dynamically via any interworking mechanism. Once congestion occurs in the WiFi part or WiMAX part, two effects could occur:

- Loss of data due to buffer overflow at the interworking device (switch or access point)
- Waste of bandwidth due to the unused transmission resources.

In the interworking deployment of WiMAX and WiFi, the subscriber station in the WiMAX solution and WiFi access point act as network bridges. The data traffic is transmitted by these two nodes in store & forward manner. Once congestion occurs for the wireless link to which the data should be forward to, the device forwarding data to this link can not forward all the traffic that should go on this link due to the congestion. However, because of the lack of dynamic adaptation, the device keeps receiving the data from the other network and storing the data in the buffer. Finally, the buffer will overflow and the lost data has to be retransmitted. As a result, the retransmission of data takes up the bandwidth could have been used to send new data traffic. Let's use a scenario as an example to explain it.

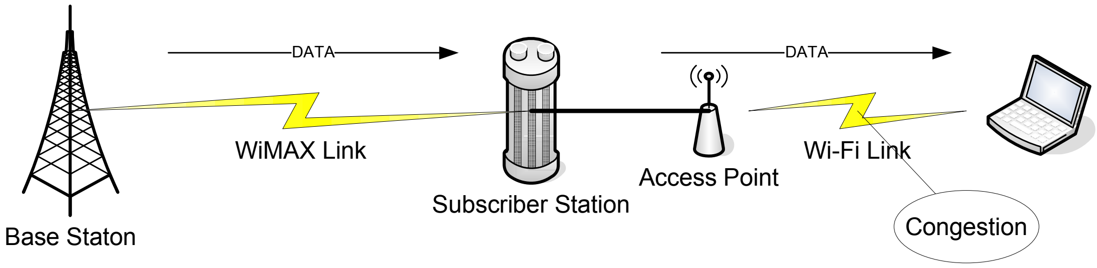

Figure 5: Downlink Transmission / The congestion occurs in WLAN network

WiMAX and WiFi transfer data at the rates which are specified according to some QoS parameters. Assuming congestion occurs in the WLAN, but the data traffic is still being transferred via the WiMAX link at the original rate to the WiFi subnet, as the WiMAX link is not aware of the congestion situation (Figure 5). The buffer in the access point or the subscriber station has to store the data. A buffer overflow will happen after a while and the lost data has to be retransmitted via the WiMAX link.

4.3 Interworking Mechanism

4.3.1 IP Layer Forwarding

The first method of interworking uses IP layer forwarding. Both wireless systems have an IP convergence layer supporting; both IPv4 and IPv6; along with functionality to support different levels of QoS. Because of the change in the IP network architecture, IPv6 supports a mechanism based on Flow Labels which is not defined in IPv4 (See Figure 6).

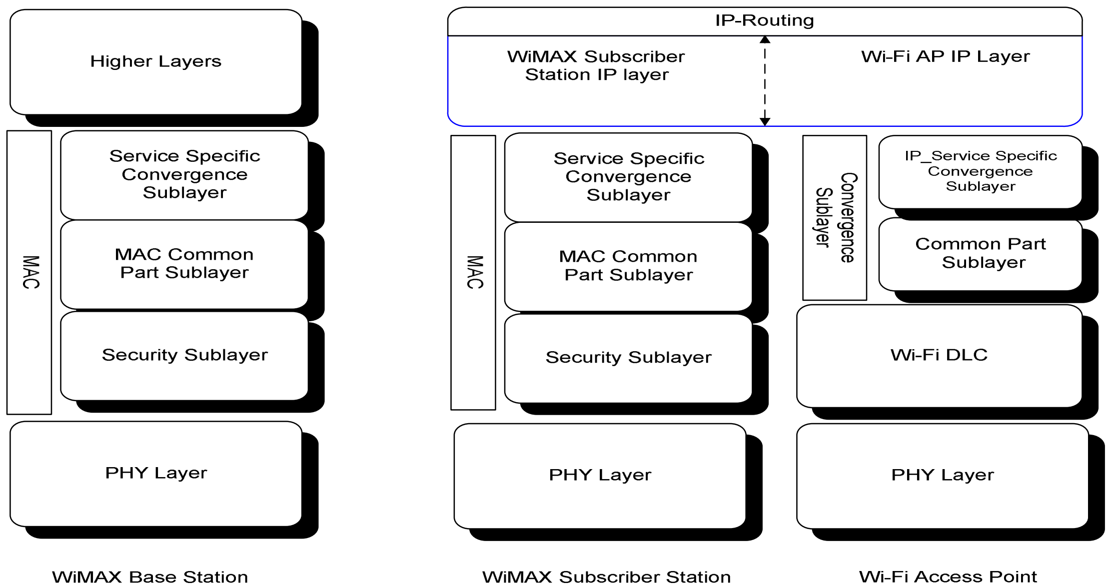

Figure 6: IP Interworking Mechanism

4.3.1.1 Priority based Interworking mechanism for both IPv4 and IPv6

The 8-bit Type of Service in the IPv4 header and the Traffic Class field in the IPv6 header are available for the originating nodes and forwarding routers to identify and distinguish between different classes or priorities of IP packets. In order to support different priorities as specified in the IP header, service flows need to be pre-provisioned and associated with these different priority levels.

Diffserv (Differentiated Services) is a protocol that defines traffic prioritization. Layer 3 network devices, such as routers, that support this protocol use Diffserv markings to identify the forwarding treatment, or per-hop behavior (PHB), that marked traffic is to receive. Diffserv markings for a packet are placed in the IP header. RFC 2474 defines the bits in the Diffserv field. The Type of Service (TOS) field in Internet Protocol version 4 (IPv4) headers and the Traffic Class field in Internet Protocol version 6 (IPv6) headers are redefined to carry Diffserv values. The first 6 bits in both Type of Service field and Traffic Class field make up the Diffserv Code Point (DSCP). The DSCP indicates how each node in the network should handle the packet. The first three bits determines the relative priority of the packet. As a result, total 8 classed have been defined, see Table 3.

Table 3: DSCP Precedence Levels

Bit 0,1 and 2 of the DSCP	Precedence Level	
111	Precedence 7	Link layer and routing protocols
110	Precedence 6	IP routing protocols
101	Precedence 5	Expressed Forwarding
100	Precedence 4	Assured Forwarding Class 4
011	Precedence 3	Assured Forwarding Class 3
010	Precedence 2	Assured Forwarding Class 2
001	Precedence 1	Assured Forwarding Class 1
000	Precedence 0	Best Effort

4.3.1.2 Flow Label based Interworking Mechanism for IPv6

The 20-bit Flow Label field in the IPv6 header may be used by a source to label sequences of packets for which it requests special handling by the IPv6 routers, such as non-default quality of service or "real-time" service. In order to specify explicit QoS requirements within the IPv6 header, a proposed format for IPv6 Flow Label field is used.

Table 4: Proposed format for IPv6 Flow Label field

Index	Reserved			Counter				Delay				Jitter				Bandwidth			
0	0	1	2	0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3

By means of these new mechanisms of the IPv4 and IPv6 header, specific QoS requirements could be announced to all systems serving the IP packet from the source to the destination. In the priority based interworking mechanism, the DSCP value announced in Type of Service in IPv4 and Traffic Class in IPv6 could be mapped onto the WiMAX Service Flow or the WiFi priority.

In a WiMAX system based on IEEE Std 802.16-2004, the Packet Convergence Sublayer takes charge of classification of the IP packets. IP Type of service/differentiated services code point (DSCP) range and mask file specify the matching parameters for the IP type of service/DSCP byte range and mask. An IP packet with DSCP value matches this parameter if tos-low <= (ip-tos AND tos-mask) <= tos-high. During the initiation of a connection between BS and SS, a WiMAX Service Flow can be created via the dynamic service addition process based on the Flow Label QoS parameters in IPv6 or the priority parameters in both IPv4 and IPv6. A set of Type/Length /Value (TLV) encoded parameters are used in Dynamic Service messages, including QoS-related encodings, packet classification rule, classifier rule priority. A CID is assigned to the Service Flow and a classifier is set up including the source address and if possible the criteria Flow Label. During an active connection all IP packets matching the classifier are mapped onto the assigned CID. The Convergence Sublayer (CS) in either BS or SS takes charge of mapping the data traffic from the layer above into the service flow of connection. Packets belonging to the CID and therewith the corresponding Service Flows are scheduled in the MAC layer in such a way that the QoS requirements are fulfilled.

Since IEEE 802.11 only supports priority based QoS mechanism, the DSCP value can be used as the priority parameter for the connections. WiFi systems achieve the QoS requirements by reading the DSCP value in Traffic Class field in the IPv6 header.

4.3.1.3 The performance of IP Interworking Mechanism

In IPv4 network architecture, only priority based QoS is supported due to the definition of IPv4 header. As a result, the IP Interworking Mechanism has a limited performance in QoS supporting. Since the priority parameter specified in the IP header is the only source for this interworking mechanism, a low implementation complexity is the advantage for IP Interworking Mechanism. No changes are required for the standards or specification of either IEEE 802.11 or IEEE 802.16.

In IPv6 network architecture, a better QoS performance is achieved by IP Interworking Mechanism because both Traffic Class and Flow Label fields in IPv6 header define more QoS parameters. However, this interworking mechanism for IPv6 requires the WiFi system and WiMAX system be able to read and interpret the IPv6 header to get QoS demands of traffic. There are some changes to the standards.

4.3.2 Ethernet

Both IEEE 802.16 based WiMAX and IEEE 802.11 based WiFi have the same interface at the logical link control layer (LLC) as IEEE 802.3 Ethernet. Hence, Ethernet bridging approach is specified as another interworking mechanism between WiMAX and WiFi (See Figure 7).

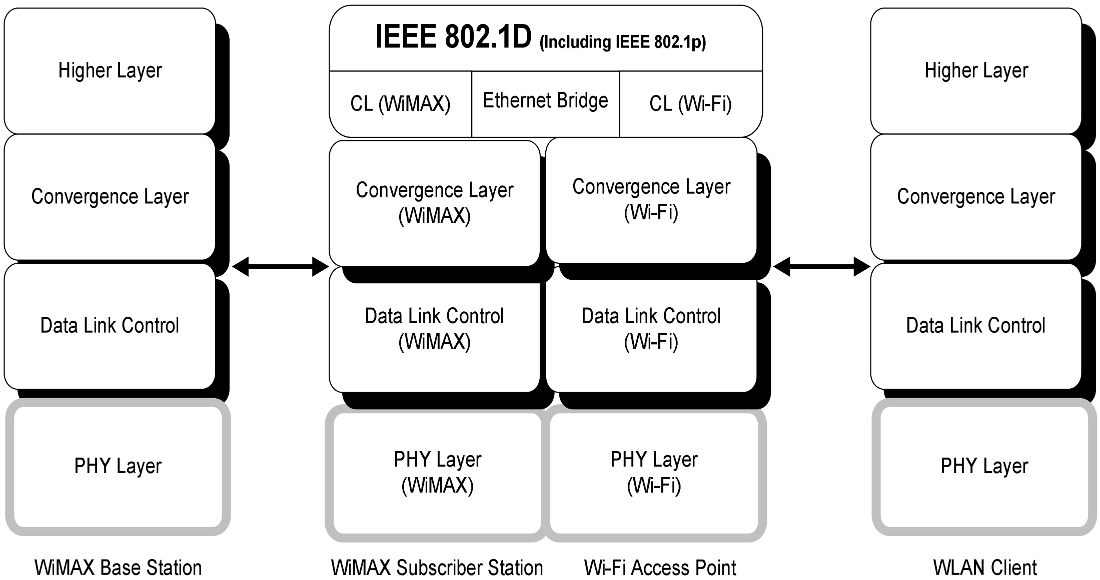

Figure 7: Ethernet Interworking Mechanism

4.3.2.1 QoS on MAC layer

The 802.1p standard covers traffic class expediting and dynamic multicast filtering of media access control (MAC) bridges, which is known as the IEEE standard 802.1D. IEEE 802.1p specification enables Layer 2 switches to prioritize traffic and perform dynamic multicast filtering. The prioritization specification works at the media access control (MAC) framing layer (OSI model layer 2). The 802.1p standard also offers provisions to filter multicast traffic to ensure it does not proliferate over layer 2-switched networks.

The 802.1p header includes a three-bit field for prioritization, which allows packets to be grouped into various traffic classes. The Ethernet packet is mapped onto 8 types of traffic with different priority according the three-bit field. IEEE 802.1D bridge will distribute packets between WiMAX, WiFi, or Ethernet-based devices.

4.3.2.2 Interworking Mechanism

IEEE Std 802.16-2004 defines Packet Convergence Sublayer taking charge of classifying the upper layer packet traffics. During the initiation of the services flow or the management of the service flow, the Packet classification rule is encoded in Dynamic Service messaging. This compound parameter contains the parameters of the classification rule. All parameters pertaining to a specific classification rule shall be included in the same Packet Classification Rule compound parameter. In this compound, there is IEEE 802.1D user_priority field specifies the matching parameters for the IEEE 802.1D user_priority bits. An Ethernet packet with IEEE 802.1D user_priority value "priority" matches these parameters if priority is greater than or equal to pri-low and priority is less than or equal to pri-high. The classification between every incoming packet and a specific CID, which identifies a specific service flow, is made according to the IEEE 802.1D User Priority bits.

On WiFi side, the Ethernet packets come from the Higher Layers (HLs), containing the user priority coded with 3 bits. The Ethernet Specific Service Convergence Sublayer (SSCS) user plane includes the traffic class mapping according to 802.1p. This function provides the mapping of different traffic classes to different priority queues, depending on how many priority queues are supported. Different traffic classes are mapped to different DLCCs (Data Link Control Connection). After connection setup the RLC (Radio Link Control) indicates which DLCC_IDs have been assigned to DLCCs in a list and traffic classes are mapped to DLCC_IDs depending on the numerical order of the value of the DLCC_IDs.

In case of IP traffic, Ethernet based Interworking Mechanism can be used also. The IP packet is inserted in an Ethernet frame and the DSCP field is mapped onto the IEEE 802.1p field. Then the frame is forwarded into the access network according to the user priority value.

4.3.2.3 The performance of Ethernet Interworking Mechanism

This kind of interworking mechanism has the same performance in QoS supporting as IP Interworking Mechanism for IPv4. Only priority based QoS is achieved due to the QoS supported by MAC layer. Additionally, the complexity of implementation is low.

Since this mechanism is deployed on link layer via the 802.3 network interface, it makes the integration into existing network infrastructures much easier. Compared with IP interworking mechanism, it uses the IEEE MAC address to identify terminals. No any information about how to reach the destination is required.

5. WiMAX solution integration

In the first half of 2005, Intel Corporation announced the availability of its first WiMAX product, providing equipment manufacturers and carriers the ability to deliver next generation wireless broadband networks around the world. The Intel® PRO/Wireless 5116 broadband interface device is based on the IEEE 802.16-2004 standard, giving carriers and end-users the confidence that equipment from different vendors will work together. After the release of the Intel® PRO/Wireless 5116 broadband interface device, several vendors announced that their first release of pre-WiMAX solutions were available in the market. WiMAX forum started the WiMAX certification process from July of 2005. Certification will address both stationary (based on the IEEE 802.16-2004 and current ETSI HiperMAN standards) and portable/mobile platforms (based on the IEEE802.16e). Currently, the certification for stationary WiMAX solution is ongoing. Initial profiles for testing will include the 3.5 GHz FDD and TDD systems for 3.5 MHz channel bandwidth. WiMAX Forum Certified equipment from multiple vendors was expected for commercial availability towards the end of 2005. Certification of additional profiles, including the 5.8 GHz profile, was expected to begin in 2006. [19]

In this chapter, I will introduce the WiMAX solution used by the WIDER project and give details regarding the configuration and integration.

5.1 WiMAX solution with point-to-multipoint mode

Although both the IEEE 802.16-2004 and current ETSI HiperMAN standards are specified as the standards of the WiMAX certificate product by WiMAX Forum, most of the vendors claimed that their WiMAX solutions are built from the ground up based on the IEEE 802.16-2004 standard. In the IEEE 802.16-2004 specification, two network topologies are motivated as the examples for sharing wireless media. They are PMP (Point-To-Multipoint) mode and Mesh mode. In accordance to section 3.5 above, mesh mode can improve the efficiency and redundancy for the WIDER system in the complicated disaster environment. However, currently, all of the vendors focus on producing the first release of the WiMAX solution which offer only the basic functionalities and wireless network services. The next generation of WiMAX product supporting mobility which is based on the IEEE 802.16e standard will become available soon. As an extension of the specification, mesh mode is not the main demand of customers. Therefore, mesh mode will be a future work according to the progress of the WiMAX industry.

As one of the motivations to utilize WiMAX in the WIDER project, the Point-To-Multipoint (PMP) topology is deployed within the WiMAX solution (Figure 3). [16] gives a detailed description of the PMP mode in the MAC common part sublayer. In PMP mode, the downlink, from the BS to the SS and the user, is generally broadcast. The IEEE 802.16 standard wireless link operates with a central BS and a sectorized antenna that is capable of handling multiple independent sectors simultaneously. Within a given frequency channel and antenna sector, all stations receive the same transmission, or parts thereof. The BS is the only transmitter operating in this direction, so it transmits without having to coordinate with other stations, except for the overall time division duplexing (TDD) that may divide time into uplink and downlink transmission periods. Subscriber stations share the uplink to the BS on a demand basis. Depending on the class of service utilized, the SS may be issued continuing rights to transmit, or the right to transmit may be granted by the BS after receipt of a request from the user.

For the purposes of mapping to services on SSs and associating varying this with a particular level of QoS, all data communications are in the context of a connection. The concept of a service flow on a connection is central to the operation of the MAC protocol. Service flows provide a mechanism for uplink and downlink QoS management. An SS requests uplink bandwidth on a per connection basis. Bandwidth is granted by the BS to an SS as an aggregate of grants in response to per connection requests from the SS. Service flows may be provisioned when an SS is installed in the system. Shortly after SS registration, connections are associated with these service flows to provide a reference against which to request bandwidth.

5.2 BreezeMAX solution from Alvarion

In this chapter, I introduce the WiMAX solution pursued for the WIDER project. I have used Alvarion's BreezeMAX family members: the MicroMAX Base Station and BreezeMAX CPE. I will give a short description on the BreezeMAX family, and then focus on the features of the specific products selected.

5.2.1 BreezeMAX

BreezeMAX 3000 is Alvarion's WiMAX platform for the licensed 3.5 GHz frequency bands. It leverages Alvarion's market-leading knowledge of Broadband Wireless Access (BWA), industry leadership, proven field experience, and core technologies including many years of experience with OFDM technology. Built from the ground up based on the IEEE 802.16/ETSI HIPERMAN standards, BreezeMAX 3000 is designed specifically to meet the unique requirements of the wireless Metropolitan Area Network (MAN) environment and to deliver broadband access services to a wide range of customers, including residential, SOHO, SME and multi-tenant customers. Its Media Access Control (MAC) protocol was designed for point-to-multipoint broadband wireless access applications, providing a very efficient use of the wireless spectrum and supporting difficult user environments. The access and bandwidth allocation mechanisms accommodate hundreds of subscriber units per channel, with subscriber units that may support different services to multiple end users.

The system uses OFDM radio technology, which is robust in adverse channel conditions and enables operation in non line of sight links. This allows easy installation and improves coverage, while maintaining a high level of spectral efficiency. Modulation and coding can be adapted per burst, to achieve a balance between robustness and efficiency in accordance with prevailing link conditions.

BreezeMAX supports a wide range of network services, including Internet access (via IP or PPPoE tunnelling), VPNs, and Voice over IP. Service recognition and multiple classifiers that can be used for generating various service profiles enable operators to offer differentiated SLAs with committed QoS for each service profile.

A BreezeMAX system comprises the following:

- Customer Premise Equipment (CPE): BreezeMAX Subscriber Units and Alvarion's Voice/Networking Gateways.
- Base Station (BST) Equipment: BreezeMAX Base Station equipment, including the modular Base Station and its components and the stand-alone Micro Base Station.
- Networking Equipment: Standard switches/routers and other networking equipment, supporting connections to the backbone and/or Internet.
- Management Systems: SNMP-based Management, Billing, and Customer Care, and other Operation Support Systems.

Figure 8 shows the BreezeMAX system architecture.

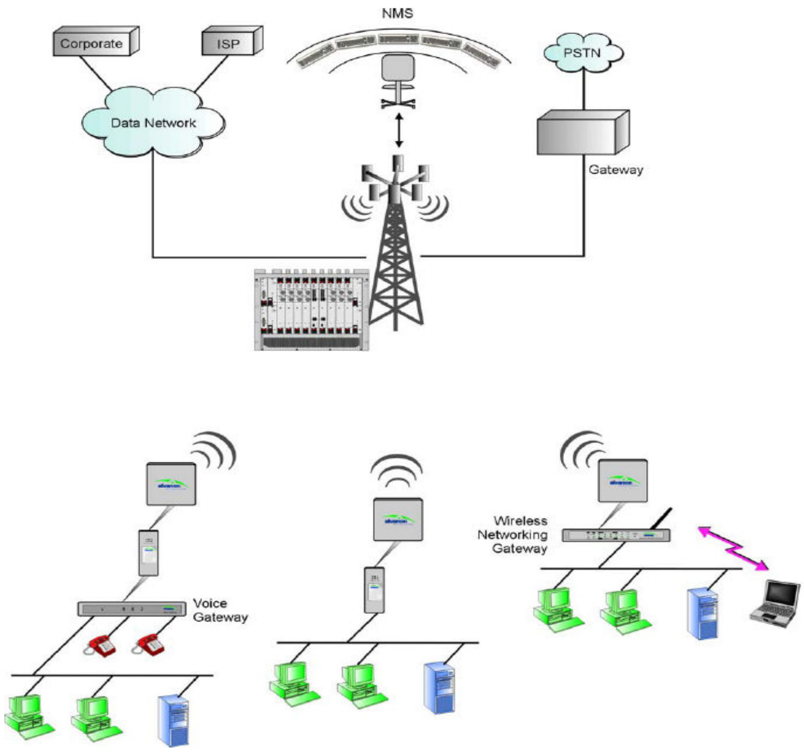

Figure 8: BreezeMAX system architecture

NMS: Network Management System

5.2.2 Micro Base Station

The BreezeMAX Base Station Equipment includes a modular Base Station that can serve up to six sectors and a stand-alone Micro Base Station. The multi carrier, high power, Full Duplex Base Station and Micro Base Station provide all the functionality necessary to communicate with subscriber units and to connect to the backbone of the Service Provider.

The Micro Base Station Unit is designed to provide an alternative to the BreezeMAX Modular Base Station at a low cost in places were the number of subscribers is limited, and only one or two sectors are necessary (i.e. communities). The Micro Base Station equipment comprises an indoor Micro Base Station Unit and an outdoor radio unit (AU-ODU). Figure 9 and Figure 10 show the pictures of these two units.

Figure 9: Micro Base Station Indoor Unit

Figure 10: Micro Base Station Outdoor Unit

The functionality of the Micro Base Station indoor unit includes:

- Backbone Ethernet connectivity via a 10/100 Base-T network interface
- Traffic classification and connection establishment initiation
- Policy based data switching
- Service Level Agreements management
- Centralized agent for managing the Micro Base Station unit and all registered CPEs.

The AU-ODU of the Micro Base Station is a high power, full duplex multi-carrier radio unit that connects to an external antenna. It is designed to provide high system gain and interference robustness by utilizing high transmit power and low noise figure. It supports up to 14 MHz bandwidth, enabling future options such as increased capacity through the use of a multiplexer or some larger channels (e.g. 7/14 MHz).

The motivation to select the Micro Base Station was because of the consideration of the requirements of WIDER. First of all, as a communication system in a disaster area, the capacity of the network required by the relief organizations is hundreds of users. Normally, there are no huge limited amounts of traffic, because the goal of WIDER is to provide an efficient way for the users to exchange information, not to provide the services offered by a high capacity backbone network. Comparing with the other products in the BreezeMAX family, the Micro Base Station is designed at a low cost which is around ten thousand dollars. From the description above, the Micro Base Station may be a better option to provide a cost effective, scalable WiMAX-ready base station solution for maximum return from their network deployment, especially targeted for low-density or rural areas. Secondly, one of the goals of WIDER is easy deployment and portability. The dimensions of Micro Base Station IDU are 5.1cm in height, 44.4cm in length and 27.2cm in width. Its weight is 3 kg. The dimensions of Micro Base Station ODU are 31.5cm in height, 15.7 in width, and 8.8 in thickness. Its weight is 2.9kg. Currently, in order to optimise the shipment and deployment of the WIDER system, all the equipment of the WIDER system is installed in a portable case. There is enough space for two Micro Base Stations. All of these statistics are suitable for the WIDER system.

5.2.3 Subscriber Station

A Subscriber Station (SS) is also called Customer Premises Equipment (CPE). All the Subscriber Stations in BreezeMAX family are installed at the customer premises; this consists of an Outdoor Unit (ODU) and an Indoor Unit (IDU). Figure 11 shows the ODU of the CPE and a Basic IDU of the CPE.

Figure 11: CPE ODU and CPE Basic IDU

The ODU includes the modem, radio, data processing, and management components of the SU, serving as an efficient platform for a wide range of services. It also includes an integral high-gain flat antenna or a connection to an external antenna. The ODU provides data connections to the Access Unit (AU), providing bridge functionality, traffic shaping, and classification. It connects to the IDU and to the user's equipment through a 10/100BaseT Ethernet port, and it can support up to 512 MAC addresses. The ODU unit included in our WiMAX solution is the WiMAX-ready PRO CPE ODU which is powered by Intel's Pro/Wireless 5116 WiMAX chip.

The indoor unit is powered from mains power and connects to the ODU via a Category 5E Ethernet cable. This cable carries Ethernet data frames between the two units as well as providing power and control signals to the ODU. Two types of indoor units were selected for the solution:

- Basic IDU, functioning as a simple interface unit with a 10/100BaseT Ethernet port that connects to the user's equipments. (Figure 12).

Figure 12: BreezeMAX CPE Basic IDU

- Wireless Networking Gateway. It provides advanced routing capabilities and can also serve as a Wireless LAN Access Point. Figure 10 is the picture of a Wireless Networking Gateway.

Figure 13: Wireless Networking Gateway

6. Test Scenarios

In order to evaluate the performance of WiMAX and to verify the parameters concerning the integration of the WIDER system and the BreezeMAX solution, a series of test scenarios were configured. All of the tests were done in cooperated with Ericsson's WiMAX Lab in Linköping, Sweden.

In accordance with the test environment, the tests are divided into two categories, lab tests and live tests. This chapter gives a detailed description of all the test scenarios. The measurements and analysis will be described in Chapter 7.

6.1 Lab tests

Unlike the fixed network system, the performance of the wireless system is very sensitive to the radio environment which is difficult to control or simulate. The lab tests focus on testing some important metrics of the communication system in an ideal test environment. The purpose of the lab test is to understand the performance of WiMAX without interference. The test results are used as a reference for live tests.

The lab tests concentrate on two aspects:

- The throughput of the end user access to the core network through the WiMAX solution
- The QoS of WiMAX

6.1.1 Test bed overview

All the lab tests were deployed in Ericsson's WiMAX Lab. The purpose of the throughput test and QoS test is to evaluate the performance of the BreezeMAX Micro Base Station and CPEs in an ideal environment. The test bed set up by Ericsson's WiMAX Lab was adopted. The motivation to use their test bed was that it was designed for professional testing scenarios of WiMAX solutions. Before testing the BreezeMAX solution, a great variety of lab tests using other WiMAX solutions had occurred. Hence, the reliability of the test bed has been proven.

The whole test environment is divided into a core network and a client network. The WiMAX solution is integrated between the core network and the client network. It provides the wireless access for clients in the client network. The architecture of the system under test is shown in Figure 14.

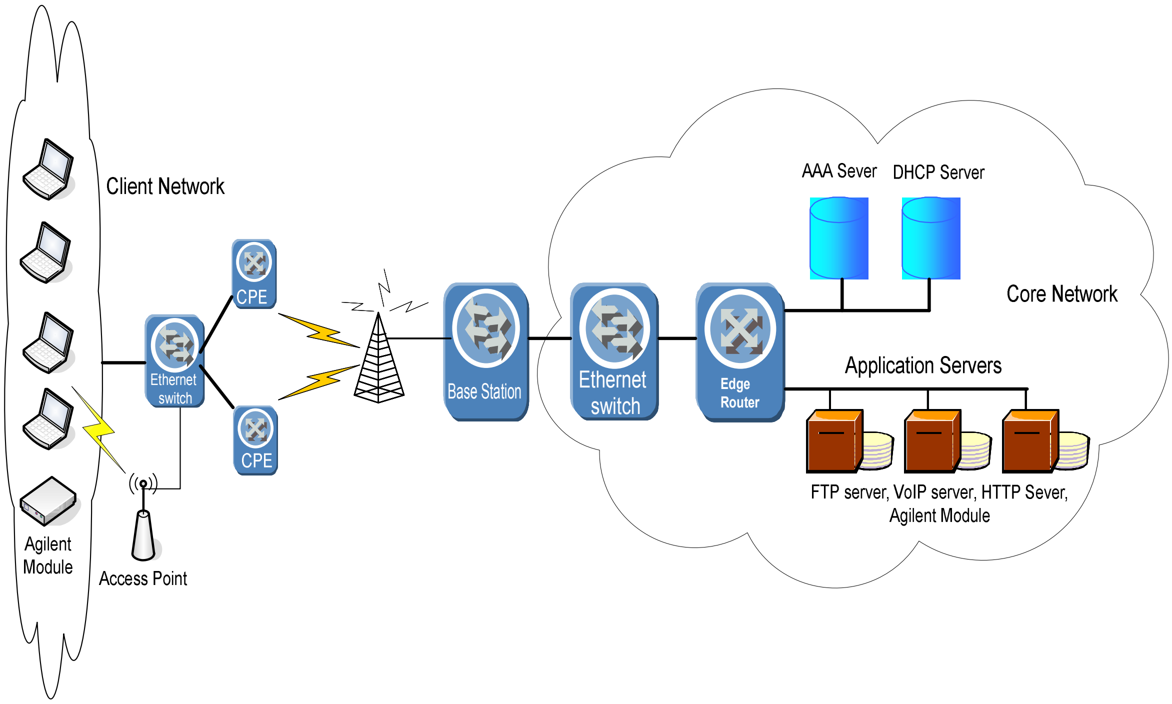

Figure 14: Lab Test System

In the core network, the Ethernet Switch takes charge of VLAN tagging and traffic classification. In order to minimize the complexity of the network and provide transparent network configuration, the functionalities of the Ethernet switch were disabled. On the Edge Router there are separate IP Gateways configured for the different services (Internet, VoIP and Video Services). Depending on the IP Gateway, the Edge Router routes the end user traffic to the different networks providing specific services. The AAA server is simply used to authenticate the end user, and then authorize them to utilize the network. When the CPEs and all the clients gain the access to the core network through the WiMAX link, they are assigned IP address by the DHCP server in the core network. Static IP address configuration (manually) is not used.

The Agilent modules in both the core network and client network are used to simulate the voice traffic for QoS tests. The details can be found in section 6.1.6.

In the lab test, the radio connection between BS and CPE is simulated by the RF cables, attenuators, and a power divider/combiner. The specification of the simulation is in Table 5.

Table 5: Radio link simulation Specification

Name of the component	Description
RF cable OAC LMR-400-1-1	Outdoor unit to Antenna Cable, for signal transmission between Micro Base Station ODU and antenna: 1m. Connectors: N male / N male 90 degree angle. Total loss @ 2.4 / 2.6 / 3.5 / 3.8 GHz: 1dB
RF cable MIL-C-17F RG	Used for signal transmission between CPE outdoor unit and the integrated antenna.
Attenuator	80 dBm attenuator. Used to reduce the input power for both BS and CPE to avoid damaging the equipment. The value is calculated based on the maximum input power and output power of the BS ODU and the CPE ODU (see Appendix A, radio specification).
Power divider/combiner	Providing two connectors for two CPE ODUs to connect to a single BS ODU

Figure 15 shows the detailed datagram of the radio link simulation in the lab tests.

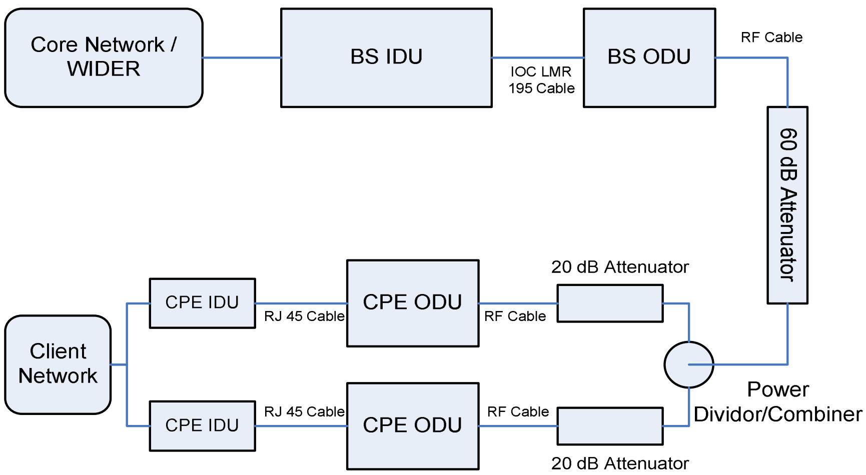

Figure 15: Radio Link Simulation

6.1.2 Hardware and Software

Table 6 describes the hardware and software used for the lab tests.

Table 6: Hardware and Software for lab test

Name		Description
Hardware	Servers	Providing services, DHCP, AAA, FTP, HTTP, and VoIP, etc.
	Juniper Router	Configured to be IP gateways for the different services (Internet, VoIP, and Video Services).
	Extreme Network Summit48i	Used as normal layer 2 switch in the lab tests
	BMAX-MBST-IDU-2CH-AC	BreezeMAX Micro Base Station Indoor Unit, AC power. Capacity limited to 20 CPEs.
	BMAX-BST-AU-ODU-2CH-3.5	BreezeMAX Base Station Outdoor Radio Unit with RF connector for a separate external antenna. The frequency is 3.5 GHz.
	BMAX-CPE-IDU-1D	BreezeMAX CPE indoor unit with one 10/100 Base-T Data Port. This CPE IDU is easy to use without extra configuration.
	BMAX-CPE-ODU-PRO-AC-3.5	BreezeMAX CPE outdoor unit with integrated vertical antenna. Receive frequency is on 3.5 GHz-3.6 GHz, transmit frequency is on 3.4 GHz-3.5 GHz, 100 MHz separation.
	Agilent Network Tester (Agilent N4190A)	Agilent Network Tester has ability to simultaneously emulate real voice, video, data, P2P traffic and millions of clients, servers. It can provide reliable test results efficiently. Agilent Network Tester is used in the QoS test to simulate voice traffic and parameters collection.
	Access Point	Cisco Aironet 1100
	4 Hewlett-Packard nc6000 laptops	2 of them are used to configure and monitor BS and CPEs. The rest 2 laptops are used as end users in client network.
Software	Alvarion BreezeLITE	Alvarion's BreezeLITE is a Simple Network Management Protocol (SNMP) application designed for on-line management of BreezeMAX system components. This utility simplifies the installation and maintenance of small size installations by easily enabling the change of settings or firmware upgrade for one Micro Base Station at a time (including the managed device's components and associated CPEs) and collecting and viewing performance data from selected system components.
	Hyper Terminal	To access the monitor program in Micro Base Station via a serial port (COM port in Window's operating systems).
	Wget / Wput	FTP client for downloading and uploading files on Microsoft Window operating system. The programs can provide the real time throughput parameters, the average throughput of a session, and the connection duration.
	Ethereal	Protocol Analyzer, http://www.ethereal.com. It is used to monitor the traffic and trouble shooting.
	Ping	The command used for testing round trip time (RTT) using an ICMP packet.
	Putty	Telnet client to access to both the BS IDU and the CPE ODU.

6.1.3 The configuration of BreezeMAX Micro Base Station and CPE

This section describes the detailed configuration of the BS in Table 7, and the configuration of the CPE ODU in Table 8.

Table 7: Micro Base Station Configuration

Parameter	Value	Comments
Management Port		
Port MAC Address	00-10-e7-22-4a-4d	Derived from the hardware
Port IP Address	10.0.0.1	Default value. It is used by BreezeLITE to access BS and CPE configuration interface.
Port Subnet Mask	255.255.255.0	Default value
Port Gateway	0.0.0.0	Default value. No gateway configured
Port Destination Subnet	0.0.0.0	Default value. No destination network
Port Destination Subnet Mask	0.0.0.0	Default value. No destination network
Port Auto Negotiation	Enabled	Default value. When the Auto Negotiation Option is enabled, the Speed and Duplex parameter in the relevant Show menus displays the detected operation mode. When the Auto Negotiation Option is disabled, the Speed and Duplex parameter in the relevant Show menus displays the configured operation mode.
Port Speed and Duplex	10 Mbps Half Duplex	Because Auto Negotiation is enabled, the port speed and duplex is detected by itself to give maximum throughput.
Data Port		
Port MAC Address	00-10-e7-22-4a-4c	Derived from the hardware
Port IP Address	10.16.255.240	Assigned by DHCP server dynamically.
Port Subnet Mask	255.255.0.0	Assigned by DHCP server dynamically.
Port Gateway	10.16.0.1	The IP address of the Edge Router in the core network. Configured manually.
Port Management VLAN ID	No VLAN	In order to simplify the network configuration, VLAN is disabled.
Port Auto Negotiation	Enabled	Default value. Referring to the comments of Management Port Auto Negotiation.
Port Speed and Duplex	100 Mbps Full Duplex	Because Auto Negotiation is enabled, the port speed and duplex is detected by itself to give maximum throughput.
Authorized Manager		
IP Address	10.0.0.10	Manually define the IP address of the management station that is allowed to manage the Micro Base Station.

Parameter	Value	Comments
Send Traps	Disable	Disable sending traps to the management station.
Read Community	Public	The SNMP Read Community string to be used by the authorized manager for read-only operations.
Write Community	Private	The SNMP Read Community string to be used by the authorized manager for write/read operations.
Air Interface		
Base Station ID	186.190.0.0.250.206	The Base Station ID is the unique identifier of a Micro Base Station. A CPE can be authenticated by a Micro Base Station only if the Base Station ID and Base Station ID Mask in the CPE match the Base Station ID configured in the Micro Base Station.
ARQ Status	Disabled	The ARQ Status parameters control whether or not to use an ARQ algorithm for detecting errors and requesting retransmissions of unicast messages.
Maximum Cell Radius (km)	20	It is fixed value for Micro Base Station
Bandwidth (MHz)	3.5	The available options are: 1.75 MHz and 3.5 MHz. 3.5 MHz is selected for better performance.
Downlink (Tx) Frequency (MHz)	3529.25	This frequency is rent only for the live test. In order to coordinate with the live test, we have configured the same frequency for the lab test also.
Tx Power	28	The power level of the transmitted signal at the antenna port of the BS ODU. The range is from 13 to 28 dBm, It is configured to provide the max power.
Multirate Support	Disable	The Multirate Support parameter controls whether or not the multirate algorithm will be used to determine current optimal rates in both the uplinks and downlinks. It is disabled in the lab test because the modulation should be changed manually for testing. It is enabled for the live test.
Uplink Basic Rate	BPSK ½	When Multirate Support is enabled, it defines the basic rate for uplink.
Downlink Basic Rate	BPSK ½	When Multirate Support is enabled, it defines the basic rate for downlink.
ATPC Support	Enable	The Automatic Transmit Power Control (ATPC) Support parameter controls whether or not the ATPC algorithm will be used to determine optimal transmit level for each of the CPEs served by the Micro Base Station.

Table 8: CPE ODUs Configuration

Parameter	Value	Comments
Configured Common Name	wider_cpe1 / wider_cpe2	The name the CPE registered in the BS.
Organization	WIDER	Optional
Address	Kista	Optional
Country	SWE	Optional
Base Station ID and Mask	186.190.0.0.250.206 / 255.255.255.0.0.0	It should be configured the same as the base station the CPE is going to register and connect.
Bandwidth (MHz)	3.5	The same as the base station
Uplink Frequency	3429.25	According to the specification of CPE ODU (Table 4), there are 100 MHz separation between receive frequency and transmit frequency.
Uplink Rate	BPSK ½	In the lab test, when Multirate Support is disabled, this parameter is configured manually according to the test scenario. In the live test, when Multirate Support is enabled, the rate is determined by the algorithm.
Downlink Rate	BPSK ½	The same as above.

6.1.4 Service Configuration

A service is a virtual connection between a Subscriber's application and a network resource. The network resource could be an Internet connection (gateway), a server operated by a Content Provider, a gateway to a corporate network, etc. The services are implemented as IEEE 802.16 connections within the wireless domain. Each Service can include up to 4 uplink and 4 downlink connections. Different QoS profiles can be assigned to these four connections. The data frames are mapped onto these connections by either IEEE 802.1p or DSCP priority tags.

Three service types are supported currently by the BreezeMAX solution.

- L2 (layer 2) Data Service
- PPPoE Data Service
- Voice Service

We named "Basic Service" which is defined to provide the best effort service for the traffic. Since WIDER aims at providing a communication system that can be easily installed and deployed, it is important to simplify the responsibility of the administrator of the system. The motivation to test with this kind of QoS profile is to evaluate the basic performance of WiMAX without complicated transmission policy. It could be used as the reference for the further development and configuration of the WiMAX solution with WIDER in future. The detailed configuration can be found in Table 9.

Table 9: Basic Service configuration

Parameter	Value	Comments
Priority Classifier		
Name	Basic service	Configured name for the service
Priority Type	802.1p	Since no priority profile is defined during the test using this service, both 802.1p and DSCP can be selected.
Uplink QoS profile	BE 12000	Best Effort (BE) service with MIR equals to 12 Mbps.
Downlink QoS profile	BE 12000	The same as above
MIR (Maximum Information Rate)	12000	The maximum information rate that the system will allow for the connection. The range is from 1 to 12000 Kbps. 12000 is configured to guarantee the maximum allowed data rate.
Priority Limits	7	This parameter enables to define the ranges, where a different QoS Profile can be assigned to each range. Since only one QoS Profile is defined here, and 802.1p is configured as priority type, the upper limit of 802.1p priority is used to guarantee all the traffic is assigned with the same QoS Profile.
Forwarding Rule		
Name	Basic service	Configured name for the rule
Type	L2	Transports layer 2 (Ethernet) frames between the subscriber's site and the network resource.
Multicast QoS Profile	BE 12000	Best Effort service with MIR equals to 12 Mbps.

6.1.5 Throughput Test

The purpose of the throughput test is to learn the data throughput that an end user might obtain through the WiMAX link with different modulation and different client network topologies. Three throughput test cases are defined in Figure 16, Figure 17, and Figure 18.

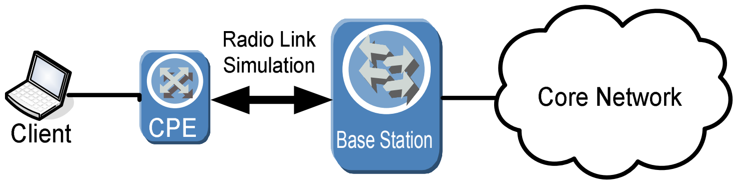

Figure 16: Basic throughput test towards one CPE

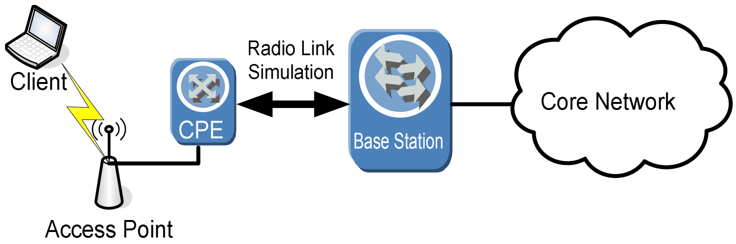

Figure 17: Throughput test with WLAN towards one CPE

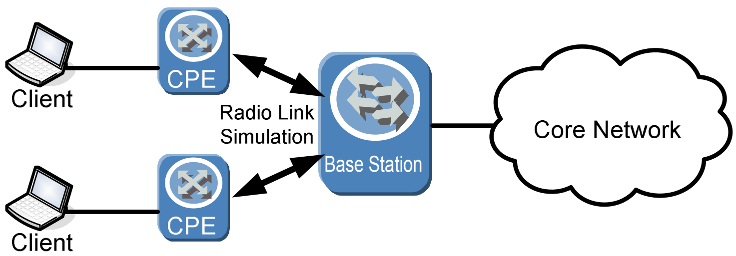

Figure 18: Basic throughput test towards two CPEs

In Figure 17, the WLAN provided by an IEEE 802.11g access point was configured for the end client. "Basic service" QoS profile is used in all three test cases. FTP traffic is used as the test traffic. As a result, all the FTP traffic in these throughput tests is assigned the same QoS, which makes the test results comparable. For the two test cases with one CPE, the download session and the upload session are tested separately in the client first. Then one download and one upload session are run simultaneously in the client, the throughput for each session is recorded. For the last test case, the download session is tested in both of the two clients at the same time, then the same test is repeated with an upload session in both clients. Finally, one download session is established in one client. Meanwhile, one upload session is established in the other client. Since eight modulations were tested, the lowest data rate on the downlink is around 1 Mbps. Considering the time spent on each test, a 32 Mbytes .txt file is used for downloading and uploading. The average throughput of both download and upload session is provided by Wget and Wput respectively.

6.1.6 QoS Test

The purpose of this series of tests is to learn and verify parameters concerning the QoS of the WiMAX solution. As a conceptual term, QoS is defined as qualitative (e.g. class of services) or quantitative (e.g. bandwidth) attributes of network service provided. QoS is a major issue in VoIP implementations. Therefore, VoIP traffic is selected as the test traffic. For the end user, the delay, jitter, and packet loss are the metrics that determine the quality of the VoIP call. As the different modulations with different data rate are adopted by WiMAX, the throughput is the one should be taken into account. These four metrics are the parameters tested. In order to guarantee the reliability and diversity of test scenario, the Agilent Network Tester is used to simulate the VoIP traffic in the different test cases because of powerful ability to emulate traffic, for both clients and servers. Two Agilent Network Tester modules were configured in the core network and the client network respectively. The one connected to the CPE acts as the caller to initiate the VoIP call sessions. Because most of the time, it is the client that starts the call. The other tester in the core network is configured as the callee. Another laptop client is connected to the CPE to measure the latency. This laptop also generates FTP traffic for two test cases. The detailed topology is shown in Figure 19.

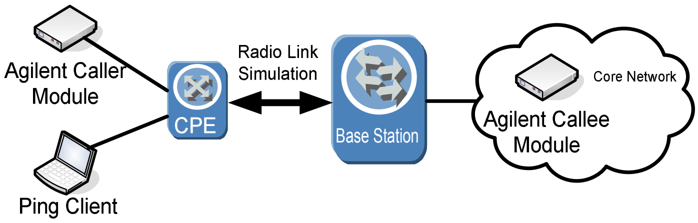

Figure 19: QoS test with VoIP traffic and latency test.

Session Initiation Protocol is adopted to create, modify, and terminate the VoIP session, since it is the most popular and common protocol used for real time multimedia applications. It makes the test be more valuable for real time applications. G.711 is the CODEC used for the voice traffic because of its popularity. ITU-T G.711 is a standard to represent 8 bit compressed pulse code modulation (PCM) samples for signals of voice frequencies, sampled at the rate of 8000 samples/second. A G.711 encoder will create a 64 Kbps bit stream without any overhead. In total, the IP/UDP/RTP headers add a fixed 40 octets to the payload. Hence, the bandwidth for the VoIP traffic generated with G.711 CODEC is 80 Kbps [20]. To evaluate the capacity and performance of WiMAX to handle VoIP traffic, test scripts with different numbers of VoIP call are defined in Agilent Network Tester and deployed. The numbers of simultaneous VoIP call tested include one VoIP call, five VoIP calls, ten VoIP calls, twenty VoIP calls, and fifty VoIP calls. Suggested by the staffs have worked in the disaster area, the fifty simultaneous VoIP calls were the limitation for the QoS test since the users in the relief organizations are not more than one hundred currently. Every test case lasts 5 minutes. Testing the simultaneous VoIP calls with times increments, it helps us to determine the QoS level WiMAX can support with different traffic loads.

To learn the behaviour of WiMAX with various loads, three additional test cases were defined. The first one is called the dynamic voice traffic test. Initially, one call session is established. Afterwards, one call session joins the traffic very 30 seconds. Finally, there are five VoIP sessions established. In the other two test cases, FTP traffic is generated during one VoIP call and five simultaneous VoIP calls.

Since BPSK ½ and QAM64 ¾ are the modulations with lowest and highest data rate respectively used by WiMAX, it is significant to compare the QoS metrics based on these two modulations. The latency is measured using Ping command, because this command is easy to configure with different size of packet. And it provides the direct RTT result. Different levels of background traffic load are used.

6.2 Live tests

The Live tests aimed to verify the radio conditions of WiMAX in a LOS/NLOS environment in a rural/urban area. The focus was learning and verifying the behaviour of the WIDER system with WiMAX integrated into it in reality. The WiMAX subsystem is implemented using the BreezeMAX family products. We expected the live tests to provide us with the measurements of several basic parameters under different real environments. By comparing these results from the lab tests, the interference caused by environmental factors would be detected. And the initial tests can be a reference for future deployment in the live practice.

The detailed test scenarios are described in following sections.

6.2.1 Test Environment

In the live tests, the WIDER system acts as the core network behind the BS. The radio link simulation used in the lab tests is replaced by the real radio link provided by the antennas connected to the BS ODU and integrated in the CPE ODU. Figure 20 shows the network topology for each of the live tests.

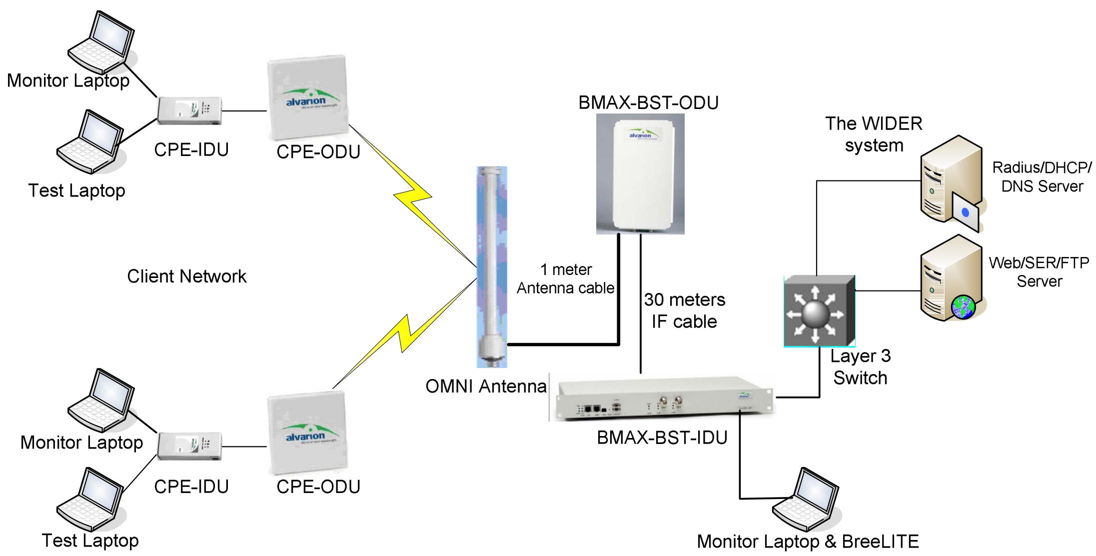

Figure 20: Live test topology

6.2.2 Hardware and Software

Table 10 shows the hardware and software used for the live test.

Table 10: Hareware and Software for the live test

Name		Description
Hardware	2 Servers PRIMAERGY RX100 S2 P4	Equipped in the WIDER system. Provide network services: RADIUS server, DHCP server, DNS, FTP server.
	Layer 3 Switch	Extreme Summit 48Si switch.
	BMAX-MBST-IDU-2CH-AC	BreezeMAX Micro Base Station Indoor Unit, AC power. Capacity limited to 20 CPEs.
	BMAX-BST-AU-ODU-2CH-3.5	BreezeMAX Base Station Outdoor Radio Unit with RF connector for a separate external antenna. The frequency is 3.5 GHz.
	BMAX-CPE-IDU-1D	BreezeMAX CPE indoor unit with one 10/100 Base-T Data Port. This CPE IDU is easy to use without extra configuration.
	BMAX-CPE-ODU-PRO-AC-3.5	BreezeMAX CPE outdoor unit with integrated vertical antenna. Receive frequency is on 3.5 GHz-3.6 GHz, transmit frequency is on 3.4 GHz-3.5 GHz, 100 MHz separation.
	Omni antenna	Omni antenna 3.5 GHz, Terminating connector: N female, Total gain: 10.5 dBi. Supports freq. range of 3.4 to 3.7 GHz.
	RF cable OAC LMR-400-1-1	Outdoor unit to Antenna Cable, for signal transmission between Micro Base Station ODU and antenna: 1m. Connectors: N male / N male 90 degree angle. Total loss @ 2.4 / 2.6 / 3.5 / 3.8 GHz: 1dB
	RF cable MIL-C-17F RG	Used for signal transmission between CPE outdoor unit and the integrated antenna.
	GPS	Positioning (GPS) client equipment with SIRF III chip and WAAS/EGNOS support. Used to record the position of measurement points.
	Power supply	12v DC to 230v AC converter for use of CPE, laptop, and GPS in a car. 500-1000 Watt.
	5 Hewlett-Packard nc6000 laptops	3 laptops were used for running monitor programs in the BS and CPE ODU. 2 laptops were used for running test scripts.
Software	Alvarion BreezeLITE	Refer to Table 29.
	Hyper Terminal	To access the monitor program in Micro Base Station via a serial port (COM port in Window's operating systems).
	TPTest	TPTest is used to measure the peak throughput with TCP and UDP packet. The TPTest server is configured in the WIDER system. The TPTest client is running in the test laptops. http://www.tptest.se/
	Wget / Wput	FTP client for downloading and uploading files on Microsoft Window operating system. The programs can provide the real time throughput parameters, the average throughput of a session, and the connection duration.

	Ethereal	Protocol Analyzer, http://www.ethereal.com. It is used to monitor the traffic and trouble shooting.
	Ping	The command used for test round trip time (RTT) for latency test.
	Putty	Telnet client to access to both the BS IDU and the CPE ODU.

Because of the complicated environment in the disaster area, an omni antenna was selected to provide full coverage. The omni antenna is positioned at N58 degrees 23.812 minutes, E 15 degrees 33.580 minutes. It is mounted on the roof the Ericsson building which is 20 meters high.

6.2.3 The configuration of the BreezeMAX Micro Base Station and CPE

Table 11 lists the parameters in the configuration of the BS as compared with the lab tests. The unchanged configuration can be found in Table 7 and Table 8.

Table 11: The modified configuration of the BS in the live test

Parameter	Value	Comments
Data Port		
Port IP Address	10.1.0.15	Static IP address.
Port Subnet Mask	255.255.0.0	
Port Gateway	10.1.0.2	The IP address of the layer 3 switch in the WIDER system.
Air Interface		
Multirate Support	Enable	Multirate Support is enabled to make the adaptive modulation mechanism available. The modulation is select by the WiMAX system according the radio link quality.
Uplink Basic Rate	BPSK ½	The basic rate for uplink.
Downlink Basic Rate	BPSK ½	The basic rate for downlink.

6.2.4 Test cases

The BS antenna was mounted at the height of 20 meters, and the CPE ODU was located on the roof a car which is around 170cm high. In the live test, the average FTP traffic throughput, the peak TCP and UDP throughput, and the latency with different packet size are the network metrics measured. The signal noise ratio (SNR) and received signal strengthen indication (RSSI) are the two parameters of radio link measured by the monitor program in the BS IDU and the CPE. The monitor program on CPE outputs the parameters very second. In order to get the best signal at each measurement point, the direction and position of the CPE ODU needed to be adjusted. We kept the CPE ODU for 30 seconds to receive the parameters information from the monitor program for each adjustment, and compared the value to fix the CPE ODU at the position with the best signal.

All of the parameters described above are tested at different measurement points. These measurement points were selected according to the distance from the BS antenna, the path (line of sight or non-line of sight condition) between the BS antenna and the CPE antenna, the density of the area between the BS and the measurement point. Since a car was used for both traveling and power supplying, the test condition of the measurement point were also taken into account. Nine measurement points were defined for the live test. Measurement Point 1 and Measurement Point 2 are LOS measurement points which mean there is direct line of sight between the BS antenna and the CPE antenna without any obstacles. Figure 21 shows these two points and the BS antenna location on the map. The remaining 7 measurement points are NLOS measurement points. Figure 22 shows the locations of these points on the map. The exact position and distance away from the BS antenna of each point can be found in Table 12.

Table 12: Position and distance of measurement points

	Distance from BS antenna [m]	Position
Point 1	400	N 58° 23,755 min. E 15° 33,760min.
Point 2	1130	N 58° 24,069 min. E 15° 34,404 min.
Point 3	540	N 58° 23,517 min. E 15° 33,392min.
Point 4	720	N 58° 23,422min. E 15° 33,287min.
Point 5	1430	N 58° 23,032min. E 15° 33,403min.
Point 6	2160	N 58° 22,635min. E 15° 33,302min.
Point 7	2700	N 58° 22,348min. E 15° 33,422min.
Ponit 8	1500	N 58° 23,654min. E 15° 34,847min.
Point 10	1429	N 58° 23,827 min. E 15° 34,830 min.

Figure 21: Map for LOS measurement points

Figure 22: Map for NLOS measurement points

7. Measurement and Analysis

This chapter describes the detailed measurements and analysis of these test results.

7.1 Evaluation of throughput test results

For each test case, a comparison of throughput with different modulations in both downlink and uplink is performed first. Two test scenarios with different access methods for the end user can be found in Figure 13 and Figure 14. The end user's throughput comparison in these two cases is considered. Finally, the scenarios with different CPE quantity are analyzed.

7.1.1 The throughput calculation of different modulation

Modulation is the process by which a carrier wave is able to carry the message or digital signal. Higher orders of modulation allow us to encode more bits per symbol or period. Eight different modulations are utilized in the WiMAX technology. Adaptive Modulation Mechanism enables the WiMAX system can determine the modulation used to carry data traffic according to the link quality. Here gives the short description of the modulation and the calculation of the maximum throughput offered by the modulation. The theoretical maximum throughput of each modulation is used as a reference for the throughput test.

The eight modulations are: BPSK ½, BPSK ¾, QPSK ½, QPSK ¾, QAM16 ½, QAM16 ¾, QAM64 ⅔, and QAM64 ¾. The OFDM signal which used by IEEE 802.16-2004 specification based WiMAX solution consists of 200 subcarriers, out of which 192 carrier data and 8 are just pilot carriers, not carrying data. Each of the 192 data subcarriers transfers the data symbols in parallel. The number of data bits carried by each symbol for the different modulations can be found in Table 13.

Table 13 Modulation and data bits

Modulation	Number of data bits
BPSK	1 Bit
QPSK	2 Bits
QAM16	4 Bits
QAM64	6 Bits

Now, we use QPSK ½ as an example to calculate the throughput. The following parameters in Table 14 defined in IEEE 802.16-2004 specification [16] are used to calculate the OFDM symbol time T_s.

Table 14 WiMAX frequency and time parameters

Nominal BW [MHz]	**Sampling factor** (Fs / BW)	**256 carrier BW** (Fs) [MHz]	**Carrier Spacing** (ΔF = Fs / 256) [kHz]	**Symbol time** (Tb = 1 / ΔF) [μSec]	**Guard interval G**	**Guard interval time** (Tg = G*Tb) [μSec]	**OFDM symbol time** (Ts = Tb+ Tg) [μSec]
3.50	8/7	4.00	15.63	64.00	1/16	4.00	68.00

For channel bandwidths that is a multiple of 1.75 MHz, then Sampling factor equals to 8/7. Guard interval G stands for the part of symbol that is not used for useful data. The value is defined by the vendor.

In the Micro Base Station, the time to transmit one frame is 10 ms. However, not all symbols carrier user data. Every frame has at least 3 symbols of Preamble and Broadcast data in DL and 2 symbols of Preambles in UL. For QPSK coding rate ½ we can get the following figures:

- Each frame (10ms) a maximum of 147 symbols are sent. (0.01/0.000068=147.05)
- Out of the 147 symbols, only 144 can carry data in DL. The other 3 are broadcast information.
- For QPSK each symbol carries 2 bits of data -> 288 bits per 10 ms per subcarrier
- There are 192 parallel subcarriers -> 288*192=55296 bits per 10ms
- The cyclic prefix is 1/16 which gives us (15/16)*55296=51840 bits per 10ms
- The coding rate is 1/2 which gives us 51840/2=25920 bits per 10ms.

This gives limit of 2592000 bits per second throughput when QPSK ½ is used. In accordance to the calculation, Table 15 gives the limit of throughput for the eight modulations used in WiMAX.

Table 15 Modulation and throughput

Modulation	**Maximum throughput [Mbps]**
BPSK ½	1.296
BPSK ¾	1.944
QPSK ½	2.592
QPSK ¾	3.888
QAM16 ½	5.184
QAM16 ¾	7.776
QAM64 ⅔	10.368
QAM64 ¾	11.664

7.1.2 One client connected to one CPE by cable

Figure 16 in section 6.1.4 shows the configuration of test network. Normal RJ 45 Ethernet cable was used to connect the client to the CPE.

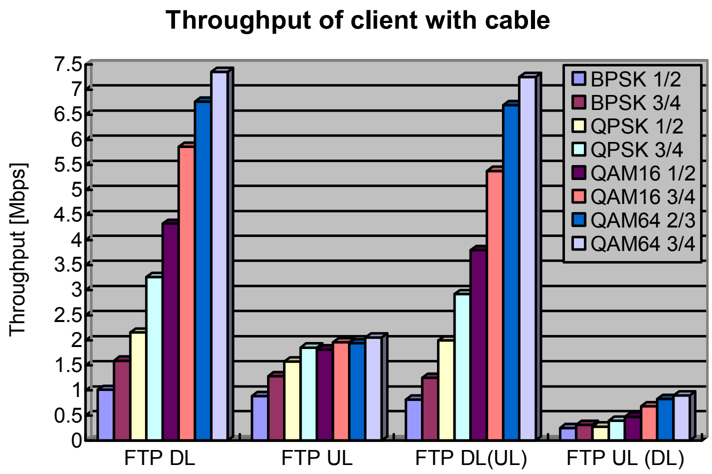

Figure 23: The throughput of the client connected to one CPE with cable

Figure 23 shows the throughput of FTP traffic when different modulations are adopted on WiMAX link. FTP DL (UL) and FTP UL (DL) stand for the throughput on the downlink and uplink when both the download and upload FTP sessions are running at the same time. It is apparent that the proportion of the increment of throughput on the downlink is much higher than the one on the uplink. The best modulation (e.g., QAM64 ¾) can provide up to 7.5 Mbps throughput on the downlink and around 2 Mbps on the uplink. The statistics in FTP DL (UL) and FTP UL (DL) show that one upload FTP session which is running with one downlink FTP session simultaneously doesn't affect the throughput on the downlink. However, the download session has serious impact on the throughput on the uplink. The values in FTP UL (DL) are roughly decreased to half of the throughput in FTP UL case. The reason is the CPE is half duplex. The bandwidth controller shall not allocate the uplink bandwidth for half duplex CUP when it is expected to receive data on the downlink channel.

7.1.3 One client connected to one CPE with WLAN

Figure 17 in section 6.1.4 shows the configuration of this test network.

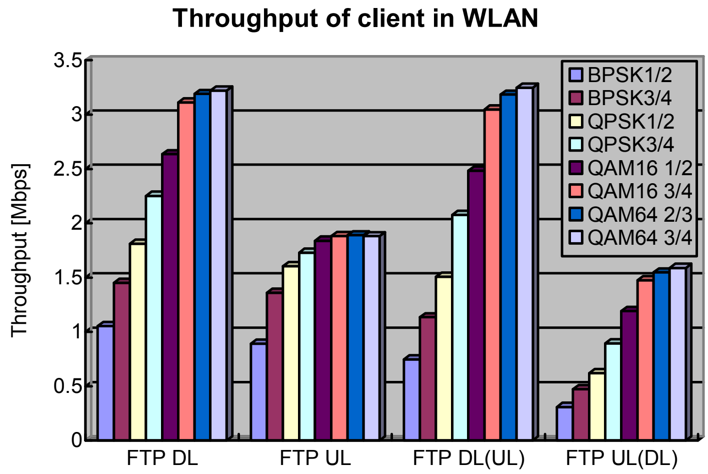

Figure 24: The throughput of the client connected to one CPE with WLAN

In Figure 24 the throughput of end user associated with a WLAN provided by the access point connected to the CPE is shown. The trends are similar to Figure 23.

7.1.4 The comparison of the RJ 45 Ethernet cable connection and the WLAN connection

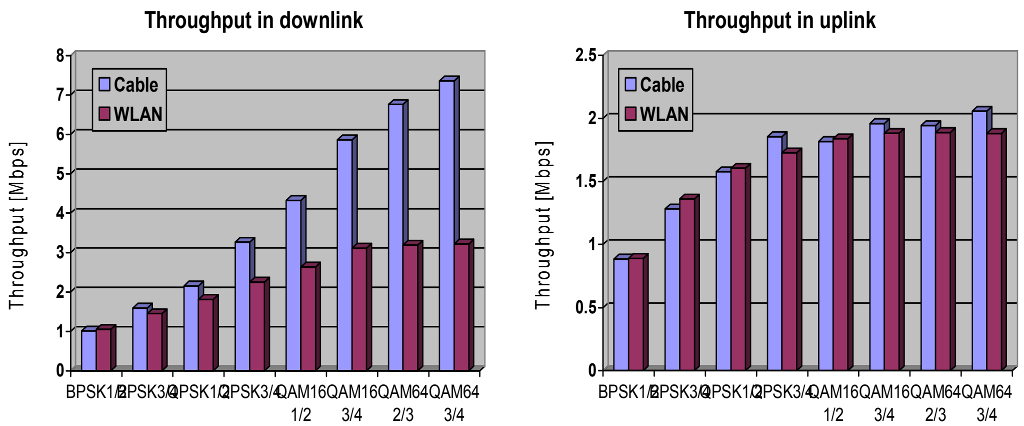

Figure 25: Cable vs. WLAN (a) downlink (b) uplink

First of all, Figure 25 (a) shows the comparison on the downlink. The throughput of the modulations supporting high data rate decreases a lot. The throughput doesn't change too much when BPSK ½ and BPSK ¾ are used. However, when the modulation on the WiMAX link is switched to one supporting a higher data rate, such as QPSK, QAM16, or QAM64, the increase in throughput of the client with a cable connection is much greater than when using a WLAN connection. The highest throughput on the downlink provided by QAM64 ¾ reduces from approximate 7.5 Mbps to 3.2 Mbps when the local access is via WLAN. The Figure 25 (b) shows that the WiFi link doesn't impact the throughput on the uplink so much as downlink. The conclusion from this comparison is the WiFi link is the bottleneck for the throughput of end user in this integrated solution.

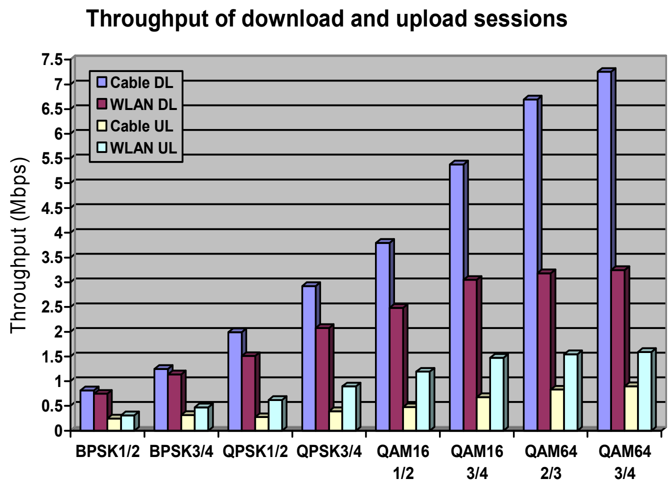

Figure 26: Cable vs. WLAN simultaneous download and upload session

Figure 26 shows the comparison of throughput on the downlink and uplink when there are FTP upload session and download session established simultaneously. The same behaviour on the downlink as the single download session can be observed. One interesting appearance is the difference in behaviour for the uplink. The throughput on the uplink doesn't reduce as much on the downlink when the WiFi link is integrated with the system. On the contrary, the values for different modulations increase at some level.

7.1.5 The comparison between one CPE scenario and two CPEs scenario

Figure 18 in section 6.1.4 describes the two CPEs test scenario.

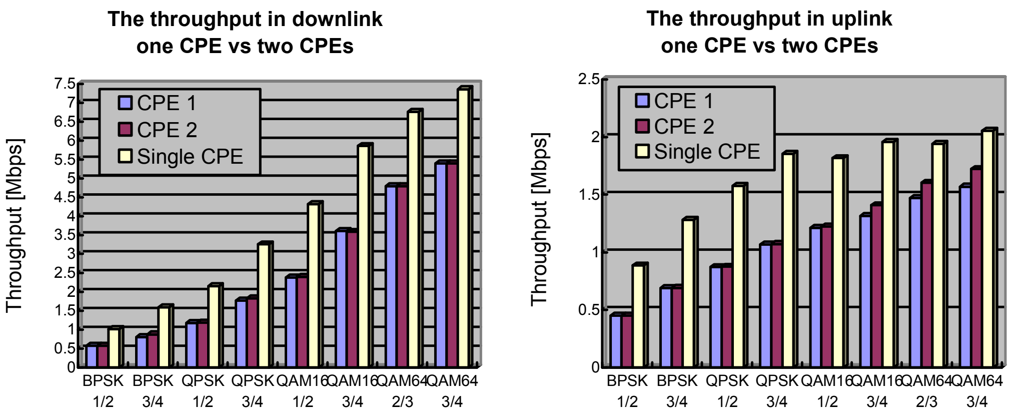

Figure 27: one CPE vs. two CPEs (a) downlink (b) uplink

In Figure 27 (a) the downlink throughput of the two clients each connected to one CPE can be observed. Figure 27 (b) shows the uplink throughput. Both of the clients obtain the same throughput on the downlink and have very similar throughput on the uplink. Compared with the one client connected with one CPE scenario, the throughput of each is lower, but the combined throughput of both clients is much higher. It can be explained by the bandwidth allocation and request mechanism specified in [16]. The SS sends a bandwidth request of the connection to the BS to ask for the bandwidth according the service flow and QoS configuration. BS allocates the request bandwidth by polling (which is the process by which the BS allocates to the SSs bandwidth specifically for the purpose of making bandwidth requests). Of course, the BS allocates the bandwidth not only according to the bandwidth request from the SSs, but also the number of connections, the condition of the channels, and the modulations.

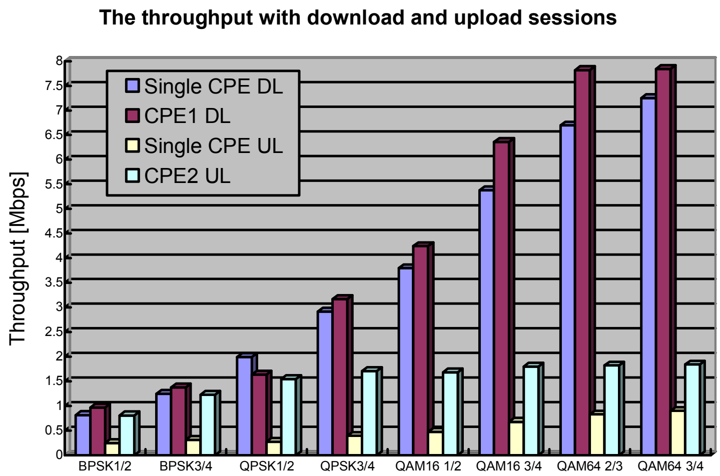

Figure 28: One CPE vs. two CPEs simultaneous download and upload session

Figure 28 shows the differences in the throughput when there is a download session and an upload session simultaneously in the different scenarios. In the two CPEs scenario, the download session and the upload session are run on the two separated connections provided by the two CPEs. As a result, they don't affect each other. In the one CPE scenario, both the download session and the upload session are run on the same connection. From the analysis of Figure 24 above, we concluded that the downlink throughput is not affect significantly by the upload session. But the uplink throughput is impacted a lot. It is apparent that the difference in the throughput on the downlink is much smaller than the uplink. Additionally, the downlink throughput in two CPEs scenario is greater than it was in the one CPE scenario most of the time. It can be concluded that the connections established between different CPEs and the BS don't interfere each other.

7.2 Evaluation of QoS test results

7.2.1 Throughput with different number of VoIP call

Throughput, delay, and jitter are the metrics considered in these QoS tests. Table 16 shows the details of the bandwidth per VoIP flow using G.711 at a default packetization rate of 50 packets per second (pps). This does not include IP/UDP/RTP overhead and does not take into account any possible compression schemes, such as Compressed Real-Time Transport Protocol.

Table 16: Voice Bandwidth Requirement of G.711

Bandwidth Consumption	Packetization Interval	Voice Payload in Bytes	Packets Per Second	Bandwidth Per Conversation
G.711 (without layer 3 overhead)	20 ms	160	50	64 kbps
G.711 (with layer 3 overhead)	20 ms	200	50	80 kbps

A more accurate method for provisioning VoIP is to include the IP/UDP/RTP overhead. Since the Agilent Network Tester was configured to use G.711 to simulate the voice traffic, the requirements of throughput for different numbers of VoIP sessions are shown in Table 17.

Table 17: Voice bandwidth needed for the different test cases

Bandwidth Consumption	1 VoIP call	5 VoIP calls	10 VoIP calls	20 VoIP calls	50 VoIP calls
50 pps	80 Kbps	400 Kbps	800 Kbps	1.6 Mbps	4 Mbps

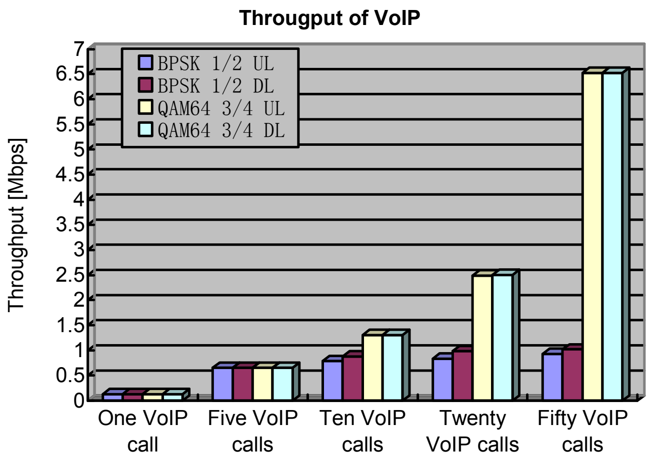

Figure 29: Throughput with different numbers of VoIP calls

According to the throughput test with FTP traffic, the maximum throughput on the downlink provided by BPSK ½ is 1 Mbps, and 0.89 Mbps on the uplink. QAM64 ¾ can provide up to 7.6 Mbps throughput on the downlink and 1.8 Mbps throughput on the uplink. Since the acknowledgement is not required by the UDP traffic, both BPSK ½ and QAM64 ¾ provide higher throughput for UDP traffic than FTP traffic. Figure 27 shows both BPSK ½ and QAM64 ¾ can provide the same best throughput for one VoIP session and five VoIP calls. When the number of VoIP call increases to ten, there is a difference in throughput both on the uplink and downlink between BPSK ½ and QAM64 3/4. By comparing the scenarios with the bandwidth required for different amount number of VoIP calls, the conclusion is QAM64 ¾ always provides the best throughput from one VoIP call to 50 simultaneous VoIP calls; when there are 10 or more VoIP calls established at the same time, BPSK ½ modulation reaches its limitation of throughput and can not perform well enough.

7.2.2 Mean delay with different number of VoIP calls

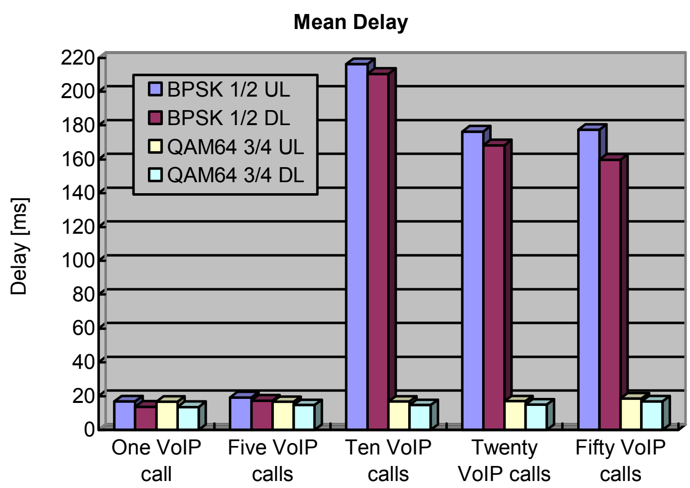

Figure 30: Mean delay with different number of VoIP calls

The bounded end-to-end latency is one of the VoIP performance requirements. Long delays make it difficult for callers to determine when the person at the other end has finished talking. This results in very unnatural speech patterns. A rule of thumb is that one-way latency should not exceed 150 milliseconds. 150 millisecond delays are noticeable, but when latency exceeds 250 milliseconds it becomes difficult to carry on a conversation. [21] Figure 30 shows that the packet delay time of voice traffic remains at almost the same level, which fulfils the requirement when QAM64 ¾ is used, regardless of the number of VoIP call (i.e., up to 50 simultaneous calls). A huge variation of the delay occurs in the 10 VoIP calls scenario. When BPSK ½ modulation is used, the delay impacts the performance of VoIP if there are more than 10 VoIP calls established simultaneously through the WiMAX link. In addition, since satellite link is used in

WIDER to provide Internet access for the end user. If any VoIP conversation is established through this link, the additional latency added due to the satellite link should be taken into account. The related measurement can be found in [22].

7.2.3 Jitter with different numbers of VoIP calls

Another key performance metric is jitter. Jitter is the variation in latency that is experienced over time. As noted above, jitter causes irregularities in the flow and delivery of data. For jitter levels under 100 milliseconds it may be acceptable to increase the de-jitter buffer size in end-systems or to enable adaptive jitter buffer operation. A de-jitter buffer temporarily stores arriving packets in order to minimize perceived delay variations. If packets arrive too late they are discarded. The size of the de-jitter buffer which is configured either too big or too small will impact the quality of voice traffic. For jitter levels over 100 milliseconds then increasing the jitter buffer size to avoid packet discards will introduce significant delay. [21]

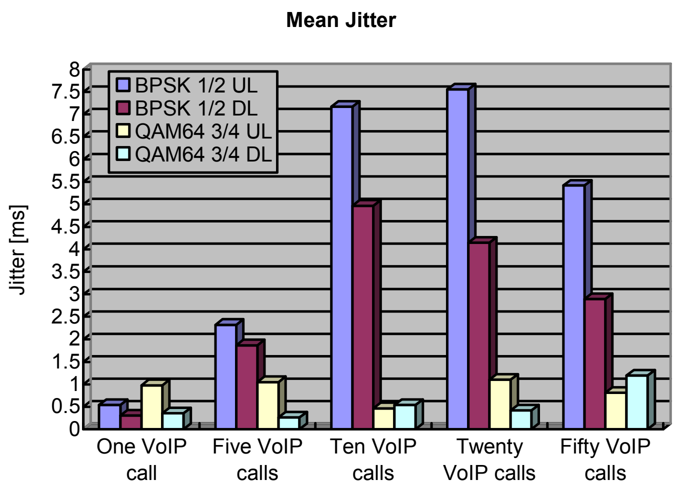

Figure 31: Mean jitter with different numbers of VoIP calls

Figure 31 shows that the maximum mean jitter value among all the test scenarios is 7.5ms when there were twenty VoIP calls established. When QAM64 ¾ is used, the mean jitter is limited to a stable range which is less than 1.2ms for both uplink and downlink. However, when using BPSK ½, some apparent changes in jitter occur as the amount of VoIP traffic increases. After the number of simultaneous VoIP calls increases to 10, jitter is variable within a wide range of values. The following figures show variation of jitter in each of the specific test scenarios.

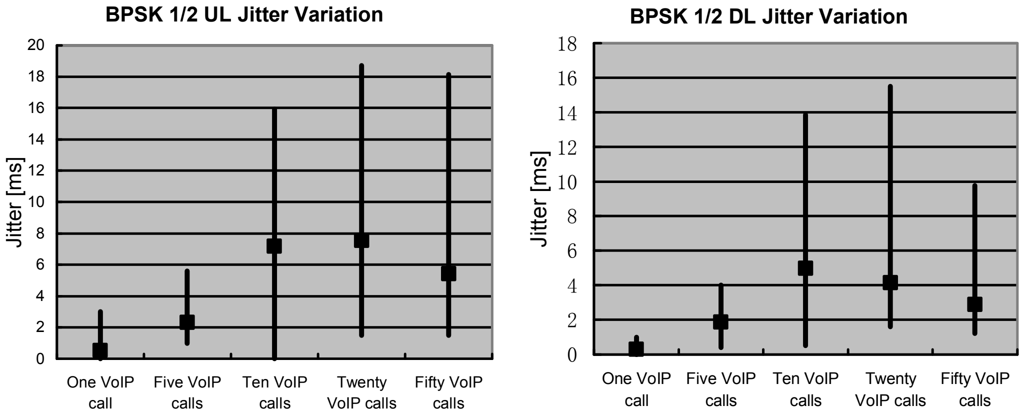

Figure 32: The jitter variation with BPSK ½ on (a) uplink (b) downlink

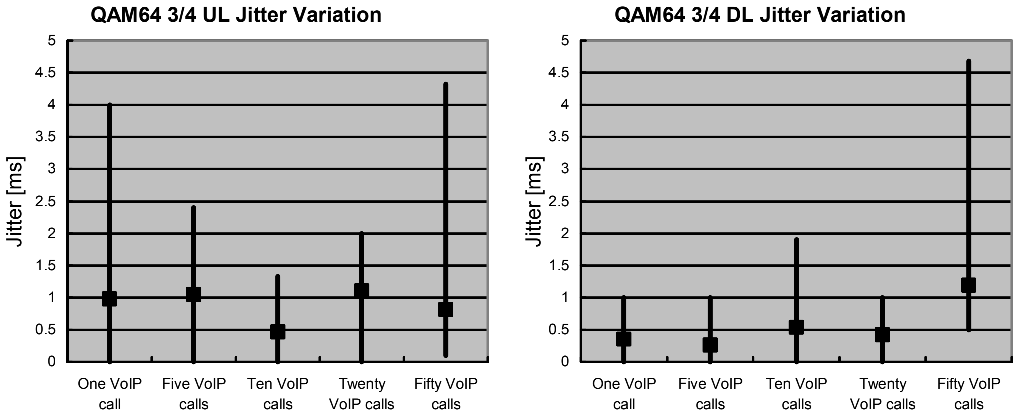

Figure 33: The jitter variation with QAM64 ¾ on (a) uplink (b) downlink

From Figure 32 and Figure 33, we see that the variation of jitter in the tests with different modulation and amounts of voice traffic. It is apparent that the jitter fluctuates more for the uplink than downlink for both BPSK ½ and QAM64 ¾. The range of the fluctuation when QAM64 ¾ is adopted is much smaller than BPSK ½. It means QAM64 ¾ provides more stable and better performance with respect to jitter than BPSK ½. By looking more deeply into Figure 32, we see the fluctuation ranges are greater when there are more than 10 VoIP calls established at the same time. Therefore, although from Figure 31, we see that the mean jitter fulfils the requirements for VoIP, jitter still impacts the quality of VoIP calls when there are more than 10 VoIP calls with BPSK ½ modulation.

By analyzing the three metrics of VoIP tests, throughput, delay, and jitter, the conclusion is QAM64 ¾ modulation can support up to 50 simultaneous VoIP calls with G.711 codec well, and BPSK ½ can support up to 10. If BPSK ½ modulation is adopted, then no more than 10 simultaneous VoIP calls should be established, otherwise the quality of the existing calls suffers. Since an adaptive modulation algorithm is enabled, one of 8 modulation levels is selected dynamically according the conditions of the radio link. The link quality can be estimated based on the SNR measurement. QAM64 ¾ is the maximum modulation which provides the best throughput. So, if the link quality is sufficient (SNR > 23 dB), the WiMAX solution can support up to 50 VoIP calls simultaneously. When BPSK ½ is adopted, which means the link condition is really bad (SNR < 7 dB), the number of VoIP calls that can be established with tolerable quality is less than 10. Hence, an adaptive admission control scheme is recommend in the system to avoid accepting more calls when conditions are bad.

7.2.4 Dynamic Voice Traffic

This test focuses on the variation during the increment with increasing voice traffic. In the test, one VoIP call starts every 30 seconds. The number of VoIP calls increases from one to five. Throughput, delay, and jitter are the metrics measured.

The following figures come from the Agilent Network Tester. The yellow carve stands for the uplink traffic and the green one represents the downlink traffic.

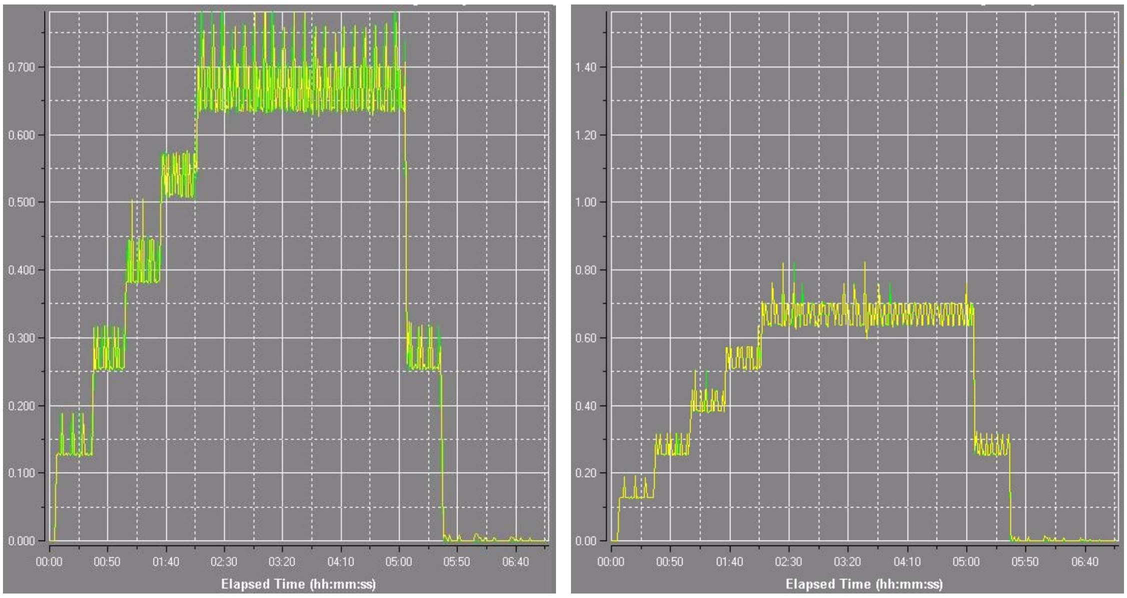

Figure 34: Dynamic voice traffic throughput (a) BPSK ½ (b) QAM64 ¾

Figure 34 shows the throughput variation through the test when BPSK ½ and QAM64 ¾ are used. The apparent increase in throughput when multiple VoIP calls utilize the WiMAX link can be observed. According to earlier analysis, both BPSK ½ and QAM64 ¾ can support 5 simultaneous VoIP calls well.

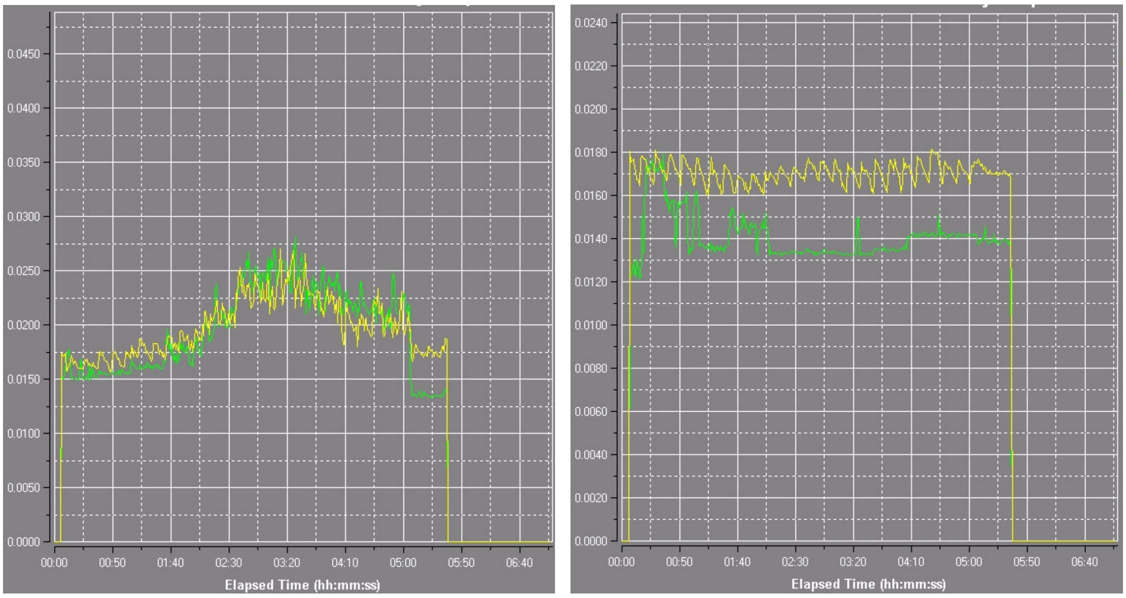

Figure 35: Dynamic voice traffic mean delay (a) BPSK ½ (b) QAM64 ¾

Figure 35 shows that the packet delay increases as the number of VoIP calls increases. The variation of the VoIP traffic does affect the delay when BPSK ½ is adopted. Figure 40 verifies that the small variation of voice traffic does not affect the delay apparently when QAM64 ¾ is used.

Figure 36: Dynamic voice traffic mean jitter (a) BPSK ½ (b) QAM64 ¾

Figure 36 shows the jitter variation through the dynamic voice traffic. Similar to delay, jitter is impacted by increasing numbers of VoIP calls when BPSK ½ is adopted, but not when QAM64 ¾ is used.

The conclusion from this test scenario is when BPSK ½ is adopted, which represents the poor link conditions, the impact due to the variation of the increasing amount of voice traffic is noticeable. The link throughput significantly limits the number of VoIP calls which can be sustained simultaneously.

7.2.5 The effect of FTP traffic during one or five VoIP calls

We generated a FTP download session with a 32 Mbytes .txt file when there was a single VoIP call and with five VoIP calls. The following figures show the variation of throughput, delay, and jitter.

7.2.5.1 The single VoIP call with FTP traffic on the downlink

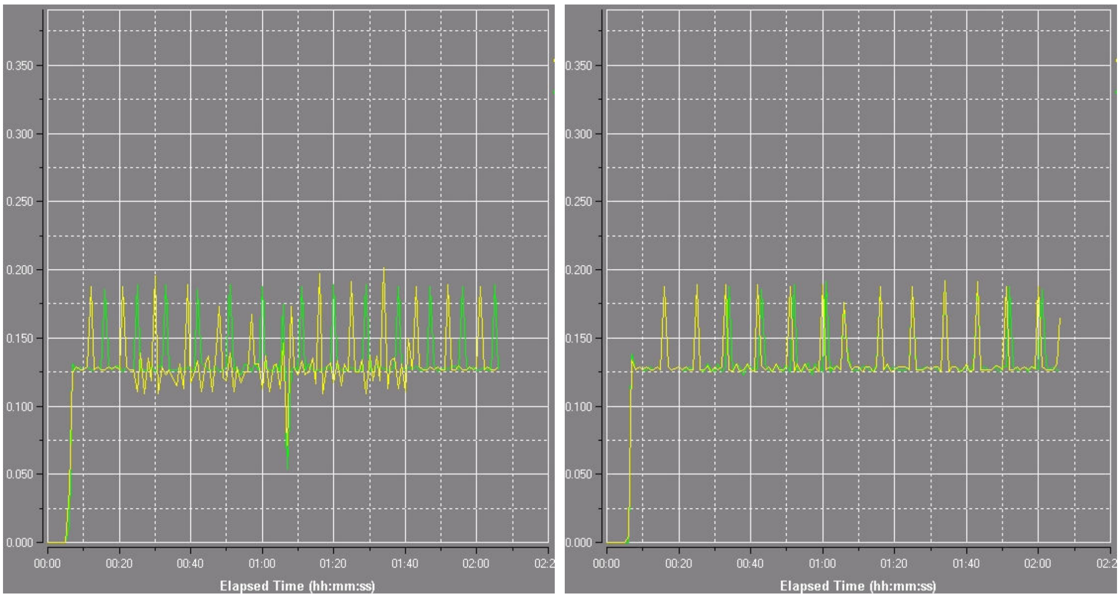

Figure 37: Throughput of single VoIP call with FTP traffic (a) BPSK ½ (b) QAM64 ¾

From Figure 37, we can not see the apparent change in throughput due to the FTP traffic. The explanation is that the bandwidth occupied by the FTP traffic on the downlink does not affect the bandwidth required by one VoIP call (which is small). However, the FTP traffic must affect the queuing mechanism in the BS and the CPE, which results in the variation of delay and jitter of the voice traffic. The following figures show the details.

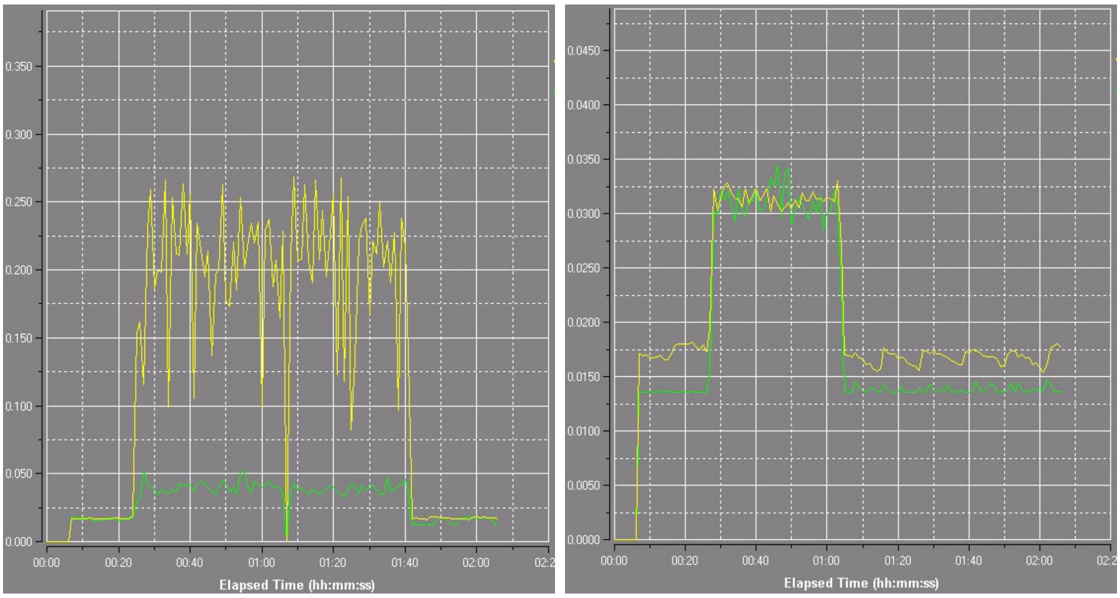

Figure 38: Mean delay of single VoIP call with FTP traffic (a) BPSK ½ (b) QAM64 ¾

The obvious variations of delay because of the FTP traffic generated during the call can be found in Figure 38. In the test scenario with BPSK ½, the delay on the downlink increases from approximate 17ms to 50ms; the delay on the uplink increases from approximate 17ms up to 265ms. In the test scenario with QAM64 ¾, the delay on the downlink increases from approximate 14ms to 34ms, and the delay on the uplink increases from approximate 17ms to 33ms. Additionally, the variation of delay with BPSK ½ is greater than that of QAM64 ¾, especially the uplink with BPSK ½. The throughput test results showed the apparent decrease of throughput on the uplink when the upload session and download session run simultaneously. This apparent decrease in throughput could explain the great increase of uplink delay.

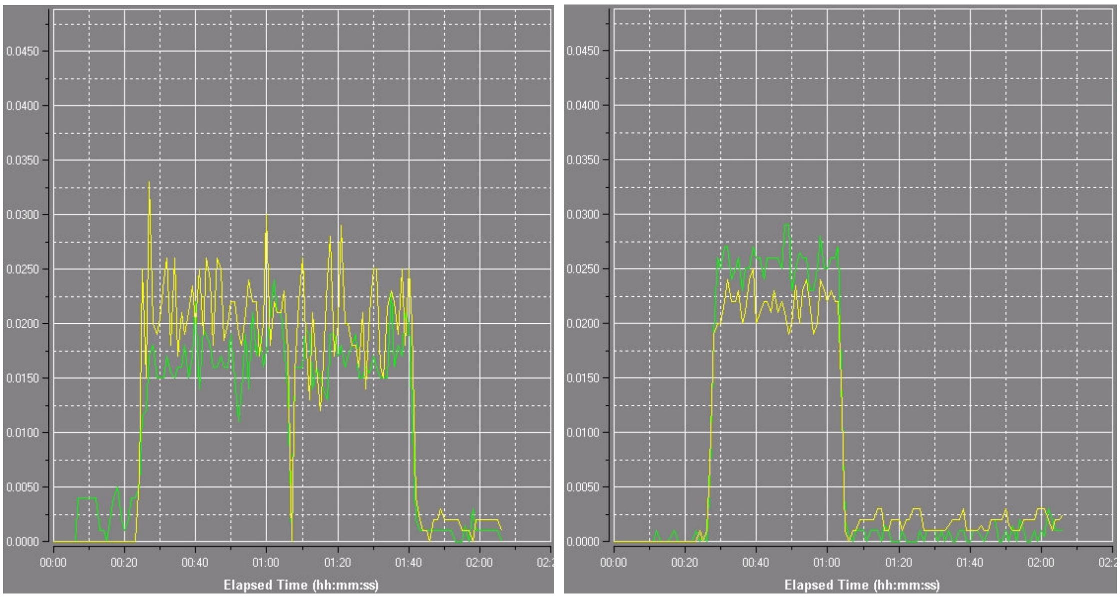

Figure 39: Mean jitter of single VoIP call with FTP traffic (a) BPSK ½ (b) QAM64 ¾

Figure 39 shows the jitter variation with BPSK ½ and QAM64 ¾ used. The generation of the FTP traffic results in the apparent increase in jitter for both BPSK ½ and QAM64 ¾. The increment with BPSK ½ is close to when QAM64 ¾ is used. The jitter when the FTP traffic was transmitted is more stable with QAM64 ¾ than BPSK ½. Another interesting appearance is when the FTP traffic was transmitted, the jitter on the uplink is greater than on the downlink when BPSK ½ was adopted most of the time. However, it is opposite with QAM64 ¾, jitter in downlink is higher than on the uplink.

7.2.5.2 Five VoIP calls with FTP traffic on the downlink

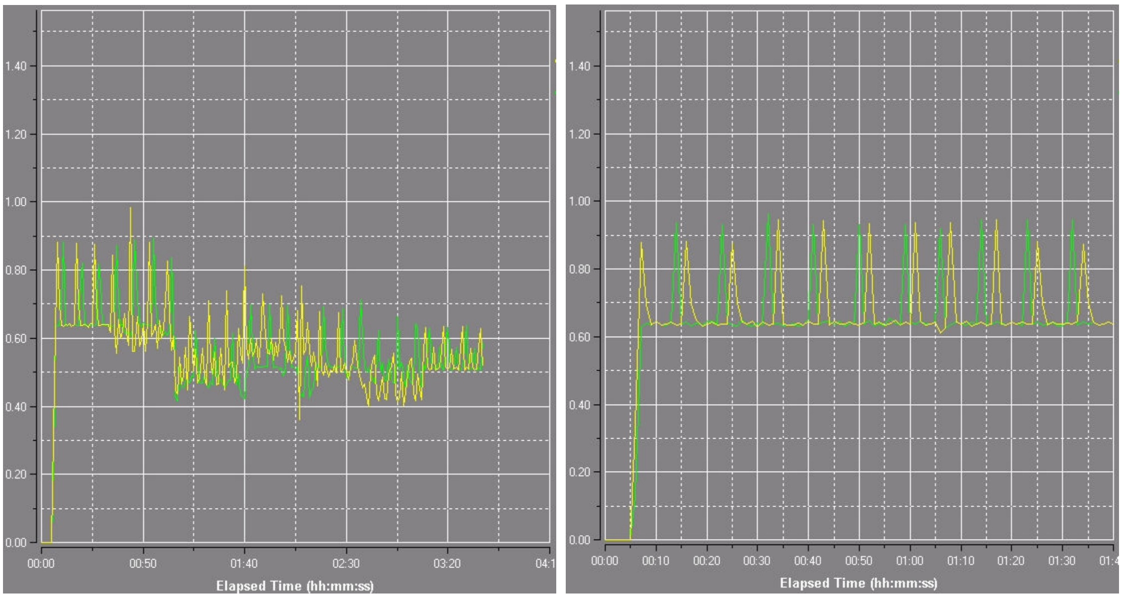

Figure 40: Throughput of five VoIP calls with FTP traffic (a) BPSK ½ (b) QAM64 ¾

Figure 40 (b) verifies that the FTP traffic doesn't affect the throughput of 5 VoIP calls when QAM64 ¾ modulation is adopted. Figure 40 (a) shows some variations in the VoIP traffic throughput. According to the former VoIP test, when 5 VoIP conversations were established simultaneously, BPSK ½ provides 0.656 Mbps throughput (Figure 29). Figure 40 (a) shows the unstable throughput which is less than 0.656 Mbps when the FTP traffic generated on the WiMAX link. The FTP traffic occupies part of the bandwidth required by 5 VoIP calls if BPSK ½ modulation is used. It did not happen to the WiMAX link with QAM64 ¾.

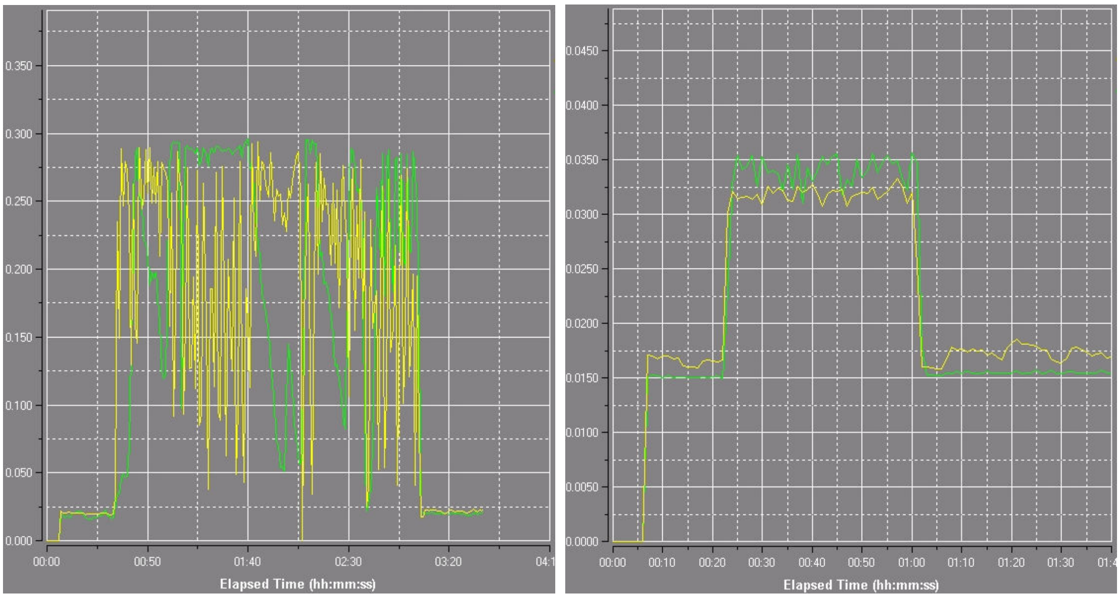

Figure 41: Mean delay of five VoIP calls with FTP traffic (a) BPSK ½ (b) QAM64 ¾

Figure 41 (a) shows almost the same increment in the delay as the one VoIP conversation scenario as soon as the FTP traffic starts when BPSK ½ is used. The variable scale is from approximate 20ms up to almost 300ms, both on the uplink and downlink, due to the insufficient bandwidth. Additionally, the fluctuation of delay time is very acute. In QAM64 ¾ case, (Figure 41 (b)), it doesn't differ too much from the test scenario with one VoIP call.

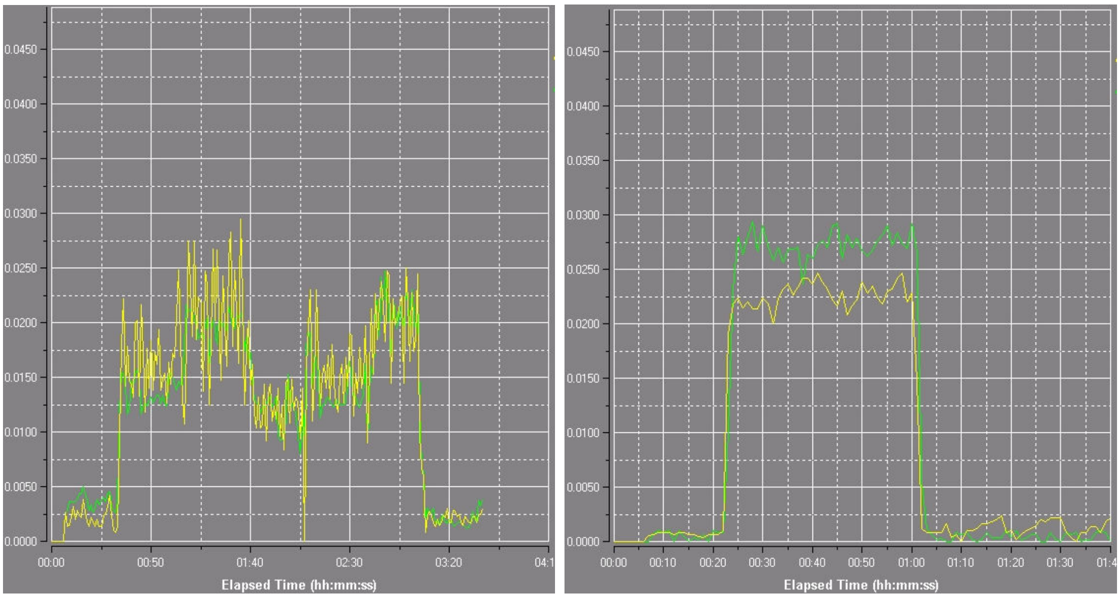

Figure 42: Mean jitter of five VoIP calls with FTP traffic (a) BPSK ½ (b) QAM64 ¾

The variable scale of jitter during the FTP traffic was transmitted with BPSK ½ is similar to the scale with QAM64 ¾. However, the fluctuation of jitter with BPSK ½ is much more acute than QAM64 ¾ which is the same as the scenario with one VoIP call.

By comparing the results of these tests, we concluded that the variation of data traffic on the WiMAX link impacts the metrics of VoIP at different levels. The throughput metric is affected if the modulation can not provide enough bandwidth for both data and voice traffic. The apparent increases of both delay time and jitter are the main effect on the performance of VoIP over the WiMAX link. Because the data traffic, such as FTP and other TCP traffic, will attempt to use all the bandwidth available. When a lower modulation is adopted, the effect is more obvious. This implication can be solved by introduction of priority based QoS. By assigning the voice traffic with the higher priority using either 802.1p or DiffServ, the voice traffic can be treated with the QoS configuration done in the BS.

7.2.6 Ping latency test

Seven packet sizes were selected for the ping latency test, 64 bytes, 128 bytes, 256 bytes, 512 bytes, 512 bytes, 1024 bytes, 1518 bytes, and 2048 bytes. The test scenarios are showed in Figure 14 and Figure 16.

7.2.6.1 The latency of the client connected to CPE with cable

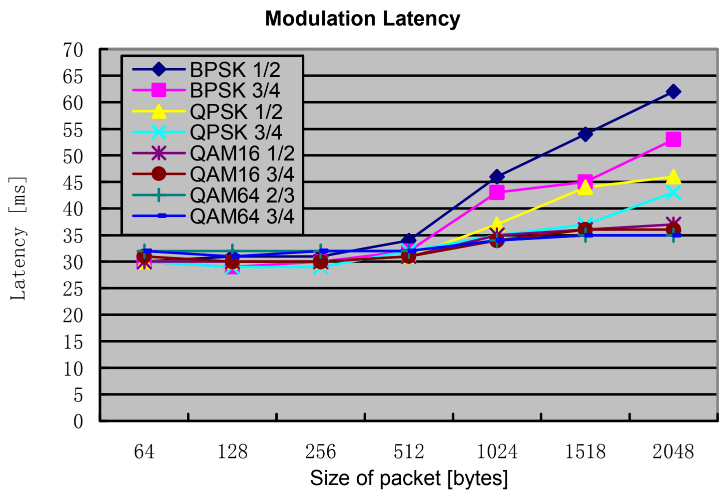

Figure 43: RTT of the client connected to CPE with cable

Figure 43 shows the latency test results with a client connected to the CPE directly. For packets smaller than 512 bytes, there is no apparent difference in the round trip time (RTT) of packets with different modulations. Once the size of packet is bigger than 512 bytes, the round trip time (RTT) with all of the modulations starts increasing with the packet size, especially for BPSK ½, BPSK ¾, QPSK ½, and QPSK ¾, the increments are apparent. When the packet size exceeds the limit of a single Ethernet frame size, which is 1518 bytes, fragment occurs in order to transmit the frame. As a result, a significant difference between different modulation schemes can be detected. The conclusion is that all of the modulations perform similarly with regard to the latency when the packet size is less than 512 bytes. Afterwards, as the size of packet increases, the latency increases obviously for modulations with lower data rates. However, the modulations with higher data rates are not affected significantly.

7.2.6.2 The latency of the client connected to CPE with WLAN

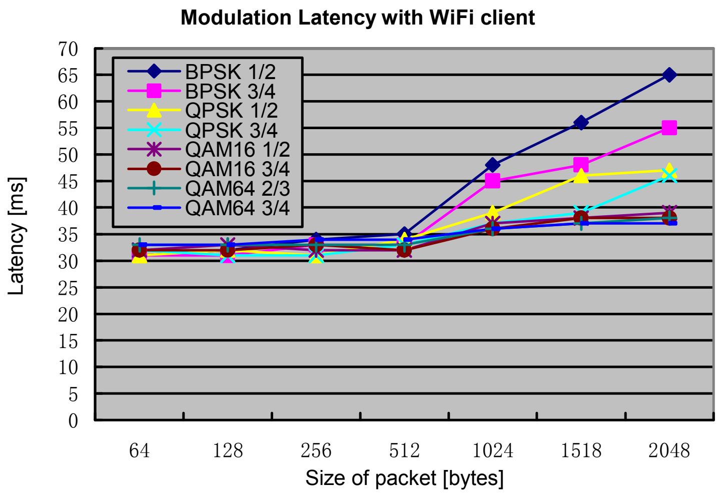

Figure 44: RTT of the client connected to CPE with WLAN

Figure 44 shows similar curves to Figure 43. Because the client was associated with the WLAN provided by the CPE, all the round trip time values in Figure 56 are a little bigger than those in Figure 43. We can conclude that the integration of WLAN into WiMAX impacts the latency metric in a roughly linear (i.e. additive) fashion.

7.3 Evaluation of live test results

The live test focuses on evaluating the throughput performance of the WIDER system integrated with WiMAX and the radio parameters of the WiMAX link under the different environments. LOS/NLOS between the BS antenna and the CPE antenna, the distance between the base station and the measurement points, and the density of the covered area are the conditions taken into account through the tests. Additionally, the behaviour of throughput with one CPE and two CPEs is compared.

During the live tests, we especially measured the time to setup a WiMAX link. It took 5 minutes 15 seconds to power on the WIDER system and the SuSE Professional 9.3 linux operating systems installed in the two servers. The time for starting the BS and the CPE was 2 minutes. Since the CPE ODU was located on the roof of the car, it is easy to change the direction of the antenna according to the position measured by the GPS. It won't take more than 5 minutes to detect the signal from the BS antenna if. The most time consuming assignment in our case is the installation of the BS antenna. In accordance with the experience of the staffs have worked in the disaster area, there were always 40 meters high masts setup by the relief organizations to mount the antenna. It may cost one person between one and two hours to finish mounting if all the hardware is equipped. So we can say the WIDER system with WiMAX integrated can be deployed in several hours in the disaster area.

7.3.1 The throughput with FTP traffic

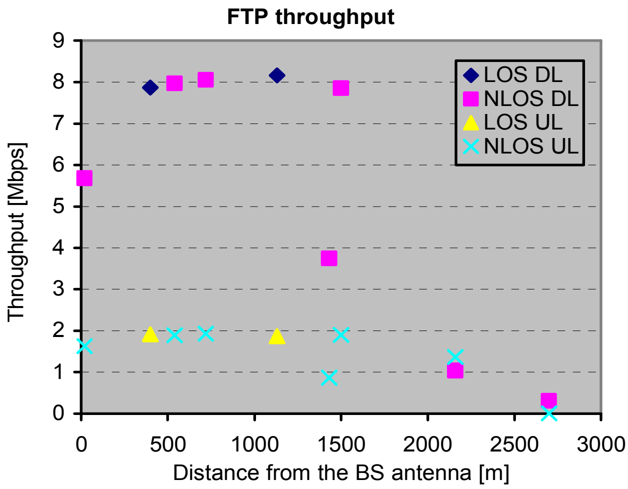

Figure 45: FTP throughput at different measurement points

In Figure 45, it is easy to compare the throughput of FTP traffic at different measurement points. Basically, the throughput of uplink and downlink decreases as the distance between the BS antenna and CPE increases. But it is not so obvious for the points closer than 1500 meters. The throughput of the measurement points in this range, both LOS and NLOS ones, achieve almost the same values except for the first and the fourth NLOS point. For these LOS points, which are 400 meters and 1130 meters away from the BS antenna respectively, can be considered still close to the BS. The 730 meters difference in the distance doesn't affect the throughput. The tests at the second, third, and fifth NLOS points provided similar throughput values as the LOS points both in uplink and downlink. This is because these points are located in a NLOS environment without too many obstacles between the BS antenna and the CPE. The environment can be defined as flat and low density. So, although the fifth point is 1500 meters away and NLOS, the throughput is still very high. The first NLOS measurement point is located at the office inside of the building where the BS antenna is mounted on the roof. The windows and the doors of the office were all closed. The CPE antenna faced to the windows. The position is the most important factor instead of the distance at this point. It is difficult to position the CPE antenna to receive a better signal. The conclusion from this is the throughput performance is degraded a lot when the CPE antenna is inside of a building.

The fourth NLOS measurement point in the figure has much worse throughput than the other points in this range. Even though it is 1430 meters away from the BS antenna and this is closer than the fifth NLOS point, both the downlink and uplink throughput decreases more than 50% of the throughput in comparison to the fifth NLOS point. From the map, it is clear that the signal received by Point 5 penetrates a small urban area with lots of buildings. It is this small urban area that imposes the degradation of the radio link and results in the decrease of the throughput.

The last two NLOS measurement points in the right part of Figure 40 have a dramatically decreased on the throughput. Both of these two points are located in the same direction as the fourth NLOS point which is Point 6. The sixth NLOS point in the figure is in the middle of a small forest and beside a road. Although the last point in the figure is Point 7 which is located in an open area, the urban area and the forest between the BS location and the point are factors lead to bad performance. Both the distance and environment impact the test results at these two points.

Another interesting observation is that the throughput on the uplink is higher than the one on the downlink at the sixth NLOS point, and higher than the uplink throughput of the fourth point which is closer to the BS antenna as well. This will be further analyzed in section 7.3.3.

7.3.2 The best TCP and UDP throughput

TPTest is used to measure the **peak** throughput of TCP traffic and UDP traffic.

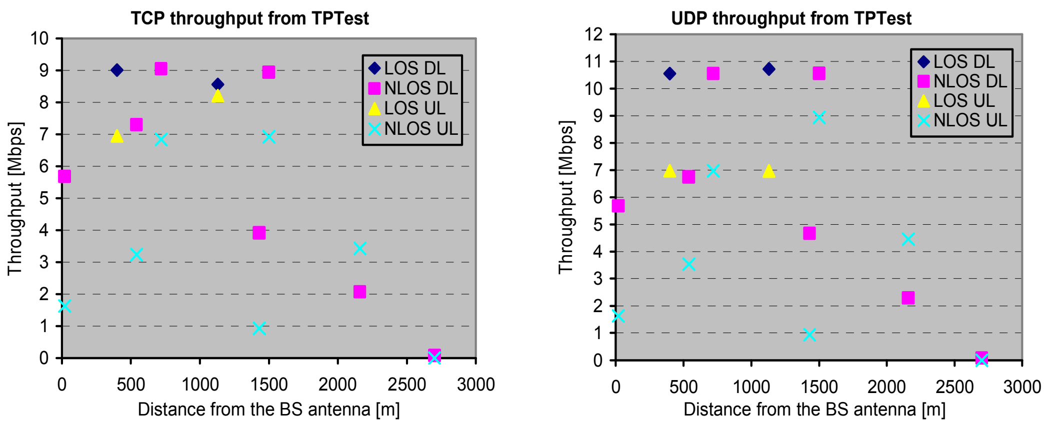

Figure 46: (a) TCP throughput (b) UDP throughput

Figure 46 displays the peak throughput values when the TCP and UDP packets are transmitted. Compared with the FTP throughput, all of these three figures follow the same change in principle of changing in the throughput value at the different measurement points as described earlier. The test results of TCP throughput are a little higher than the FTP throughput shown earlier because the FTP test showed the average value and TPTest showed the peak TCP throughput instead. The UDP throughput test results are higher than TCP because UDP doesn't require acknowledgment of receiving packets. Hence, the next UDP packet can be transmitted without any delay. It can still be seen that the throughput on the uplink is better than over the downlink at the point which is 2160 meters away from the BS antenna for both TCP and UDP traffic.

7.3.3 The radio parameters analysis

SNR and RSSI are the parameters used to evaluate the radio link quality in WiMAX. The parameters on downlink are measured by the performance monitor program running in CPE, while the uplink parameters are measured by the monitor program in the BS.

Table 18: Radio parameters and modulation

	LOS		NLOS						
Distance [m]	400	1130	20	540	720	1430	1500	2160	2700
SNR DL [dB]	34	35	24	34	35	20	33	21	8
SNR UL [dB]	30	N/A	18	30	28	5.5	28	5	4
RSSI DL [dBm]	-42	-55	-77	-66	-58	-85	-69	-84	-96
RSSI UL [dBm]	-71	N/A	-88	-72	-73	-98	-76	-99	-100
DL Modulation	QAM64 ¾	QAM64 ¾	QAM64 ⅔	QAM64 ¾	QAM64 ¾	QAM16 ¾	QAM64 ¾	BPSK ½	BPSK ½
UL Modulation	QAM64 ¾	QAM64 ¾	QAM16 ¾	QAM64 ¾	QAM64 ¾	BPSK ¾	QAM64 ¾	BPSK ¾	BPSK ½

7.3.3.1 RSSI

The power of the signal received is the one parameter determined by the wireless system. RSSI which stands for Received Signal Strength Indicator is introduced to describe the link quality. RSSI is a measurement of the strength (not necessarily the quality) of the received signal strength in a wireless environment, in arbitrary units. When collection of RSSI measurements is mandated by the BS, an SS can obtain an RSSI measurement from the OFDM downlink preambles. From a series of RSSI measurements, the SS derives and updates its estimate of the mean and the standard deviation of the RSSI, and reports these values to the BS. RSSI is used to calculate the SNR value for the system to determine the most suitable modulation and power level for transmission.

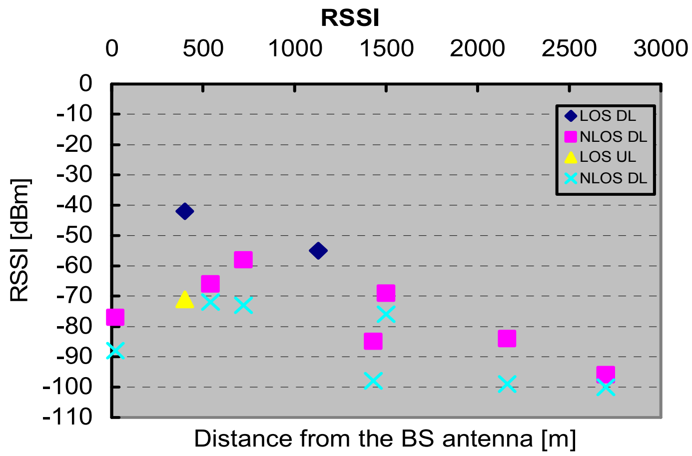

Figure 47: RSSI

Figure 47 shows that the value of the RSSI for the downlink and uplink ranges from minus 40 dBm to approximate minus 100 dBm. The RSSI in the LOS environment is higher than the NLOS environment. All of the RSSI values for the uplink are lower than downlink. This is because the transmitter power of CPE is lower than the BS's.

7.3.3.2 SNR

An Adaptive Modulation Algorithm is enabled in WiMAX implementations. It changes the modulation level dynamically according to link conditions. The purpose is to increase the probability of using the maximum possible modulation level at any given moment. If the link quality is not sufficient, then the maximum modulation level is decreased, as higher modulation levels increase the error rate. In such conditions, a higher modulation level increases the number of retransmissions before the modulation level is reduced by the Adaptive Modulation Algorithm. A high number of retransmissions reduce the overall throughput.

Equation 1 SNR Equation

$$\mathrm{SNR(dB)} = 10\log_{10}\left(\frac{P_{\mathrm{signal}}}{P_{\mathrm{noise}}}\right) = 20\log_{10}\left(\frac{A_{\mathrm{signal}}}{A_{\mathrm{noise}}}\right)$$

where P is average power and A is RMS amplitude. Both signal and noise power are measured within the system bandwidth.

The link quality can be estimated based on the SNR measurement both in downlink and uplink. If the measured SNR is less than a certain threshold, the maximum modulation level adopted is decreased in accordance with Table 19. [23]

Table 19: SNR and modulation reference

SNR [dB]	Modulation
SNR < 7	BPSK ½
7 <= SNR < 8	BPSK ¾
8 <= SNR < 10	QPSK ½
10 <= SNR <13	QPSK ¾
13 <= SNR < 16	16QAM ½
16 <= SNR < 21	16QAM ¾
21 <= SNR < 25	64QAM ⅔
25 <= SNR	64QAM ¾

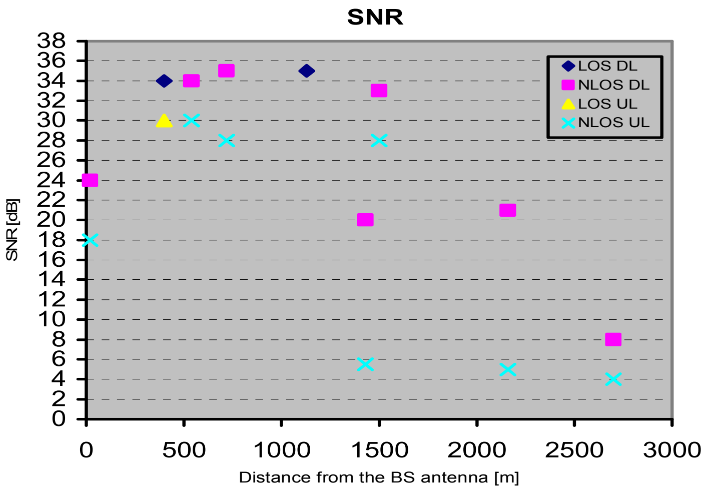

Figure 48: SNR at the measurement points

Figure 48 shows the average SNR measurements for the downlink and uplink at all the measurement points. SNR is used by the WiMAX solution to evaluate the link quality which determines the modulation adopted to transmit data. From the figure, it is clear that the SNR values at 2 LOS points and 3 NLOS points are assemble between 26 dB and 36 dB. Although the first NLOS point is closed to the BS antenna, the SNR value is much lower than some other points which are further away because it is located inside of the building. The environment results the degradation of received signal strength.

Another apparent variation occurs at the two points--both of which are approximate 1500 meters away. They are Point 5 and Point 8. There is an obvious decrease in SNR for both the downlink and uplink at Point 5 which is closer to the BS. The source of this reduction is the urban area with many buildings between the BS antenna and the measurement point. However, the SNR in downlink can still achieve 20 dB, and QAM16 ¾ was adopted for data transmission which provides up to 3.7 Mbps throughput with FTP traffic (Figure 45).

Figure 48 also shows that all of the SNRs on the uplink are smaller than downlink. The differences vary with the different environments. The main reason is the transmit power in uplink limited by the CPE. In the BreezeMAX solution, ATPC (Automatic Transmit Power Control) is enabled in the Pro CPE. Hence the Pro CPE can negotiate with the BS to decide upon the optimised transmit power. The maximum power is 20 dBm. While 28 dBm transmit power is configured in the BS. The position of the CPE antenna is another issue that affects the receiving and transmission of frames.

In Table 20 the modulations selected under certain SNR measurements in the live test can be observed.

Table 20: SNR and modulation in live test

SNR [dB]	Modulation
4, 8, 21	BPSK ½
5, 5.5	BPSK ¾
18, 20	16QAM ¾
24	QAM64 ⅔
28, 30, 33, 34, 35	QAM64 ¾

Comparing Table 18 with Table 20, we can see the difference between the reference table for Adaptive Modulation Algorithm and the live performance. For the higher modulation levels, such as QAM64 and QAM16, the range of SNR is similar to Table 18. But the SNR when BPSK is selected are very variable. In order to specify how SNR determines the modulation selection, it is important to pay more attention to the fluctuation of SNR. Figure 49 displays the variation of SNR at every test point on the uplink and downlink. The line at each point indicates the range over which SNR fluctuates, and the black dot represents the mean SNR.

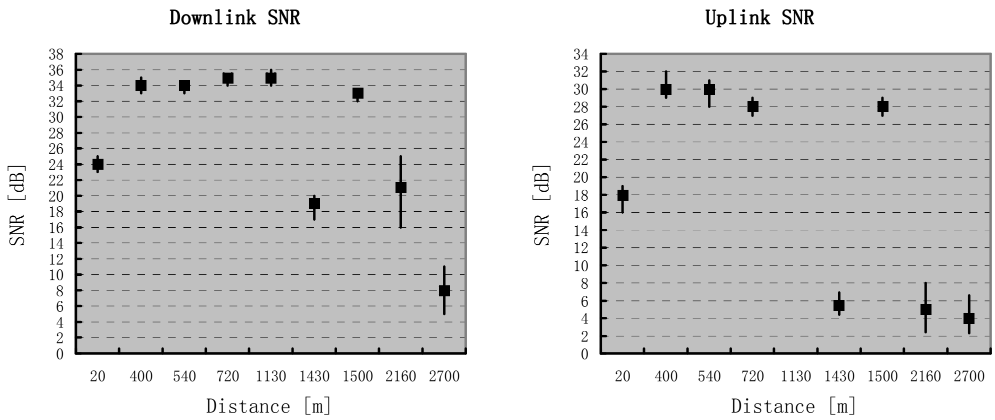

Figure 49: SNR (a) downlink (b) uplink

In Figure 49 (a), it is apparent that the downlink SNR at the last two points fluctuates over a wide range. According to Table 6, the higher modulation level was supposed to be selected for transmission over the downlink. Because of the unstable SNR values, BPSK was adopted even through the mean SNR is 21 dB.

7.3.4 The throughput with different number of CPE

The two CPEs test scenario was deployed at the LOS measurement point which is 1130 meters away from the BS and the office inside of the building in which the BS locates. One script was configured in the client connected to the CPE in the office which keeps the FTP download session running. The FTP throughput, the best TCP throughput, and the best UDP throughput were measured at the client connected to the CPE at the LOS measurement point 1130 meters away. The comparison between the only single CPE running and two CPEs running simultaneously can be observed in Figure 45. It verifies the result from the same test scenario in the lab test (Figure 22 and Figure 23).

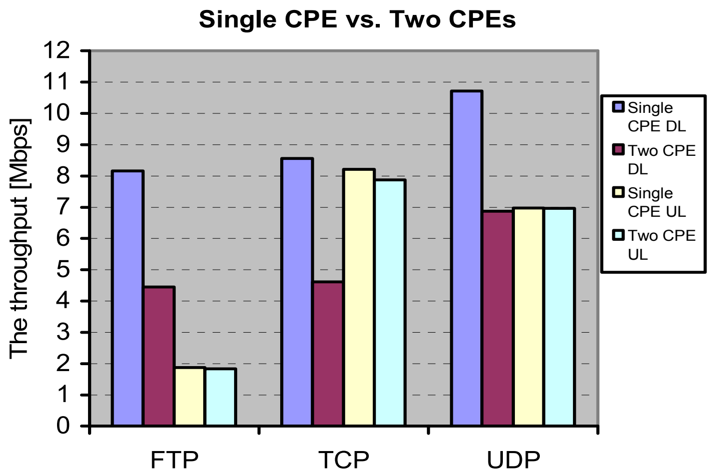

Figure 50: Throughput comparison

Figure 50 shows the decrease in throughput on the downlink when there were two CPEs running simultaneously. This behaviour is similar to the lab test scenario with different numbers of CPE. Since one CPE only had downlink traffic transmitted during the two CPEs' test, the throughput of uplink did not change too much.

7.3.5 The measurement points with different environment

In order to detect the impact caused by the obstacles and obstacles density between the BS and the CPE, we ran the additional tests at Measurement point 8 and Measurement point 10. Measurement point 8 is 1500 meters away from the BS and Measurement point 10 is 1429 meters. The distance is close. The most important different feature is Measurement point 8 locates in a flat and open area with low density. Measurement point 10 is located at an area behind a building. From the test results, it is easy to see the impact upon the performance caused by the obstacle.

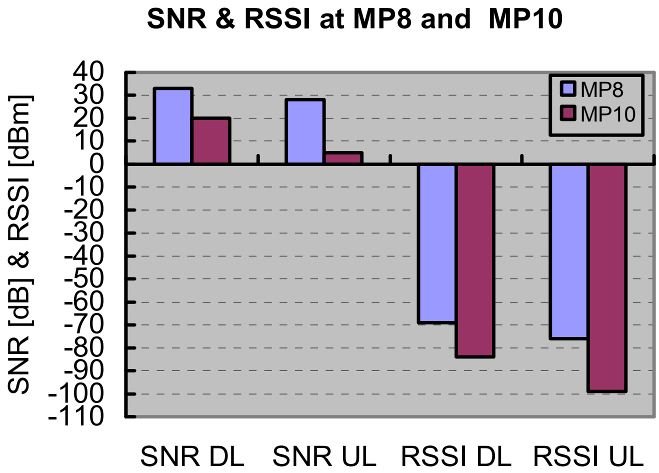

Figure 51: Radio parameters at MP8 and MP10

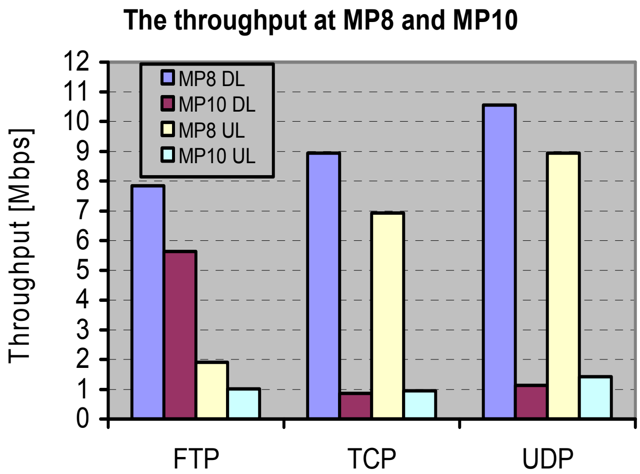

Figure 52: Throughput at MP8 and MP10

Both of these measurement points are in a NLOS environment, and the positions are close to each other. Figure 51 shows the radio parameters measured at these two points. The differences in the RSSI and SNR result in the different modulations used at these two points. Table 15 shows that QAM64 ¾ was adopted for Measurement point 8 on both downlink and uplink; QAM 16 ¾ was selected on downlink for Measurement point 10, and BPSK ¾ was used for uplink because of the lower transmit power in the CPE. In Figure 52, it is clear that there is a huge difference in the throughput of the FTP traffic, the best TCP throughput, and the best UDP throughput at these two points. The conclusion is the obstacles around the location of the CPE antenna have a serious impact on the throughput performance of the WiMAX link. Although WiMAX technology has advantage can work in a NLOS condition, the different NLOS environments affect the performance of the radio and data link significantly.

8. Conclusion

After 3 years' development, the WIDER central system has been optimized with respect to security [22] , services, and availability. In order to utilize the functionalities and services offered by the system, and provide adequate efficiency for the end user in the disaster area, the wireless access in WIDER is required to provide full NLOS coverage, point-to-multipoint wireless connection, and sufficient throughput with sufficient QoS. Currently, a wireless bridge based on the IEE 802.11 standard is adopted. Practical results from utilization in disaster areas prove that the wireless bridge can not fulfil the requirements which results in that the whole solution was compromised. After some deeper analysis and theoretical comparison of the available standardized wireless solutions, the WiMAX technology which is based on the IEEE 802.16 was examined. WiMAX's satisfactory performance in terms of coverage, throughput, multiple wireless connections, and QoS makes it suitable for enhancing WIDER.

The throughput tests show that the WiMAX solution which is operated with 3.5 MHz bandwidth can provide up to 8 Mbps throughput on the downlink and approximate 2 Mbps on the uplink with one CPE connected to the BS. As the number of CPE in the network increases, the throughput allocated to each connection is reduced; however, the total throughput increases. The integrated WiFi access into the WiMAX solution is the bottleneck on the downlink throughput for the end user. The QoS tests verify that a number of simultaneous real time applications (VoIP calls) can be supported by WiMAX with different modulations. When BPSK ½ is used, the number of simultaneous VoIP calls should not be more than ten in order to guarantee the quality of conversations. QAM64 ¾ can support up to 50 simultaneous calls. The lower the data rate supported by the modulation, the more serious problems to the real time applications experience due to variation in traffic over the WiMAX link. The live tests tell us the significant affection to the wireless access caused by the environment. In the LOS environments and the NLOS environments with low density of obstacles, the WIDER system integrated with WiMAX can provide the best throughput both on the downlink and uplink within approximate 1.5 km. When faced with a high density of obstacles, the distance is the most important metric impacting the performance of the system. At a range of 2 km with lots of obstacles, the system provides more than 1 Mbps throughput both on downlink and uplink. However, even though the signal can be detected by the CPE at a location which is 2.7 km away, but the data link is unstable.

From the test results, we can conclude that WiMAX can fulfil the requirements of WIDER in the NLOS environment within 2 km and with low obstacle density. After the configuration of the system, the whole system can be deployed easily and quickly in a disaster area. The NLOS coverage facilitates the concerning of specific location for base station antenna and CPE antenna. Several approaches can improve the system's performance. First, the omni directional antenna can be replaced by a directional antenna with more gain; secondly, the height of the CPE antenna can be increased to improve reception; finally, a BS with higher transmit power can be used.

9. Future work

More live tests can be done with the solution to obtain more statistics of the performance in different environments. A comprehensive model can be establish with the live test results to show the variation of the radio parameters, adaptive modulation scheme, and the throughput of the system with the diverse environments. A multiple CPE live test would also be worthy carrying out. By doing this test, the exact coverage of the WiMAX solution with one BS and the interference among CPEs can be determined. All of these tests can provide Ericsson Response with additional information so that they can provide an efficient communication system which is suitable to different disaster response requirements. The mesh extension topology can be considered for the future development to provide redundancy and efficiency.

As a rapidly developing technology, new solutions designed based on IEEE 802.16 standard group are and IEEE 802.20 standard will be available, such as the latest mobile WiMAX solution based on 802.16e. Meanwhile, some other new wireless solutions, such as 4G are emerging. How to utilize the new technology in the disaster response to make it more reliable and efficient is the future work for all the researchers in this field.

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Appendix A

BreezeMAX Radio Specification

Item	Description		
Frequency	Unit/Band	Uplink (MHz)	Downlink (MHz)
	AU-ODU-3.5a	3399.5-3453.5	3499.5-3553.5
	AU-ODU-3.5b	3450-3500	3550-3600
	SU-ODU-3.5	3399.5-3500	3499.5-3600
	AU-ODU-3.3e	3366-3385	3316-3335
	AU-ODU-3.3f	3381-3400	3331-3350
	SU-ODU-3.3	3366-3400	3316-3350
Operation Mode	AU, Micro Base Station	FDD, Full duplex	
	SU	FDD, Half Duplex	
Channel Bandwidth	■ 3.5 MHz ■ 1.75 MHz		
Central Frequency Resolution	0.125 MHz		
Antenna Port (SU-ODU-E, AU-ODU)	N-Type, 50 ohm		
Max. Input Power (at antenna port)	AU-ODU	-60 dBm before saturation, -17 dBm before damage	
	SU-ODU	-20 dBm before saturation 0 dBm before damage	
Output Power (at antenna port)	AU-ODU	28 dBm +/-1 dB maximum. Power control range: 15dB 18-28 dBm @ +/-1 dB, 13-18 dBm @ +/-2 dB	
	SU-ODU	20 dBm +/-1 dB maximum, ATPC Dynamic range: 40 dB	

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