Integrated Project - EUWB

Contract No 215669

Deliverable

D6.2.2

Study of capability in UWB picocells and higher layer requirements for heterogeneous networks

Contractual data:	**M18**
Actual data:	**M19**
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Participants:	**UZ, TID, THA, WIS**
Work package:	**WP6**
Security:	**PU**
Nature:	**Report**
Version:	**1.0**
Total number of pages:	**72**

Abstract

This deliverable analyses the possible use of UWB as an access technology on all-IP Heterogeneous Access Networks. UWB capabilities are assessed and compared to other radio access technologies such as UMTS, WiMAX and Wi-Fi. Throughput provided by UWB WiMedia systems is evaluated both theoretically and experimentally. The requirements to provide wireless access to IP networks are identified and different higher layer protocols (WLP, WUSB) are analysed. Finally, mobility within heterogeneous networks is discussed as well as the throughput difference between the different technologies.

Keywords

UWB, Heterogeneous, Access Networks, 4G, All-IP, WiMedia, WLP, WUSB, mobility.

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Abbreviations

3GPP	3rd Generation Partnership Project
AC	Access Category
ACK	Acknowledgement
AES	Advanced Encryption Standard
AIFS	Arbitration Inter-Frame Spacing
API	Application Programming Interface
BPSK	Binary Phase-Shift Keying
CCM	Counter with Cipher Block Chaining Message Authentication Code
CDID	Connection Device ID
CDMA	Code Division Multiple Access
CHID	Connection Host ID
CK	Connection Key
CN	Correspondent Node
CoA	Care of Address
CSMA	Carrier Sense Multiple Access
CTS	Clear To Send
CW	Contention Window
DHCP	Dynamic Host Configuration Protocol
DNTS	Device Notification Time Slot
DRP	Distributed Reservation Protocol
DWA	Device Wire Adapter
EUWB	CoExisting Short Range Radio by Advanced Ultra-WideBand Radio Technology
FA	Foreign Agent
FCS	Frame Check Sequence
FDD	Frequency-Division Duplex
FDS	Frequency-Domain Spreading
FEC	Forward Error Correction
FFI	Fixed-Frequency Interleaving
GTK	Group Temporal Key
HA	Home Agent
HCS	Header Check Sequence

HD	Hard Disk
HDR	High Data Rate
HSDPA	High-Speed Downlink Packet Access
HSUPA	High-Speed Uplink Packet Access
HWA	Host Wire Adapter
IE	Information Element
IEEE	Institute of Electrical and Electronics Engineers
IMT	International Mobile Telecommunications
IP	Internet Protocol
LDR	Low Data Rate
MAC	Media Access Control
MAP	Mobile Application Part
MAS	Medium Access Slot
MB-OFDM	MultiBand Orthogonal Frequency Division Multiplexing
MIC	Message Integrity Code
MIFS	Minimum Inter-Frame Spacing
MIMO	Multiple Input Multiple Output
MIP	Mobile IP
MM	Mobile Management
MMC	Micro-scheduled Management Command
MN	Mobile Node
MSD	Mass Storage Device
MT	Mobile Terminal
MTU	Maximum Transmission Unit
NG	Next Generation
OS	Operating System
PAL	Protocol Adaptation Layer
PCA	Prioritized Contention Access
PHY	Physical Layer
PLCP	Physical Layer Convergence Protocol
PPDU	PLCP Protocol Data Unit
PPP	Point to Point Protocol
PSDU	PHY Service Data Unit

PTK	Pair-wise Temporal Key
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase-Shift Keying
RTS	Request To Send
SIFS	Short Inter-Frame Spacing
SIR	Signal-to-Interference Ratio
TCP	Transmission Control Protocol
TDD	Time-Division Duplex
TDMA	Time Division Multiple Access
TDS	Time-Domain Spreading
TFC	Time-Frequency Code
TFI	Time-Frequency Interleaving
TG	Transaction Group
TSPEC	Traffic Specification
TXOP	Transmission Opportunity
UDP	User Datagram Protocol
UMTS	Universal Mobile Telecommunications System
USB	Universal Serial Bus
UTRA	UMTS Terrestrial Radio Access
UWB-RT	Ultra WideBand-Radio Technology
WiMAX	Worldwide Interoperability for Microwave Access
WLP	WiMedia Logical link control Protocol
WPAN	Wireless Personal Area Network
WSS	WiMedia Service Set
WUSB	Wireless USB

1 Executive summary

The purpose of this document is to analyse the possible use of UWB technology to provide network access in picocells, evaluating the capabilities offered by the UWB technology and analysing the requirements that must be fulfilled by the higher layers in order to integrate UWB as an access technology into all-IP heterogeneous networks.

In Chapter 3, the characteristics of UWB as a network access technology are analysed and compared to the other access technologies such as UMTS, WiMAX and 802.11 in terms of throughput, range, channelization and multiple access scheme. As the goal is to provide very high data rate access to wireless users in short-range picocells, the document focuses mainly on High Data Rate (HDR) UWB, i.e. WiMedia systems, and Low Data Rate (LDR) UWB systems are not considered. Nevertheless LDR UWB can also provide network access in specific applications such as remote access to sensor or localization networks, low data rate access in home automation environments, etc.

WiMedia PHY and MAC layers are analysed in depth in order to assess the effective throughput that can be achieved and experimental results of tests carried out with both Development Kits and WUSB commercial products from Wisair are also presented.

In Chapter 4 the focus is on the higher layers. On the one hand the challenges of providing wireless access to IP networks, and how they are accomplished by WiMedia PHY and MAC and higher layer protocols such as WLP and WUSB, are analysed. While WLP is specifically designed to provide network access, WUSB has been also considered as it is the most extended in commercial developments.

On the other hand, the integration of different access technologies into all-IP heterogeneous access networks requires the support of mobility among different networks and technology, i.e. vertical handover. This is not exclusive to UWB and has been, and still is, subject of extensive research. In this document a summary of the most important macro-mobility solutions, mainly based on IP mobility, is presented.

2 Introduction

In the last few decades, the proliferation of fixed and mobile access technologies and networks has provided a large choice to the network operators to offer a variety of services. These emerging access technologies and networks complement each other and offer different data rates and coverage that captures the needs and requirements of mobile users. For instance, the new generation of wireless networks such as Wi-Fi, WiMAX, UWB, etc. offers high data rates at low cost but does not guarantee a global coverage and high mobility. In contrast, the traditional and advanced cellular networks such as GSM/GPRS and UMTS provide wide area coverage and high mobility at high cost but do not offer high data rates.

In this context, HDR UWB arises as a potential access technology providing very high data rate access in short-range picocells. Data rates up to 480 Mbps provided by WiMedia are unmatched as only IEEE 802.11n is theoretically able to reach higher data rates, but with a much higher level of complexity so no solutions have been implemented so far. Wireless USB (WUSB) interfaces are expected to be embedded on laptops and, thanks to the low complexity, low cost and low power consumption of UWB technology, are also likely to be embedded on handheld devices. For example, battery lifetime of handheld devices such as smartphones and PDAs is highly reduced when Wi-Fi is used, which could be improved with low power consumption and better power management of UWB.

In such a diverse environment, the concept of being always connected becomes always best connected. This refers to being not only always connected, but also being connected in the best possible way by exploiting the heterogeneity offered by the access networks. Moreover, mobile hosts are being increasingly equipped with multiple interfaces capacitating access to different wireless networks, all of which introduces the need for network interoperability in this heterogeneous environment via a common IP-based core network.

Internet protocol (IP) provides a universal network-layer protocol for wireline packet networks, and is viewed as an attractive candidate to play the same role in wireless systems. IP provides a globally successful open infrastructure for creating and providing services and applications. All-IP wireless networks will enable the abundant applications and software technologies developed for wired IP networks to be used over wireless networks. With IP as the common network layer protocol, an IP-based mobile device with multiple radio interfaces could roam between different wireless systems.

Nevertheless, IP faces several challenges in mobile wireless networks. Communication over wireless links is characterized by limited bandwidth, high latencies, high bit-error rates and temporary disconnections that must be dealt with by network protocols and applications. In addition, protocols and applications have to handle user mobility and the handoffs that occur as users move from cell to cell in cellular wireless networks.

Furthermore, heterogeneous networks require mobility among the different network and technologies. IP is ill-suited for mobility, as IP address is not only used to uniquely identify a host, but also to route traffic through the network as it identifies the network that the host belongs to. Inter-domain roaming or macromobility has been and is still being subject of extensive research, with Mobile IP as the general term for several proposed solutions to this problem.

Therefore, one of the research challenges for next generation all-IP-based wireless systems is the design of intelligent mobility management techniques that take advantage of IP-based technologies to achieve global roaming among various access technologies.

3 UWB as a network access technology

This section analyses the capabilities of UWB as a network access technology in terms of physical data rate, achievable throughput, range, multiple access scheme and channelization scheme. First, other radio access technologies such as UMTS, WiMAX and 802.11 (Wi-Fi) are analysed. Then the WiMedia PHY and MAC layers are presented and WiMedia capacity is assessed. Finally, some experimental results with commercial devices are presented.

3.1 Radio access technologies

3.1.1 UMTS

Universal Mobile Telecommunications System (UMTS) is one of the third-generation (3G) mobile telecommunications technologies. It is specified by 3GPP and is part of the global ITU IMT-2000 standard. It is also referred to as W-CDMA.

UMTS Terrestrial Radio Access (UTRA) provides several different terrestrial air interfaces. The most widely extended is UTRA-FDD (also referred to as IMT-2000 CDMA Direct Spread or UMTS-FDD), but UTRA-TDD (also referred to as IMT-2000 CDMA TDD or UMTS-TDD) is also considered mainly for microcellular and indoor environments. Both UTRA-FDD and UTRA-TDD are part of 3GPP UMTS Release 99 standard. In the Release 4 UTRA-TDD 1.28 Mcps Low Chip Rate (also referred to as TD-SCDMA or UMTS-TDD 1.28 Mcps LCR) was also defined, although it has only been adopted in China.

UMTS-FDD uses frequency division duplexing (FDD) with separate radio channels for uplink and downlink. On the other hand, UMTS-TDD uses time division duplexing (TDD). Unlike UMTS-FDD, it does not need separate frequency bands for up- and down-stream. Instead, time slots within the frame are allocated in fixed percentage for downlink and uplink.

In 1997, the ECC allocated the 1900 – 1980 MHz, 2010 – 2025 MHz and 2110 – 2170 MHz bands for the introduction of UMTS and consequently most of the currently deployed networks operate in these bands. Later the ECC also allowed the use of other frequency bands, such as the band 2500 – 2690 MHz and the GSM bands (880 – 915 MHz, 925 – 960 MHz, 1710 – 1785 MHz and 1805 – 1880 MHz).

According to the latest ECC decisions, the following frequency bands are allocated for UMTS systems operation:

- The frequency band 1920 – 1980 MHz (uplink) paired with 2110 – 2170 MHz (downlink) for FDD operation.
- The frequency band 1900 – 1920 MHz may be used either for TDD or for FDD uplink.
- The frequency band 2010 – 2025 MHz may be used either for TDD or for FDD uplink.
- The frequency band 2500 – 2570 MHz (uplink) paired with 2620 – 2690 MHz (downlink) for FDD operation
- The frequency band 2570 – 2620 MHz may be used either for TDD or for FDD downlink.
- The frequency band 880 – 915 MHz (uplink) paired with 925 – 960 MHz (downlink) for FDD operation.

- The frequency band 1710 – 1785 MHz (uplink) paired with 1805 – 1880 MHz (downlink) for FDD operation.

UMTS uses a Direct Sequence CDMA (DS-CDMA) channel access method. Each user in a CDMA system uses a different code to modulate their signal. Radio channels are 5MHz wide with a constant chip rate of 3.84 Mcps. QPSK and BPSK modulations are used in the downlink and uplink respectively. As channel bandwidth is 5 MHz, 12 FDD channels are available in the 1920 – 1980 MHz (uplink) and 2110 – 2170 MHz (downlink) bands, while 4 and 3 TDD channels are available in the 1900 – 1920 MHz and 2010 – 2025 MHz bands respectively. Due to the correlation characteristics of pseudo-noise (PN) sequences, a channel frequency reuse of 1 can be used, which means that the same channel can be used in adjacent cells.

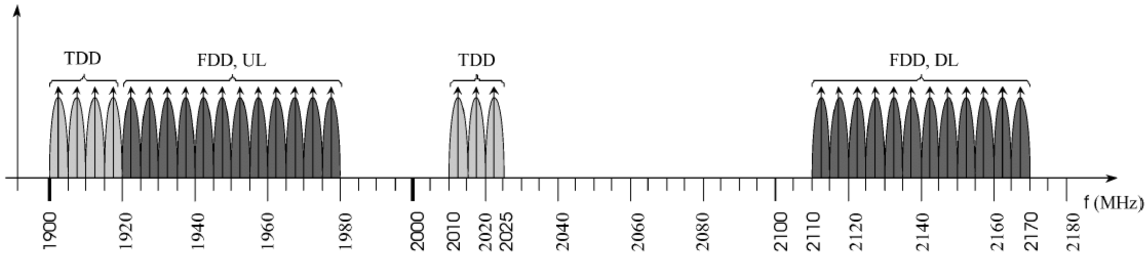

Figure 3-1: UMTS channel layout in 1900-1980 MHz, 2010-2025 MHz and 2110-2170 MHz bands

Variable user data rate is supported with different spreading factors. Systems based on UMTS Release 99 provide users with downlink rates of 384 kbps and uplink rates of 64 kbps, although data rates are enhanced in subsequent releases with HSDPA in Release 5 and HSUPA in Release 6.

High-Speed Downlink Packet Access (HSDPA) is an enhanced 3G mobile telephony communication protocol in the HSPA family, also referred to as 3.5G, which allows UMTS networks to have higher data transfer speeds and capacity. Current HSDPA deployments support downlink speeds of 1.8, 3.6, 7.2 and 14.4 Mbps. HSDPA is part of the UMTS standards since 3GPP Release 5, which also accompanies an improvement on the uplink providing a new bearer of 384 kbps. The previous maximum bearer was 128 kbps. As well as improving data rates, HSDPA also decreases latency and so the round trip time for applications. Newly introduced are the High Speed Downlink Shared Channels (HS-DSCH), the adaptive modulation QPSK and 16QAM and the High Speed Medium Access protocol (MAC-HS) in base station. The HS-DSCH delivers the improved downlink performance using adaptive modulation and coding (AMC), fast packet scheduling at the base station, and fast retransmissions from the base station, known as hybrid automatic repeat-request (HARQ). The HS-DSCH downlink channel is shared between users using channel-dependent scheduling to make the best use of available radio conditions. Each user device periodically transmits an indication of the downlink signal quality, as often as 500 times per second. Using this information from all devices, the base station decides which users will be sent data on the next 2 ms frame and how much data should be sent for each user. More data can be sent to users which report high downlink signal quality.

High-Speed Uplink Packet Access (HSUPA) is a 3G mobile telephony protocol in the HSPA family with uplink speeds up to 5.76 Mbps. The name used to refer to HSUPA within 3GPP is Enhanced Uplink (EUL). The specifications for HSUPA are included in 3GPP UMTS Release 6 standard. The technical purpose of the Enhanced Uplink feature is to improve the performance of uplink dedicated transport channels, i.e. to increase capacity and throughput and reduce delay. HSUPA uses an uplink enhanced dedicated channel (E-DCH) on which it employs link adaptation methods similar to those employed by HSDPA, namely shorter Transmission Time Interval (TTI) enabling faster link adaptation and HARQ with incremental redundancy making retransmissions more effective.

Maximum range of UMTS systems is approximately 35 km. Nevertheless, achievable throughput is dependent on the distance to the base station. Furthermore, as channel capacity must be shared among the users, cell size is usually limited by the amount of users and traffic patterns. This way, three cell categories are defined:

- Macrocell: Coverage radius between 1 km to 35 km in rural areas and along roads. Offers data rates up to 144 kbps to high speed users (vehicles).
- Microcell: Coverage radius between 50 m and 1 km in densely populated urban and suburban areas. Offers data rates up to 384 kbps to users with limited mobility (pedestrian).
- Picocell: Coverage radius up to 50 m in indoor environments. Offers data rates up to 2 Mbps to stationary/nomadic users.

Achievable throughput with HSDPA is also dependent on distance. Maximum throughput (14.4 Mbps) can be achieved up to 1km from a base station, while at 6 km, the data rate drops to less than 1 Mbps.

Capacity of CDMA systems such as UMTS is not constant and it depends on the interference level, which is proportional to the number of users. Maximum number of users in a cell depends on the QoS requirements of each user in terms of data rate and SIR. Maximum number of voice users in a cell is approximately 50-60, but if 384 kbps data transmissions are considered, maximum number of users per cell would be reduced to 5-6.

Concerning HSDPA, a maximum of 15 channelization codes can be allocated to HSDPA. As HS-DCSH channel is shared between users, there is no limitation on the maximum number of users, although throughput available for each user will decrease as the number of users increase. For example, if 15 codes are allocated, a maximum total throughput of 10.1 Mbps can be achieved with 16-QAM which will be shared among all the users. Therefore, almost 30 simultaneous 384 kbps users could be served.

3.1.2 WiMAX

The WiMAX technology is part of the 802.16 Standards from IEEE. The 802.16 specification applies across a wide swath of the RF spectrum, and WiMAX could function on any frequency below 66 GHz. Nevertheless, there is no uniform global licensed spectrum for WiMAX, although the WiMAX Forum has published three licensed spectrum profiles: 2.3 GHz, 2.5 GHz and 3.5 GHz. WiMAX supports very high data throughput and is intended to deliver services at several Mbps to customers.

WiMAX equipments are built around 2 main versions: the 802.16d (or 802.16-2004), also known as “fixed WiMAX”, and the 802.16e (or 802.16-2005) also called “mobile WiMAX”.

3.1.2.1 WiMAX 802.16d

IEEE 802.16d is part of the WiMAX family standards for fixed applications and uses OFDM waveform with 256 carriers. Both TDD and FDD are part of the standard. The standard is defined by the IEEE standardisation and the WiMAX Forum makes its promotion by providing different profiles (for interoperability).

The WiMAX Forum has developed a certification program that extensively tests subscriber devices and base stations to ensure that they conform to the standards, perform as expected, and interoperate with equipment from other vendors. Today certification focuses on conformance to the standard at the Physical (PHY) and Media Access Control (MAC) layers, and on interoperability.

A certification profile is closely associated to appropriate regulation: it defines a spectrum band, one or multiple channel sizes, and a duplexing mode. Active profiles for 802.16d are the followings:

Table 3-1: 802.16d profiles certification by WiMAX Forum

Frequency Band	**Duplex mode**	**Channel bandwidth**
3.4-3.6 GHz	TDD	3.5MHz
3.4-3.6 GHz	FDD	3.5MHz

Concerning range, for a 3.5 MHz channel in the 3.5 GHz band, range varies from 30 to 50 km in line-of-sight and from 4 to 9 km in non-line-of-sight. Nevertheless, WiMAX can either operate at higher bitrates or over longer distances but not both: operating at the maximum range of 50 km data rate must be reduced in order to maintain bit error rate. Conversely, a shorter distance to the base station allows a device to operate at higher bitrates.

Consequently, throughput between subscriber stations and the base station is determined largely by proximity. Although theoretically maximum achievable throughput is 70 Mbps, there are no known examples of WiMAX services being delivered at bit rates over around 40 Mbps. In practice, users will have a range of 2-3 Mbps services.

Like most wireless systems, available bandwidth is shared between users in a given radio sector. 802.16 MAC uses a scheduling algorithm for which the subscriber station needs to compete only once (for initial entry into the network). After that it is allocated an access slot by the base station. The time slot can enlarge and contract, but remains assigned to the subscriber station. The scheduling algorithm also allows the base station to control QoS parameters by balancing the time-slot assignments among the application needs of the subscriber stations.

3.1.2.2 WiMAX 802.16e

In December, 2005 the IEEE ratified the 802.16e amendment to the 802.16 standard. This amendment adds the features and attributes to the standard necessary to support mobility.

3.1.2.2.1 Physical layer

The Mobile WiMAX Air Interface adopts Orthogonal Frequency Division Multiple Access (OFDMA) for improved multi-path performance in non-line-of-sight environments. Scalable OFDMA (SOFDMA) is introduced in the IEEE 802.16e Amendment to support scalable channel bandwidths from 1.25 to 20 MHz. A benefit of the 802.16e OFDMA specification is that the bandwidth of the system is scalable. There is a fixed relationship between the occupied bandwidth and the FFT sizes: 128, 512, 1024, and 2048. 802.16e systems may provide the users with a downlink and uplink rate a little bit higher than the 802.16d standard.

As for the 802.16d, certification profiles are defined by the WiMAX Forum. The following table details these profiles.

Table 3-2: 802.16e profiles certification by WiMAX Forum

Frequency Band	Duplex mode	Channel bandwidth
2.3-2.4GHz	TDD	5, 8.75, 10MHz
2.496-2.69GHz	TDD	5, 10MHz
3.4-3.6GHz	TDD	5, 7, 10MHz

WiMAX 802.16e offers a wide range of possible data rates according to the modulation, code rate and channel bandwidth. Physical data rate is dynamically adapted to the transmission conditions in order to achieve the best performance on each situation.

The Table below summarizes the modulation and coding supported in 802.16e. Support for QPSK, 16QAM and 64QAM are mandatory in the 802.16e. Both Convolutional Code (CC) and Convolutional Turbo Code (CTC) with variable code rate and repetition coding are supported.

Table 3-3: Mobile WiMAX Supported Code and Modulation

		Download	Upload
Modulation		QPSK, 16QAM, 64QAM	QPSK, 16QAM, 64QAM
Code Rate	CC	1/2, 2/3, 3/4, 5/6	1/2, 2/3, 5/6
	CTC	1/2, 2/3, 3/4, 5/6	1/2, 2/3, 5/6
	Repetition	x2, x4, x6	x2, x4, x6

The combination of various modulations and code rates provides a fine resolution of data rates as shown in the table below which shows the data rates for 5 and 10 MHz.

Table 3-4: Mobile WiMAX PHY Data Rate

Parameter	Downlink	Uplink	Downlink	Uplink
FFT Size	512		1024	
Null Sub-Carriers	92	104	184	184
Pilot Sub-Carriers	60	136	120	280
Data Sub-Carriers	360	272	720	560
Sub-Channels	15	17	30	35
Symbol Period, Ts	102.9 microseconds			

<table>
<tr><td colspan="2">Frame Duration</td><td colspan="4">5 milliseconds</td></tr>
<tr><td colspan="2">OFDM Symbols/Frame</td><td colspan="4">48</td></tr>
<tr><td colspan="2">Data OFDM Symbols</td><td colspan="4">44</td></tr>
<tr><td rowspan="2">Mod.</td><td rowspan="2">Code Rate</td><td colspan="2">5 MHz Channel</td><td colspan="2">10 MHz Channel</td></tr>
<tr><td>Downlink Rate (Mbps)</td><td>Uplink Rate (Mbps)</td><td>Downlink Rate (Mbps)</td><td>Uplink Rate (Mbps)</td></tr>
<tr><td rowspan="5">QPSK</td><td>1/2 CTC, 6x</td><td>0.53</td><td>0.38</td><td>1.06</td><td>0.78</td></tr>
<tr><td>1/2 CTC, 4x</td><td>0.79</td><td>0.57</td><td>1.58</td><td>1.18</td></tr>
<tr><td>1/2 CTC, 2x</td><td>1.58</td><td>1.14</td><td>3.17</td><td>2.35</td></tr>
<tr><td>1/2 CTC, 1x</td><td>3.17</td><td>2.28</td><td>6.34</td><td>4.70</td></tr>
<tr><td>3/4 CTC</td><td>4.75</td><td>3.43</td><td>9.50</td><td>7.06</td></tr>
<tr><td rowspan="2">16QAM</td><td>1/2 CTC</td><td>6.34</td><td>4.57</td><td>12.67</td><td>9.41</td></tr>
<tr><td>3/4 CTC</td><td>9.50</td><td>6.85</td><td>19.01</td><td>14.11</td></tr>
<tr><td rowspan="4">64QAM</td><td>1/2 CTC</td><td>9.50</td><td>6.85</td><td>19.01</td><td>14.11</td></tr>
<tr><td>2/3 CTC</td><td>12.67</td><td>9.14</td><td>25.34</td><td>18.82</td></tr>
<tr><td>3/4 CTC</td><td>14.26</td><td>10.25</td><td>28.51</td><td>21.17</td></tr>
<tr><td>5/6 CTC</td><td>15.84</td><td>11.42</td><td>31.68</td><td>23.52</td></tr>
</table>

3.1.2.2.2 Capacity

802.16e uses scalable orthogonal frequency-division multiple access (SOFDMA) as MAC layer allowing the reuse schemes to increase the capacity.

Although base stations have a limit of active connections, e.g. 512 active connections per sector, the maximum number of subscribers that can be served in general depends on the mix of services and consequent data rates. For example, with reference to Table 3-4, at 10 MHz, and using the modulation scheme 64 QAM 3/4, an uplink data rate of 21 Mbps can be supported as a peak value. Hence, if circuit emulation guaranteed services are provided at 256 kbps uplink rate, a maximum of about 80 subscribers can be supported per sector. If 2x2 MIMO is used with spatial multiplexing, the number can rise to about 150. A multicast video service at 6Mbps, for example, uses up 25% of the capacity of a 10 MHz system which is 28 Mbps for downlink, so just 4 subscribers would be supported.

In order to increase the number of users that may be served, different techniques can be applied such as sectorization, MIMO spatial multiplexing, increasing channel bandwidth or adding more channels (radio cards) to the base station.

3.1.2.2.3 Link budget

Even if there are several profiles for 802.16e which include various channel bandwidths in various frequency bands, the link budget characteristics are pretty common.

For mobile services the range will usually be limited by the uplink not the downlink. Since subscriber station devices have to be small and lightweight to be truly mobile, battery and antenna size are limited. This limits the transmit power and the antenna gain. Devices for portable and nomadic use, such as laptops will often have higher antenna gains and, since in many cases will have access to AC power, will also be capable of higher transmit power. Subscriber devices for fixed applications will have even greater antenna gains.

The location of mobile subscribers also plays a key role in determining the link budget. Active subscribers may be in an outdoor location, a moving vehicle, or deep inside a building requiring that signals have to penetrate multiple walls.

The subscriber station antenna height relative to the base station antenna height can also impact the link budget by several dB. Subscriber location alone can result in a 20 to 25 dB variation in the link budget.

Figure 3-2 provides a view of the relative ranges for different customer terminals in varied locations.

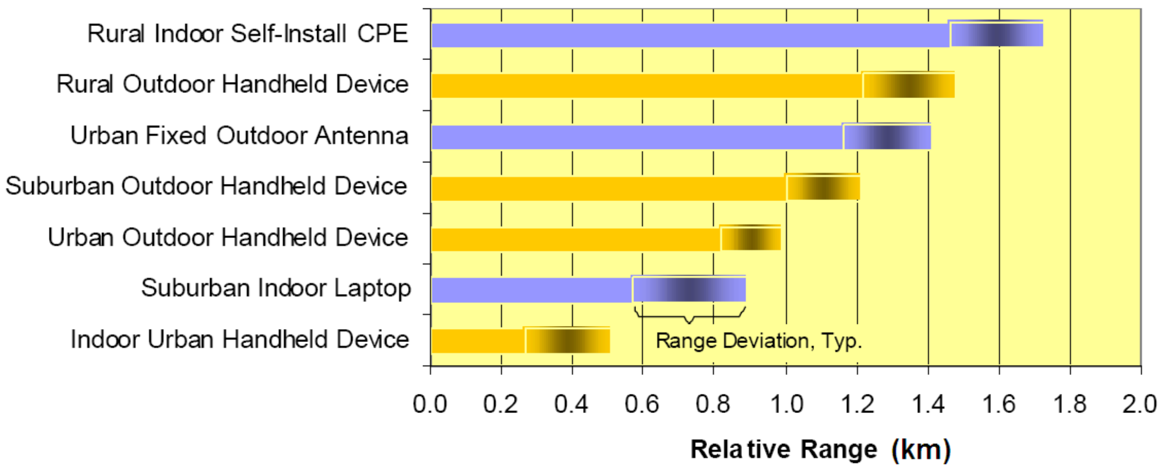

Figure 3-2: WiMAX mobile: Range relative to device type and location

3.1.2.3 802.16e downlink channel capacity

This part provides a summary of the predicted relative downlink channel capacity. The results are based on a simulation methodology developed by 3GPP2, the traffic is assumed to be full buffer FTP traffic and proportional fair scheduling is assumed. The simulations assume a deployment of nineteen 3-sector base stations with a spacing of 2.8 km and a heterogeneous mix of mobile users as summarized in the table below:

Table 3-5: Mobile WiMAX: Summary of users for throughput simulation

ITU Channel Multipath Model	Paths	Speed	Fading	% of Users
ITU Pedestrian A	1	3km/hr	Jakes	30%
ITU Pedestrian B	3	10km/hr	Jakes	30%
ITU Pedestrian A	2	30km/hr	Jakes	20%
ITU Pedestrian A	1	120km/hr	Jakes	10%
Single Path	1	0, fDoppler=1.5Hz	Jakes	10%

The parameters used for the simulation are the following:

Table 3-6: Mobile WiMAX: Parameters used for throughput simulation

Parameters	Value
Frequency Band	2500 MHz
Duplex	TDD
Channel Bandwidth	10 MHz
BS to BS Spacing	2.8 km
BS Maximum Tx Power	+40dBm
Mobile Station Maximum Tx Power	+23dBm
BS Antenna Gain	15dBi
Mobile Station Antenna Gain	-1dBi
Mobile Station Antenna	Tx:1; RX:2
BS Antenna Height	32 meters
Mobile Station Antenna Height	1.5 meters

The relative Channel capacity by users with variable Antenna Configurations is the following:

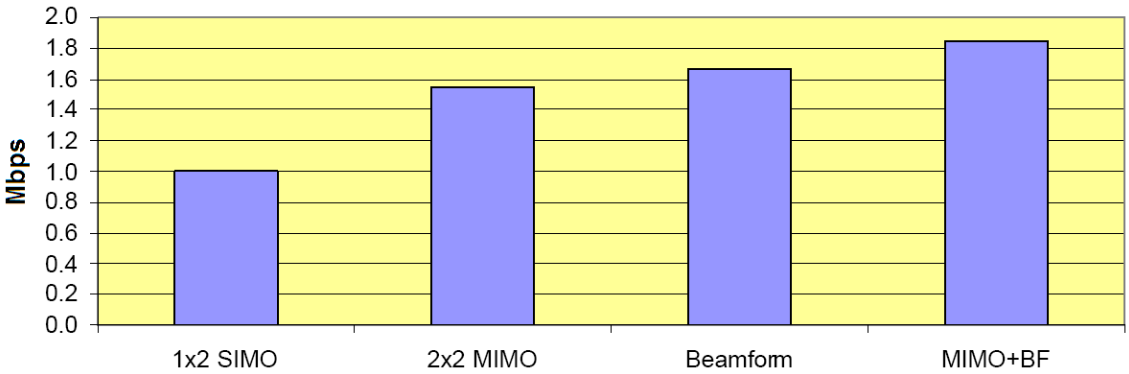

Figure 3-3: WiMAX mobile: Relative Channel Capacity per users for varied Antenna Configuration

WiMAX Mobile with the OFDMA technology supports different reuse schemes to improve overall spectrum efficiency. Two common frequency reuse configurations for a multi-cellular deployment with 3-sector base stations are a sector reuse of 3 and a sector reuse of 1 (also referred to as universal frequency reuse). With a frequency reuse of 1 the same channel is deployed in each of the three base station sectors. This approach has the advantage of using the least amount of spectrum and in many cases, may represent the only deployment reuse alternative due to limited spectrum availability. As a result, there are areas subject to interferences and some downlink channel capacity is sacrificed since some subcarriers will not be fully utilized throughout the entire cell. Nevertheless, the downlink spectral efficiency for WiMAX with universal reuse is still quite high.

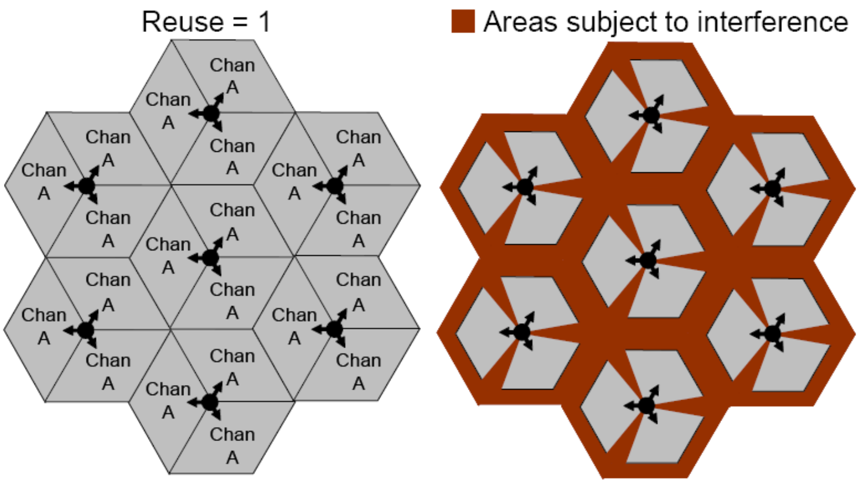

Figure 3-4: WiMAX mobile: frequency reuse of one

With reuse 3, each sector is assigned a unique channel. It eliminates interference at the sector boundaries and significantly decreases co-channel interference between neighbouring cells. Adjacent channel interference at the sector boundaries is controlled by the orthogonal nature of the subcarriers inherent with OFDMA. A reuse of 3 enables greater use of all of the subcarriers thus increasing the spectral efficiency of each channel, but requires three times as much spectrum.

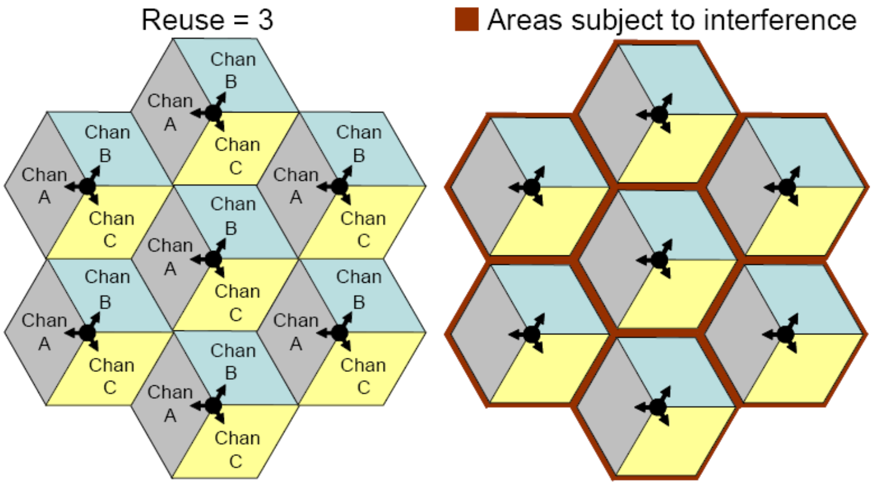

Figure 3-5: WiMAX mobile: frequency reuse of three

3.1.3 802.11

802.11 is the IEEE standardization group devoted to WLAN networks. The original recommendation was published in 1997 and since then several standards have been developed, most notably 802.11a, 802.11b, 802.11g and 802.11n. Except for 802.11a, which only operates at 5 GHz, and 802.11n, which optionally operates at 5 GHz, 802.11 devices have primarily used the spectrum in 2.4 GHz.

Each one of the above-described bands is divided into channels. For example the 2.4000–2.4835 GHz band is divided into 13 channels each of width 22 MHz spaced 5 MHz apart, to which Japan adds a 14th channel 12 MHz above channel 13. Availability of channels is regulated by country, constrained in part by how each country allocates radio spectrum to various services.

As channel bandwidth is 22 MHz and channels are spaced only 5MHz apart, adjacent channels overlap and will interfere with each other, as it is shown in Figure 3-6. One consequence is that stations can only use every fourth or fifth channel without overlap. Typical channel layouts are 1/7/13 or 1/5/9/13. Overlap between the channels may cause unacceptable degradation of signal quality and throughput. However, overlapping channels may be used under certain circumstances. This way, more channels are available.

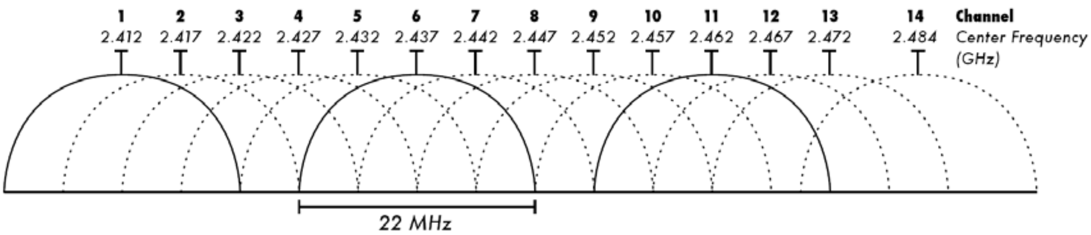

Figure 3-6: 802.11b/g channel layout for 2.4 GHz band

Table 3-7 specifies the channels and centre frequencies for the 2.4 GHz band (802.11b/g/draft-n) and their availability in United States, Europe and Japan.

Table 3-7: Channel availability for 2.4 GHz band (802.11b/g/draft-n)

Channel	Frequency (MHz)	United States	Europe	Japan
1	2412	Yes	Yes	Yes
2	2417	Yes	Yes	Yes
3	2422	Yes	Yes	Yes
4	2427	Yes	Yes	Yes
5	2432	Yes	Yes	Yes
6	2437	Yes	Yes	Yes
7	2442	Yes	Yes	Yes
8	2447	Yes	Yes	Yes
9	2452	Yes	Yes	Yes
10	2457	Yes	Yes	Yes
11	2462	Yes	Yes	Yes
12	2467	No	Yes	Yes
13	2472	No	Yes	Yes
14	2484	No	No	.11b only

Concerning the 5 GHz frequency band (802.11a/h/j/draft-n), 19 non-overlapping 20 MHz channels are available in the 5170-5330 GHz and 5490-5710 GHz bands. In the United States there are also 5 channels available in the 5735-5835 GHz band, while 4 channels in the 4910-4990 GHz band are available in Japan. Table 3-8 summarizes channel availability for the 5 GHz band.

Table 3-8: Channel availability for 5 GHz band (802.11a/h/j/draft-n)

Channel	Frequency (MHz)	United States	Europe	Japan
36	5180	Yes	Yes	Yes
40	5200	Yes	Yes	Yes
44	5220	Yes	Yes	Yes
48	5240	Yes	Yes	Yes
52	5260	Yes	Yes	Yes
56	5280	Yes	Yes	Yes
60	5300	Yes	Yes	Yes
64	5320	Yes	Yes	Yes
100	5500	Yes	Yes	Yes
104	5520	Yes	Yes	Yes
108	5540	Yes	Yes	Yes
112	5560	Yes	Yes	Yes
116	5580	Yes	Yes	Yes
120	5600	Yes	Yes	Yes
124	5620	Yes	Yes	Yes

128	5640	Yes	Yes	Yes
132	5660	Yes	Yes	Yes
136	5680	Yes	Yes	Yes
140	5700	Yes	Yes	Yes
149	5745	Yes	No	No
153	5765	Yes	No	No
157	5785	Yes	No	No
161	5805	Yes	No	No
165	5825	Yes	No	No
184	4920	No	No	Yes
188	4940	No	No	Yes
192	4960	No	No	Yes
196	4980	No	No	Yes

All the devices connected to an access point share the channel using CSMA/CA (Carrier sense multiple access with collision avoidance), that may be supplemented with the exchange of Request To Send and Clear To Send packets to avoid the problem of hidden terminal. The maximum number of users that can be connected to an access point is not limited theoretically. Nevertheless, real access point implementations limit this value in order to avoid global performance degradation. A typical default value for the maximum number of devices is 100.

The original 802.11 standard in 1997 supported physical data rates of 1 Mbps and 2 Mbps. 802.11b extended physical data rates to 5.5 Mbps and 11 Mbps. 802.11a and 802.11g are able to operate with 8 different physical data rates in the range between 6 Mbps and 54 Mbps. 802.11n increases physical data rate through different PHY and MAC improvements, most notably the use of multiple antennas (up to 4) in transmission and reception (MIMO) and the possibility to use 40 MHz channels. Expected maximum data rates are 300 Mbps for 20MHz channels and 600 Mbps for 40MHz channels, although currently certified devices only use 2 antennas and feature physical data rates of 144.4 Mbps for 20MHz channels and 300 Mbps for 40MHz channels.

Nevertheless, due to PHY and MAC overhead, channel access technique (CSMA/CA), guard intervals and acknowledgement policies, achievable throughput is approximately 50% of maximum physical data rate. For 802.11a and 802.11g, throughputs of 22-27 Mbps are typically obtained. Concerning 802.11n, throughputs of 110-130 Mbps have been experienced with current developments.

The range of 802.11 systems depends on the selected physical data rate and the environment characteristics, so all the values specified must be considered as approximated. For 802.11b, range varies from 150 m. at 1 Mbps to 50 m. at 11 Mbps in indoor environments. For 802.11a and 802.11g range varies from 70-90 m. at 6 Mbps to 10-30 m. at 54 Mbps in indoor environments. In outdoor environments, values for maximum range are multiplied by a factor of 3.

Concerning 802.11n, range can be extended taking advance of spatial diversity provided by the use of multiple antennas. This way, range is expected to be between two and four times the range achieved by 802.11g for similar data rates. As data rate increases, range is reduced and values around 100 m. and 30 m. are expected for data rates of 100 Mbps and 300 Mbps respectively.

3.2 Study of UWB capabilities in picocells

High Data Rate UWB systems are candidates to provide network access in picocells. This section presents the main characteristics of UWB concerning capabilities (data rates, throughput, range, number of users, channelization) for network access in picocells, focusing on the widely extended WiMedia system.

3.2.1 PHY layer

The ECMA-368 Standard [3] specifies the WiMedia UWB physical layer (PHY) and Medium Access Control Layer (MAC). The UWB spectrum is divided into 14 bands, each with a bandwidth of 528 MHz. The WiMedia Standard specifies a MultiBand Orthogonal Frequency Division Modulation (MB-OFDM) scheme to transmit information. A total of 110 subcarriers (100 data carriers and 10 guard carriers) are used per band to transmit the information. In addition, 12 pilot subcarriers allow for coherent detection.

The WiMedia PHY transmits a waveform constructed from the output of an IFFT function to produce an OFDM symbol. All symbols are the same length and have an effective raw data rate of 640Mbps. As sampling frequency is 528 MHz and each OFDM symbol has 165 samples (128 from IFFT plus 37 zero-padded prefix), symbol duration is 312.5 ns. Data is coded across the carriers of the OFDM symbol and also across blocks of 6 consecutive symbols. Consequently, symbols are always transmitted in blocks of 6.

As all symbols carry data at the same raw rate (640Mbps), the payload data rates are obtained by redundantly coding the data over the OFDM symbols. Coding of the inputs to the IFFT provides a range of coded data rates (53.3, 80, 106.7, 160, 200, 320, 400 and 480 Mbps). Frequency-domain spreading (FDS), time-domain spreading (TDS), and forward error correction (FEC) coding are used to vary the data rates. The FEC used is a convolutional code with coding rates of 1/3, 1/2, 5/8 and 3/4. Higher redundancy improves the probability of successfully decoding the data at the cost of a lower data rate. Table 3-9 shows the modulation, coding rate and spreading schemes used to produce each one of the available payload data rates, as well as the amount of information bits coded in each block of 6 OFDM symbols.

Table 3-9: PSDU rate-dependent parameters

Data Rate (Mbps)	Modulation	Coding Rate	FDS	TDS	Coded bits / 6 OFDM symbol	Info bits / 6 OFDM symbol
53.3	QPSK	1/3	YES	YES	300	100
80	QPSK	1/2	YES	YES	300	150
106.7	QPSK	1/3	NO	YES	600	200
160	QPSK	1/2	NO	YES	600	300
200	QPSK	5/8	NO	YES	600	375
320	DCM	1/2	NO	NO	1200	600
400	DCM	5/8	NO	NO	1200	750
480	DCM	3/4	NO	NO	1200	900

Information sent over the WiMedia PHY is organized in sets of symbols forming frames. Figure 3-7 below shows the general structure of a WiMedia frame:

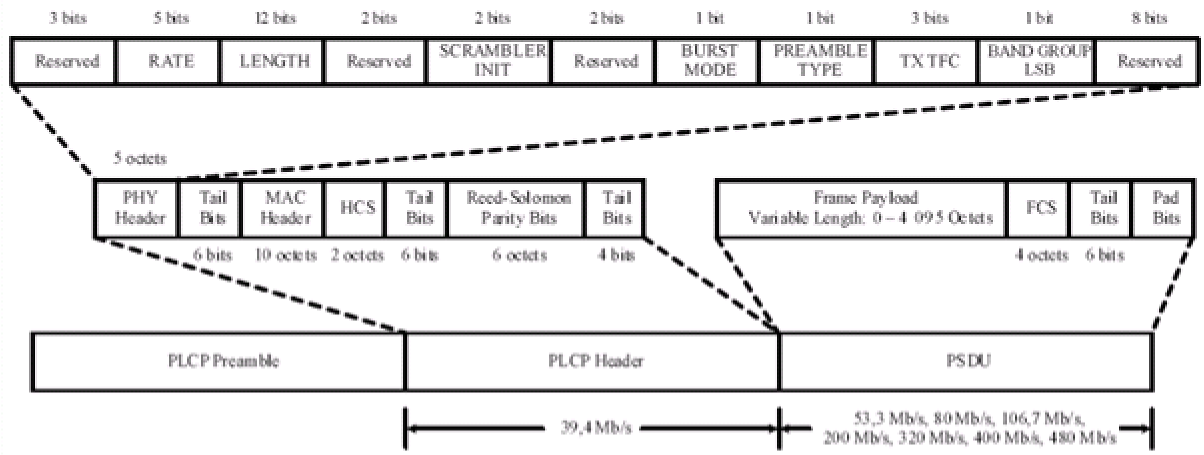

Figure 3-7: Standard PPDU structure

Frames are made up of three parts:

• A Standard or Burst PLCP Preamble

The PLCP preamble is the first component of the PPDU and can be further decomposed into a packet/frame synchronization sequence, and a channel estimation sequence. The goal of the PLCP preamble is to aid the receiver in timing synchronization, carrier-offset recovery, and channel estimation. Frames can use standard preambles or burst preambles. Standard preambles are used in most cases and burst preambles can be used in bandwidth-critical applications where the overhead of a standard preamble would be too large.

• A PLCP Header

The Header contains information about the nature of the frame and how to process it. It specifically targets one receiving device or a group of devices, gives information on the sender and indicates if this frame is part of a sequence of frames. The PLCP header can be further decomposed into a PHY header, MAC header, header check sequence (HCS), tail bits, and Reed-Solomon parity bits.

• An optional PSDU that contains the Payload, FCS and Tail/Pad bits

The PSDU is the last major component of the PPDU and is formed by concatenating the frame payload with the frame check sequence (FCS), tail bits, and finally pad bits, which are inserted in order to align the data stream on the boundary of the symbol interleaver. The payload contains the actual data to be transmitted. For non-data frames it may contain information that supports the protocol layers in various tasks. For data frames its content depends on the application. The payload can vary from 1 byte to 4095 bytes or can even be completely omitted. When an application needs to transmit more than 4095 bytes, it has to split the total amount into several frames. A Frame Check Sequence (FCS) is added at the end of the payload, unless the payload is omitted, to help detect transmit errors. Depending on payload length, pads bit may be added in order to complete the block of 6 OFDM symbols.

The PLCP header is always sent at a data rate of 39.4 Mbps, while the PSDU is sent at the desired data rate of 53.3 Mbps, 80 Mbps, 106.7 Mbps, 160 Mbps, 200 Mbps, 320 Mbps, 400 Mbps or 480 Mbps. In Table 3-10 the main PHY parameters are summarized:

Table 3-10: WiMedia PHY parameters summary

Parameter	Value
Sampling frequency	528 MHz
Total number of subcarriers (FFT size)	128
Number of data subcarriers	100
Number of pilot subcarriers	12
Number of guard subcarriers	10
Subcarrier frequency spacing	4.125 MHz
Number of samples in zero-padded suffix	37
Symbol interval	312.5 ns
Total number of samples per symbol	165
Number of symbols in the PLCP preamble	Standard preamble: 30 Burst preamble: 18
Duration of the PLCP preamble	Standard preamble: 9.375 µs Burst preamble: 5.625 µs
Number of symbols in the PLCP header	12
Duration of the PLCP header	3.75 µs
Maximum payload length	4095 bytes

Considering the maximum payload length (4095 bytes) and 480 Mbps as the payload data rate, the PSDU would comprise 222 OFDM symbols. Adding 18 symbols of burst preamble and 12 symbols of PLCP header we obtain a packet length of 252 symbols, which entails a packet duration of 78.75 µs. Therefore effective equivalent bit rate equals to 416 Mbps and an overhead of 13.33% is obtained.

Nevertheless, due to the fact that PSDU length must be aligned to blocks of 6 symbols, the maximum payload length is not necessarily the optimum. Considering the maximum payload length (4095 bytes) and 480 Mbps as the payload data rate, 502 pad bits must be added to complete the 222 symbols, while considering a payload length of 4045 only 2 pad bits are needed to complete 216 symbols, resulting in an effective equivalent bit rate of 420.9 Mbps and an overhead of 12.30%.

Table 3-11 summarizes packet durations and effective bit rates obtained for the different payload data rates considering both maximum and optimum payload length. Note that burst preambles are only permitted for payload data rates above 200 Mbps. As it can be observed, as the payload data rate decreases, the packet duration increases and the effective bit rate decreases. Since the time needed to transmit the preamble and header does not vary with payload data rate it constitutes a proportionally larger portion of frames sent at higher data rates. This explains why the % of overhead increases with the nominal data rate. On the other hand, burst preambles entail less overhead than standard preambles, thus increasing effective bit rate. Consequently, burst preambles should be used in bandwidth-critical applications.

Table 3-11: WiMedia PHY effective equivalent bit rate and % overhead

Payload data rate (Mbps)	Preamble	Maximum payload (payload length = 4095 bytes)			Optimum payload			
		Packet duration (µs)	Effective equivalent bit rate (Mbps)	Overhead (%)	Payload length (bytes)	Packet duration (µs)	Effective equivalent bit rate (Mbps)	Overhead (%)
480	Burst	78.75	416	13.33%	4045	76.875	420.9	12.30%
	Standard	82.5	397.1	17.27%	4045	80.625	401.3	16.38%
400	Burst	91.875	356.6	10.86%	4026	90	357.9	10.53%
	Standard	95.625	342.6	14.35%	4026	93.75	343.6	14.11%
320	Burst	112.5	291.2	9%	4045	110.625	292.5	8.59%
	Standard	116.25	281.8	11.94%	4045	114.375	282.9	11.58%
200	Standard	178.125	183.9	8.04%	4073	176.25	184.9	7.56%
160	Standard	219.375	149.3	6.67%	4082	217.5	150.1	6.16%
106.7	Standard	320.625	102.2	4.24%	4095	320.625	102.2	4.24%
80	Standard	423.75	77.3	3.36%	4082	421.875	77.4	3.24%
53.3	Standard	628.125	52.2	2.15%	4095	628.125	52.2	2.15%

Figure 3-8 shows graphically the evolution of effective PHY bit rate in relation to payload data rate.

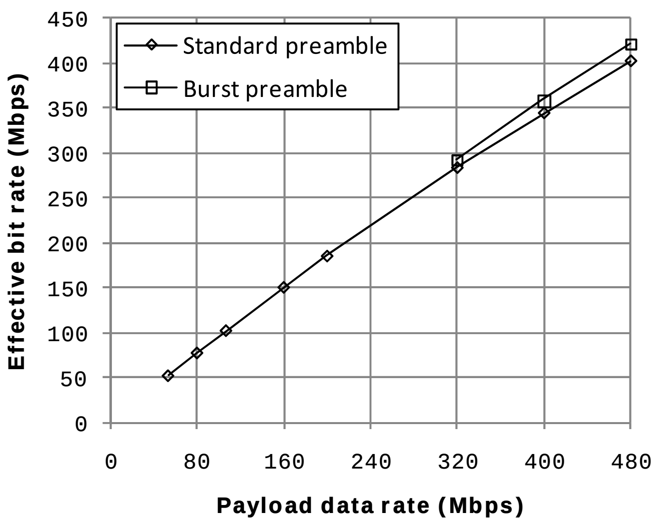

Figure 3-8: Dependence of PHY effective equivalent bit rate on payload data rate

Using large frames is the dominant factor in attaining good performance, as it can be observed in Figure 3-9, which shows effective bit rate as a function of payload length for 480 Mbps and burst preamble and for 53.3 Mbps and standard preamble. For 480 Mbps, using frames with 512 bytes or less is dramatically less efficient than using larger frames, so short frames should be avoided in high-bandwidth applications. There is a ramp effect due to the addition of pad bits. On the other hand, effective bit rate for 53.3 Mbps is less sensitive to payload length as, for payload length higher than 512 bytes, preamble and header duration is much shorter than payload duration.

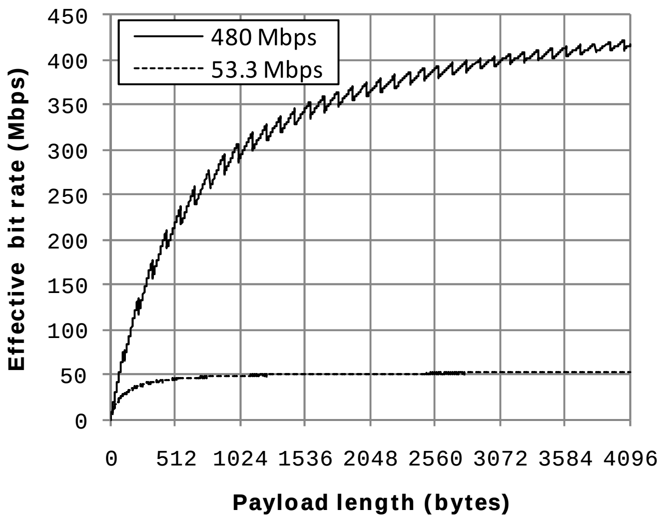

Figure 3-9: Dependence of PHY effective equivalent bit rate on payload length

If we take for example an application that needs to send a large amount of data at 480 Mbps it must carefully choose the frame length. If the maximum payload length of 4095 bytes is chosen, the application will not reach the optimal throughput. The best throughput at 480 Mbps is reached with frames of 4045 bytes, as shown in Table 3-11 and Figure 3-9.

3.2.2 MAC layer

The MAC sublayer is designed to enable mobility, such that a group of devices may continue communicating while merging or splitting from other groups of devices. To maximize flexibility, the functionality of this MAC is distributed among devices. These functions include distributed coordination to avoid interference between different groups of devices by appropriate use of channels and distributed medium reservations to ensure Quality of Service. The MAC sublayer provides prioritized schemes for isochronous and asynchronous data transfer. To do this, a combination of Carrier Sense Multiple Access (CSMA) and Time Division Multiple Access (TDMA) is used. A Distributed Reservation Protocol (DRP) is used to reserve the medium for TDMA access for isochronous and other traffic. For network scalability, Prioritized Contention Access (PCA) is provided using a CSMA scheme. The MAC has policies that ensure equitable sharing of the bandwidth.

The basic timing structure for frame exchange is a superframe. The superframe is composed of 256 medium access slots (MASs), where MAS duration is 256 μs. Each superframe starts with a Beacon Period, which extends over one or more contiguous MASs. The structure of the superframe is shown in Figure 3-10.

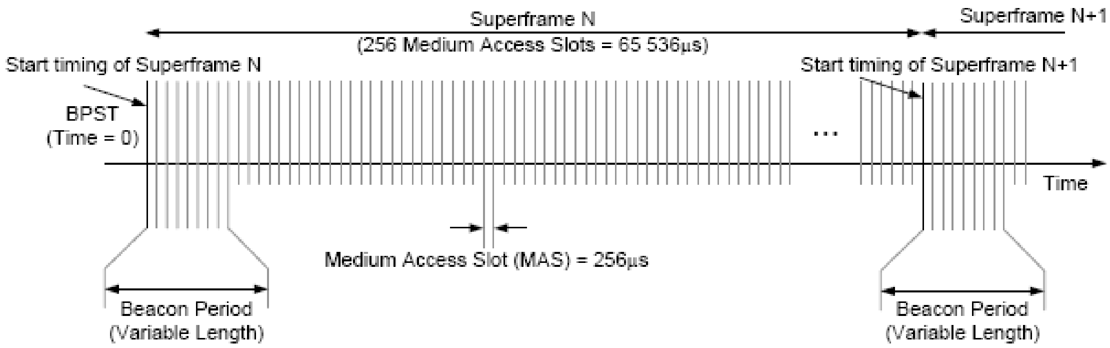

Figure 3-10: MAC superframe structure

In Table 3-12 the main MAC parameters are summarized:

Table 3-12: WiMedia MAC parameters summary

Parameter	**Value**
Superframe length	256 MAS
MAS duration	256 μs
Maximum beacon period length	96 beacon slots
Beacon slot length	85 μs
Beacon transmit rate	53.3 Mbps
Guard time	12 μs
Short inter-frame space (SIFS) duration	10 μs
Minimum inter-frame space (MIFS) duration	1.875 μs

3.2.2.1 Beacon Period

Each superframe starts with a beacon period, which has a maximum length of 96 beacon slots. The length of each beacon slot is 85 μs. The first two beacon slots of a beacon period are referred to as signalling slots and are used to extend the beacon period length of neighbours.

In the simplest case (point-to-point configuration) we will need only two beacons, each to identify a single device. These two devices will use two beacons slots, to which we add two extra beacon slots reserved for signalling beacons. These four beacon slots will take 4 * 85 μs = 340 μs and will occupy the first two MAS that consequently cannot be used for data transmission. In other words, 0.8% of the superframe is unavailable for application data.

Adding devices to a beacon group will add beacons to the beacon period. A beacon period is limited to 96 beacon slots, totalling 96 * 85 μs = 8160 μs, or 32 MAS. In this worst case example, 12.5% of the superframe is unavailable for application data. As we can see, the overhead due to the presence of devices is quite small when only a few devices are active, but it becomes more significant when many devices are operating in the same beacon group.

As all the active devices must transmit a beacon in the beacon period, beacon period length limits the maximum number of active users. As the beacon period has a maximum length of 96 beacon slots and two slots are reserved for signalling, the maximum number of active devices in the same beacon group is 94.

3.2.2.2 Inter-frame space (IFS)

The PHY needs some time between the frames to properly send or receive them. Three types of IFS are defined in the WiMedia Standard:

- Minimum inter-frame space (MIFS). Burst frame transmissions are those frames transmitted from the same device where the timing of each frame after the first frame in the burst is related to the preceding frame through use of the PHY burst mode. In this case MIFS duration will occur between frames in the burst. A device shall not start transmission of a frame on the medium with non-zero length payload earlier than MIFS after the end of a frame it transmitted previously on the medium.

- Short inter-frame space (SIFS). Within a frame transaction, all frames shall be separated by a SIFS interval. A device shall not start transmission of a frame on the medium with zero length payload earlier than SIFS after the end of a frame it transmitted previously on the medium. A device shall not start transmission of a frame on the medium earlier than SIFS duration after the end of a previously received frame on the medium.

- Arbitration inter-frame space (AIFS). The AIFS is the minimum time that a device using PCA defers access to the medium after it determines the medium to have become idle.

The actual values of the MIFS, SIFS, and AIFS are PHY-dependent. The length of MIFS is given by the pMIFS parameter (1.875 µs). The length of SIFS is given by the pSIFS parameter (10 µs). There are four values of AIFS depending on the access category of the traffic.

3.2.2.3 Request To Send (RTS) / Clear To Send (CTS)

An RTS/CTS exchange, when used, precedes data, aggregated data, or command frames to be transferred from a source device to a recipient device. Without a frame body, the RTS frame allows the source device to regain medium access relatively quickly in case of an unsuccessful transmission. The RTS and CTS frames prevent the neighbours of the source and recipient devices from accessing the medium while the source and recipient are exchanging the following frames.

A source device may transmit an RTS frame as part of one or more frame transactions with another device in an obtained PCA TXOP (Transmission Opportunity) or an established reservation block. If a reservation target receives an RTS frame addressed to it in the reservation block, it shall transmit a CTS frame pSIFS after the end of the received frame. On receiving an expected CTS response, the source device shall transmit the frame, or the first of the frames, for which it transmitted the preceding RTS frame pSIFS after the end of the received CTS frame.

RTS and CTS frames have no payload and therefore their length is 42 symbols (30 symbols of standard preamble and 12 symbols of PLCP header) and their duration is 13.125 µs. Consequently, the duration of a RTS/CTS exchange is 46.25 µs (2*13.125 µs + 2*10 µs of inter-frame space).

3.2.2.4 Acknowledgement policies

WiMedia standard defines three acknowledgement policies: no acknowledgement (No-ACK), immediate acknowledgement (Imm-ACK) and block acknowledgement (B-ACK). A frame with ACK policy set to No-ACK shall not be acknowledged by the recipient. On reception of a frame with ACK Policy set to Imm-ACK, a device shall respond with an Imm-ACK frame transmitted pSIFS after the end of the received frame. The B-ACK mechanism allows a source device to transmit multiple frames and to receive a single acknowledgement frame from the recipient indicating which frames were received and which need to be retransmitted.

Imm-ACK frames have no payload and therefore their length is 42 symbols (30 symbols of standard preamble and 12 symbols of PLCP header) and their duration is 13.125 µs. B-ACK frames payload will be in general no longer than 6 symbols, leading to 48 symbols of length and 15 µs of duration.

3.2.2.5 Channel Access Control

A device can use the Distributed Reservation Protocol (DRP) to reserve some MAS for exclusive or non-exclusive use. It can also use the Prioritized Contention Access (PCA) to transmit frames without reservations.

- Distributed Reservation Protocol

Two or more devices willing to communicate using DRP can negotiate to reserve some MAS. The DRP mechanism itself uses very little bandwidth because DRP management information is carried in beacons. The use of MAS successfully reserved in a DRP negotiation is respected by all WiMedia compliant devices, which respect the MAS boundaries of the reservation.

The time defined by the reserved MAS is available for frame transmissions except for a small overhead at the end of a reservation block (guard time). Frames are not allowed to cross reservation block boundaries and so there may be some unused time at the end of each reservation block, depending on the length of the data frames and their transmission start times within the reservation block.

- Prioritized Contention Access

PCA is a random access scheme with a backoff mechanism used to resolve contention for the channel. The PCA mechanism provides differentiated, distributed contention access to the medium for four access categories (ACs) of frames buffered in a device for transmission. The WiMedia MAC specification defines 4 access categories: voice, video, best effort and background. A device employs a prioritized contention procedure for each AC to obtain a Transmission Opportunity (TXOP).

The overheads associated with the backoff mechanism are dependent on the number of contending devices and the priority of the traffic being transmitted. The following parameters are defined for each Access Category:

- Arbitration inter-frame space (AIFS). A device shall wait for the medium to become idle for AIFS before obtaining a TXOP or starting/resuming decrementing the backoff counter. AIFS depends on the Access Category and it must be greater than pSIFS.
- Contention window (CW). A device shall set CW to an appropriate integer in the range [mCWmin, mCWmax] after invoking a backoff for the AC, and shall set the backoff counter for the AC to an integer sampled from a random variable uniformly distributed over the interval [0,CW].
- TXOP limit. A device shall not initiate a frame transaction in a TXOP it obtained for an AC unless the frame transaction can be completed within mTXOPLimit of the start of the TXOP.

When the traffic profile is bursty, such as for web browsing, PCA can provide a more efficient use of the channel resource since the channel can be used by other devices when there is no traffic for a device to send.

3.2.2.6 Security

A frame payload can be secured in order to ensure it comes from the expected sender and has not been modified. Enabling security requires an exchange of keys, which is done only once, and 20 additional bytes sent in the payload of every secure frame. A secure payload begins with a Security Header of 12 bytes and ends with a Message Integrity Code (MIC) of 8 bytes. Everything else is the secure payload.

A non-secure frame can contain a payload of between 0 and 4095 bytes. Since the overhead of the security model is 20 bytes the secure payload is limited to 4075 bytes. In other words, a secure frame of N bytes needs N+20 bytes.

Since 20 bytes are required independently of the frame size the resulting overhead is quite large for small frames. However, depending on the frame length, the PHY requires the addition of pad bits to fill the last interleaver block. If the frame length is chosen carefully, the security overhead can fit within the pad bits required by the PHY, effectively providing secure frame format at no cost. Other frame lengths will still introduce an overhead when the pad bit area is not large enough to contain the 20 bytes needed for the security mechanism.

More than 80% of payload lengths do not introduce any overhead for WiMedia security. About 20% of payload lengths add some overhead, which is less than 5% for frame lengths greater than 1536 bytes. On average, the security layer adds less than 2% overhead for small frames and less than 0.5% for large frames.

3.2.2.7 MAC layer overhead

The precise quantification of MAC layer overhead is very complex, as there are multiple factors that must be taken into account, such as beacon period length, RTS/CTS use, acknowledgement policy, inter-frame spacing, security policy, channel access method, reservation block size, number of users, traffic priority, packet length... Furthermore, if multiple devices are considered, an occupation of 100% of available resources is almost impossible to achieve, as there would be collisions between different devices aiming to reserve or contending for the same resources. And if traffic is not uniform, there will be idle periods combined with congestion periods. In [4] it is stated that WiMedia MAC has about 20% protocol overhead, which gives a maximum possible user throughput of 384 Mbps for each channel.

Nevertheless, we can approximate the expected throughput at the MAC layer. Table 3-13 shows the upper bound of the expected throughput at the MAC layer for different channel access methods (DRP and PCA), acknowledgment policies (No-ACK, B-ACK and Imm-ACK) and payload data rates (53.3, 200 and 480 Mbps). We have considered a beacon period duration of 8 MAS, which allows up to 22 active users, secure frames and optimum packet length (see Table 3-11). For the Distributed Reservation Protocol method we have considered that there are no collisions between different user's reservations and 100% of the available slots are successfully reserved in every superframe. We have considered a reservation block size of 8 slots with no RTS/CTS exchange. For the Prioritized Contention Access method we have considered that there are multiple users contending for the resources so every time one of the users gets a 0 in the random back-off counter, so medium access time only depends on the AIFS defined for that traffic class. Video and Best-effort classes and RTS/CTS exchange have been considered.

Table 3-13: Maximum expected throughput at MAC layer

Payload data rate (Mbps)		480		200	53.3
Preamble		Burst	Standard	Standard	Standard
Channel access	ACK policy				
DRP	No-ACK	390	339	167	49
DRP	B-ACK	385	335	165	48
DRP	Imm-ACK	N/A	271	148	46
PCA-Video	N-ACK	364	322	155	46
PCA-BE	B-ACK	307	277	131	39
PCA-BE	Imm-ACK	N/A	219	116	39

As it can be observed, maximum achievable throughput is obtained for DRP access with NO-ACK and 480 Mbps with burst preamble and is approximately 390 Mbps. This fits with the maximum throughput of 389 Mbps that is presented in [5]. As payload data rate decreases, % overhead is reduced and throughput is closer to physical data rate. As it was already mentioned in Section 3.2.1, burst mode is more efficient than standard mode. Concerning acknowledgement policies, B-ACK is much more efficient than Imm-ACK, especially for high payload rates. Note that Imm-ACK is not allowed in burst mode.

Regarding channel access methods, DRP presents less overhead than PCA as reservation management is performed in the beacon period. With PCA, a Video traffic class (high priority) with No-ACK has been considered to evaluate streaming and Best Effort with B-ACK and Imm-ACK to evaluate web-browsing. Video traffic class presents lower throughput than DRP with No-ACK, while for Best Effort traffic class throughput is further reduced, especially if Imm-ACK is used, and can be as low as 219 Mps for a payload rate of 480 Mbps. DRP is especially recommended for uniform traffic such as video-streaming, while PCA is well suited for low rate traffic with bursty profile, such as web-browsing.

3.2.3 Channelization

The PHY layer channelization scheme is based on the definition of band groups and the definition of Time-Frequency Codes (TFCs). The UWB spectrum is divided into 14 bands, each with a bandwidth of 528 MHz. As shown in Figure 28, five band groups are defined, consisting of four band groups of three bands each and one band group of two bands. The band allocation is summarized in Table 3-14.

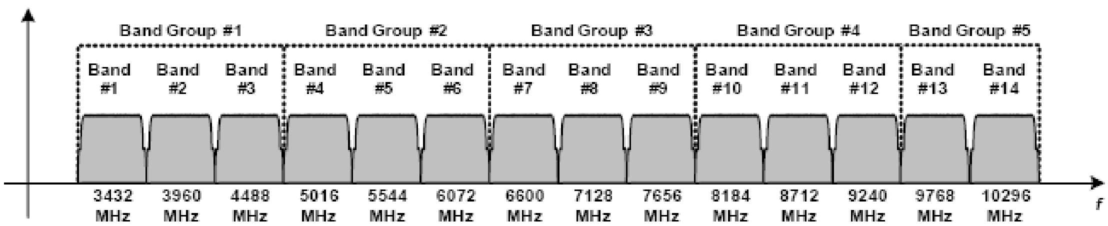

Figure 3-11: Diagram of the band group allocation

Table 3-14: Band group allocation

Band Group	Band_ID	Lower Frequency (MHz)	Centre Frequency (MHz)	Upper Frequency (MHz)
1	1	3168	3432	3696
	2	3696	3960	4224
	3	4224	4488	4752
2	4	4752	5016	5280
	5	5280	5544	5808
	6	5808	6072	6336
3	7	6336	6600	6864
	8	6864	7128	7392
	9	7392	7656	7920
4	10	7920	8184	8448
	11	8448	8712	8976
	12	8976	9240	9504
5	13	9504	9768	10032
	14	10032	10296	10560

Unique logical channels are defined by using a time-frequency code. The ECMA-368 standard specifies two types of time-frequency codes: one where the coded information is interleaved over three bands, referred to as Time-Frequency Interleaving (TFI); and, one where the coded information is transmitted on a single band, referred to as Fixed Frequency Interleaving (FFI). Within each of the first four band groups, four time-frequency codes using TFI and three time-frequency codes using FFI are defined; thereby, providing support for up to seven channels per band. For the fifth band group, two time-frequency codes using FFI are defined. Therefore, 30 channels are specified in total.

The TFCs and the associated base sequences (and corresponding preambles) for band group 1 are defined in Table 3-15 as a function of BAND_ID values. Similarly the TFCs and the associated base sequences (and corresponding preambles) for band groups 2, 3, 4, and 5 can be defined. For band group 5, only TFC 5 and 6 shall be defined.

Table 3-15: Time-Frequency Codes and Preamble Patterns for Band Group 1

TFC Number	Base Sequence / Preamble	BAND_ID for TFC					
1	1	1	2	3	1	2	3
2	2	1	3	2	1	3	2
3	3	1	1	2	2	3	3
4	4	1	1	3	3	2	2
5	5	1	1	1	1	1	1
6	6	2	2	2	2	2	2
7	7	3	3	3	3	3	3

Channelization scheme is summarized in Table 3-16. The PHY channels are identified by channel numbers that take on values from 0−255. The values not defined in Table 3-16 are reserved for future use. Channel numbers 9−15 are mandatory.

Table 3-16: Mapping of Channel Number to Band Group and Time-Frequency Code

Channel Number (decimal)	Channel Number (octal)	(Band Group, TF Code)	Mandatory / optional
9 – 15	011 – 017	(1, 1 – 7)	Mandatory
17 – 23	021 – 027	(2, 1 – 7)	Optional
25 – 31	031 – 037	(3, 1 – 7)	Optional
33 – 39	041 – 047	(4, 1 – 7)	Optional
45 – 46	055 – 056	(5, 5 – 6)	Optional

3.2.4 Range and power consumption

Due to the low transmission power allowed by the regulatory rules for this technology, the scope of UWB applications is limited to short range. Range depends on PHY data rate, and is progressively reduced as PHY data rate increases. In a typical indoor multipath environment (e.g. home, office), the 53.3 Mbps and 480 Mbps link could be sustained at 15 and 3.5 m. respectively [4].

On the other hand, WiMedia UWB systems have been designed for low power consumption, taking advantage of the low transmission power [6]. Typical peak power values are around 400 mW, but they offer 200-300 Mbps throughput, resulting in 1.5-2 mW/Mbps and with a roadmap well below the target 1 mW/Mbps.

In contrast, state-of-the-art 802.11g radios typically consume 300 mW in receive mode and 400 mW in transmit mode. This translates to 15-20 mW/Mbps, assuming 20-30 Mbps throughput. This value is an order of magnitude larger than WiMedia UWB power consumption. 802.11n power consumption characteristics are difficult to obtain because manufacturers do not provide them. However, since the 802.11n standard requires multiple radios to achieve 100 Mbps throughput, we can extrapolate that these multiple radios must require more power than comparable 802.11g solutions. Using the data available for 802.11g systems, and assuming 100 Mbps and two transmit and receive chains, the power consumption would be 600 to 800mW, which results in 6 to 8 mW/Mbps, still larger than WiMedia UWB figures.

Therefore the use of UWB as an access technology is restricted to picocells with a range of a few meters, but has the advantage of lower power consumption, which is one of the most important requirements for use with portable, battery-operated devices.

3.3 Experimental results

3.3.1 Point to point

3.3.1.1 DV9110M Development Kit

In order to verify the theoretical computations concerning WiMedia UWB capacity presented in the previous section, a set of tests have been performed using the DV9110 Development Kit from Wisair. With that purpose, the packet generator implemented in the Development Kit has been used, and the test parameters and results have been controlled through Wisman, a software application provided by Wisair. Wisman allows modifying different parameters such as payload data rate, % of time for transmission on each device, ACK mode or payload length (up to 1512 bytes). Figure 3-12 shows the throughput measured at MAC layer depending on the payload data rate for the different ACK modes and for both unidirectional (one device transmitting 100% of time) and bidirectional traffic (each device transmitting 50% of time). Payload length was set to 1512 bytes. For bidirectional traffic, throughput represented in the figure is the sum of the throughput observed at each one of the devices. Theoretical values of effective PHY bit rate computed on Section 3.2.1 are also included as a reference.

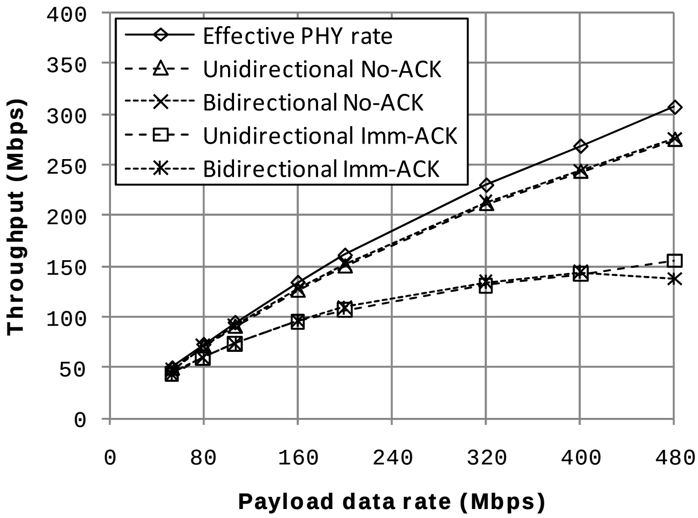

Figure 3-12: DV9110M measured MAC throughput depending on payload data rate

The difference between the throughput measured at MAC level and the effective PHY bit rate is due to the different overheads on MAC layer that were presented in Section 3.2.2. As most of the overhead sources have a fixed duration (beacon period, inter-frame spacing, ACK frames...) the overhead becomes more significant as payload data rates increases. Note that for 480 Mbps only 275 Mbps are obtained. This is due to the limitation of payload length to 1512 bytes in the Wisman application which limits effective PHY bit rate to 307 Mbps. Nevertheless, MAC throughputs up to 380 Mbps can be achieved if higher payload lengths (i.e. 4045 bytes) are used. There is also a big difference between the use of No-ACK mode and Imm-ACK mode that becomes more significant as payload data rate increases. In fact, duration of a packet with 1512 bytes of payload at 480 Mbps is 39.375 µs (plus 10 µs of inter-frame spacing), while ACK frame duration is 13.125 µs (plus 10 µs of inter-frame spacing), leading to a loss of efficiency around 45%. In order to reduce this loss of efficiency due to acknowledgements, payload length should be increased and B-ACK mode could be used. On the other hand, there is no significant difference between unidirectional and bidirectional transmissions.

In Table 3-17 the experimental results obtained for 53.3 Mbps, 200 Mbps and 480 Mbps are compared with the effective PHY bit rate and expected MAC throughput as computed in Section 3.2.2. Nevertheless, this comparison must be considered approximated, as DV9110M MAC, although it is based on WiMedia, is not fully compliant with the WiMedia standard. Furthermore, some of the parameters considered on Section 3.2.2 for theoretical MAC throughput estimation (beacon period length, inter-frame spacing, reservation block size...) may differ from the implementation of DV9110M kits.

Table 3-17: DV9110M measured MAC throughput

		Effective PHY bit rate (Mbps)	Expected throughput (Mbps)	Measured throughput (Mbps)
480 Mbps	No-ACK	339.5 (burst) 307.2 (standard)	304.7 (burst) 231.5 (standard)	274.6
	Imm-ACK		158.1	155.6
200 Mbps	No-ACK	161.3	135.1	149.6
	Imm-ACK		105.6	106.5
53.3 Mbps	No-ACK	50	45.1	48.8
	Imm-ACK		41	43.4

In Figure 3-13 and Figure 3-14 the effect of payload length on throughput is analysed for payload data rates equal to 480 Mbps and 53.3 Mbps respectively. As it can be observed, for 480 Mbps the payload length is a critical factor and efficiency is severely degraded as payload length decreases. As it was shown in Section 3.2.1, effective PHY rate is highly dependent on payload length, as preamble and header duration are fixed so consequently % of overhead increases as payload length decreases. Concerning MAC overhead, computed as the difference between MAC throughput and effective PHY rate, it also increases from 10% at 1512 bytes to 20% at 256 bytes. Throughput degradation due to payload length is not so critical for low payload data rates, as payload duration will be longer in relation to preamble and header duration. MAC overhead for 53.3 Mbps is lower than for 480 Mbps, although is also dependant on payload length, increasing from 2.4% at 1512 bytes to 8% at 256 bytes.

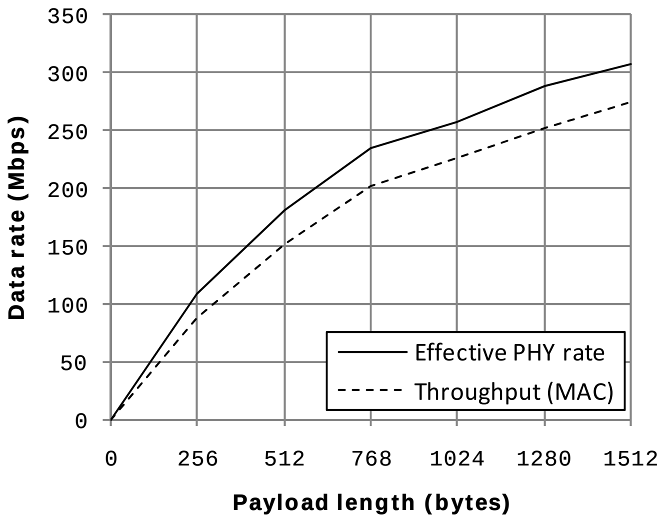

Figure 3-13: DV9110M measured MAC throughput depending on payload length @ 480 Mbps

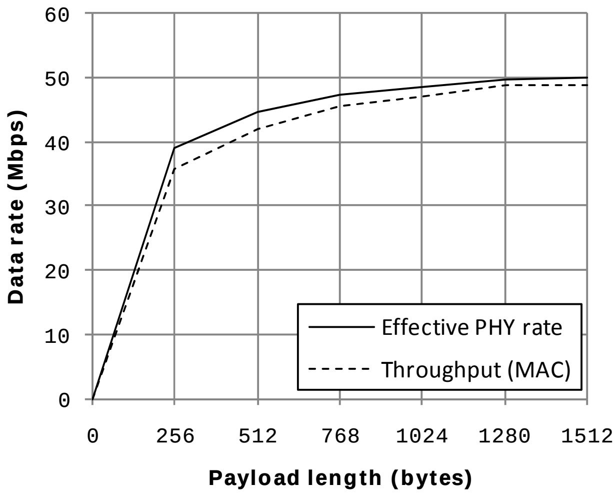

Figure 3-14: DV9110M measured MAC throughput depending on payload length @ 53.3 Mbps

Another set of test have been performed in order to evaluate throughput at the application layer. With this purpose, a commonly used network testing tool called Iperf has been used. Iperf can create TCP and UDP data streams and measure the throughput of a network that is carrying them, either unidirectionally or bi-directionally. Iperf allows the user to set various parameters (such as the datagram size) that can be used for testing a network, or alternately for optimizing or tuning a network.

Unfortunately, application throughput tests are limited to 100 Mbps due to the Ethernet data interface of the DV9110 development kits. Therefore, tests have only been performed with payload data rates of 53.3, 80 and 106.7 Mbps. Table 3-18 shows the throughputs observed for both symmetric and asymmetric UDP traffic. Theoretically computed effective equivalent PHY bit rate and empirical MAC throughput measured with WisMan software are also presented as a reference. As it can be observed, application throughput is slightly lower than MAC throughput due to IP and UDP headers. As expected, throughputs observed for Imm-ACK mode are always lower than for No-ACK mode, and the difference between the two modes is higher as payload data rate increases. On the other hand there are no big differences in terms of throughput between asymmetric and symmetric transmissions. Note that values measured for 106.7 Mbps and No-ACK mode (marked with an asterisk) are lower than expected, although this is due to the limitation of the Iperf traffic generator and the Ethernet link.

Table 3-18: Measured application throughput

Payload data rate (Mbps)	MAC ACK mode	Effective equivalent PHY bit rate (Mbps)	Asymmetric		Symmetric	
			MAC throughput (Mbps)	Application throughput (Mbps)	MAC throughput (Mbps)	Application throughput (Mbps)
53.3	No-ACK	50	48.8	47	47.3	47
	Imm-ACK		43.4	41.6	43.9	41.4
80	No-ACK	73.3	70.9	68	71.2	66.5
	Imm-ACK		59.9	57.2	59.8	55.7
106.7	No-ACK	94.9	90.2	71.6*	91.2	82*
	Imm-ACK		73.4	70.1	73.9	69

The effect of payload length on application throughput has been also evaluated for 53.3 Mbps and No-ACK mode. As it can be observed in Figure 3-15, as the payload length decreases, the overhead due to IP and UDP headers becomes more important and the difference between MAC throughput and application throughput increases. This emphasizes even more the importance of a careful selection of packet size.

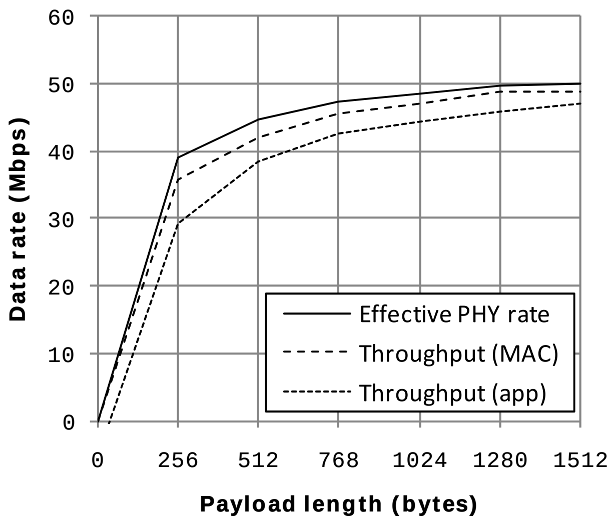

Figure 3-15: Measured application level throughput depending on payload length

Concerning DV9110M range, tests were already performed within PULSERS PHASE-II project and results were included in [7]. Figure 3-16 shows the packet loss rate measured with the DV9110M for different PHY data rates as the distance between the UWB devices increases. As it can be observed, for the maximum PHY data rate, 480 Mbps, packet loss rate severely degrades for distances over 2 metres. PHY data rate of 400 Mbps shows a better performance compared to 480 Mbps, maintaining a packet loss rate under 1% for distances up to 4 meters. The other available data rates (80, 160 and 320 Mbps have not been included in the graphic in order to improve visibility) show all very similar performances and achieve the best results, with packet loss rates under 1% up to 5 meters and negligible losses for distances less than 3 metres.

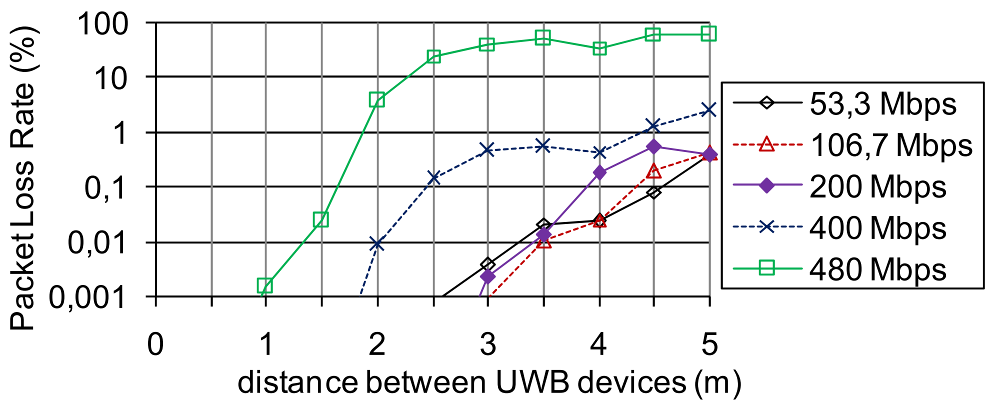

Figure 3-16: DV9110M packet loss rate depending on distance and PHY data rate

3.3.1.2 Wireless USB Adapter Set (based on WSR601 single chip from Wisair)

As explained in [8], since Wisair's Wireless USB adapter set is provided in form of USB dongle and can be included easily in user devices, it has been identified and considered within WP6 as a key component for the integration of UWB-RT into user terminals.

Currently, Wisair is working on the API (Application Programming Interface) to allow accessing some physical parameters of the Wireless USB adapter set, such as the transmitted power and the working frequency band, in order to develop some collaborative mechanisms when UWB and other wireless technologies interwork in close proximity.

3.3.1.2.1 Evaluation of Wisair's Adapter Set: June 2008-driver

The set-up shown in Figure 3-17 has been implemented to assess the actual performance of the WUSB adapter set. These results have been already presented in [8], [9].

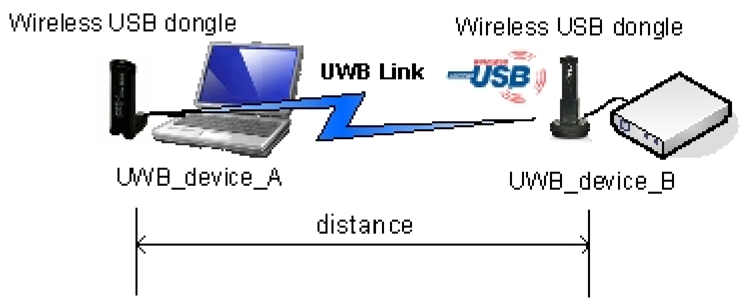

Figure 3-17: WUSB adapter set: point to point measurement set-up

The HD Tach, a computer program that measures the hard disk (HD) transfer rate (read speed), has been used to calculate the effective transfer rate of the WUSB link. Firstly, the HD throughput without the WUSB connection has been evaluated, i.e. with a direct USB cable, and then with the WUSB link between the HD and the laptop. As it can be seen in Table 3-19, the limiting factor is the wireless USB connection. The "Auto" mode provides the optimum data rate depending on the environment conditions.

Table 3-19: WUSB adapter set: Transfer Rate vs. Physical Rate

Connection	PHY Rate	Transfer Rate
USB cable	--	200 Mbps
WUSB link	Auto	52 Mbps
	53 Mbps	25.6 Mbps
	80 Mbps	32 Mbps
	106.7Mbps	38.4 Mbps
	160 Mbps	42.4 Mbps
	200 Mbps	44 Mbps

	320 Mbps	48 Mbps
	400 Mbps	52 Mbps
	480 Mbps	52 Mbps

The limitation of 52 Mbps is due to the WUSB standard that limits the maximum bandwidth that an isochronous connection can request to 40 Mbps plus 30% for retries, which makes 52 Mbps [24]. The purpose of this limitation is to guarantee that the available bandwidth is fairly shared between all the devices within a WUSB Cluster. This performance is very similar to the specifications provided by the manufacturer:

- Wisair WSR601 Evaluation Kit Version 100.0.0.66 (June 17, 2008)
  - Firmware/Software
    - HWA FW version 1.0.0.56
    - DWA Plus FW version 5.0.0.13
    - WinDrivers version 13.0.40.0
  - Maximum Throughput at 480 Mbps PHY rate
    - Read: 61.5 Mbps
    - Write: 51.2 Mbps

In Table 3-20 and Table 3-21, it is detailed the transfer rate depending on the distance between UWB_device_A and UWB_device_B, and also as a function of the physical rate of the WSR601 link. It must be taken into account that these measurements have been carried out under line-of-sight (LOS) conditions, and with no obstacles. The degradation due to the attenuation of people, walls, etc, would get worse the overall performance of the link, decreasing the throughput and the range.

Table 3-20: WUSB adapter set: Transfer Rate vs. Distance and Physical Rate (I)

PHY rate	**Transfer Rate (Mbps) vs. Distance**						
	0.3 m	**1 m**	**2 m**	**3 m**	**4 m**	**5 m**	**6 m**
Auto	52	52	48.8	48.8	48.8	48.8	33.6
53 Mbps	25.6	25.6	25.6	25.6	25.6	24.8	24.8
80 Mbps	32	32	32	32	32	31.2	31.2
106.7Mbps	36.8	36.8	36.8	36.8	36.8	34.4	36.8
160 Mbps	42.4	42.4	42.4	41.6	42.4	40.8	41.6
200 Mbps	45.6	45.6	44.8	44.8	44	40	44

320 Mbps	49.6	50.4	48.8	48.8	49.6	49.6	28
400 Mbps	52	52	50.4	49.6	49.6	44	--
480 Mbps	52	52	46.4	27.2	--	--	--

Table 3-21: WUSB adapter set: Transfer Rate vs. Distance and Physical Rate (II)

PHY rate	**Transfer Rate (Mbps) vs. Distance**							
	7 m	**8 m**	**9 m**	**10 m**	**11 m**	**12 m**	**13 m**	**14 m**
Auto	44,6	42.4	38.8	34.8	31.2	23.84	23.28	19.2
53 Mbps	24.8	24.2	24.2	24.2	24	23.6	21.6	19.2
80 Mbps	31.2	29.8	29.8	30	29.9	19.2	--	--
106.7Mbps	36.0	33.4	33.2	33.1	32.8	--	--	--
160 Mbps	40.8	39.4	38.4	38.4	24.6	--	--	--
200 Mbps	40	40.6	--	--	--	--	--	--
320 Mbps	--	--	--	--	--	--	--	--

For a distance between UWB_device_A and UWB_device_B up to 4 meters and a PHY rate of 400 Mbps, the transfer rate increases from 25 Mbps to 50 Mbps with the PHY rate. The maximum distance between UWB devices to guarantee a transfer rate of 40 Mbps is 8 meters. Moreover, as shown in the tables, when increasing the distance, the maximum allowed PHY rate decreases.

3.3.1.2.2 Evaluation of Wisair's Adapter Set: May 2009-driver

The set-up shown in Figure 3-17 has been upgraded with the latest version of Wisair's driver (Production Software Release 100.0.2.18, published in May 2009). In this version, it is not possible to change the physical data rate, and its default value is "Auto". Moreover, the channel number or TFC has been fixed by region (for instance, in Europe, the link can only be established over the channel 15 or TFC 7).

The general behaviour (1 meter-separation between host and device) of each link depicted in Figure 3-18, working separately (if link A is on, link B will be B off and vice versa), is detailed as follows:

UWB_link_A (between laptop and HD):

- HD Tach on UWB_device_A: 52 Mbps (read)
- File transfer rate:
    - UWB_Host → UWB_device_A: 52 Mbps (write)

- o UWB_device_A → UWB_Host: 48.8 Mbps (read)

UWB_link_B (between laptop and pendrive):

- HD Tach on UWB_device_B: 52.8 Mbps (read)
- File transfer rate:
  - o UWB_Host → UWB_device_B: 30 Mbps (write)
  - o UWB_device_B → UWB_Host: 49.6Mbps (read)

The performance as a function of the distance between the host and the device is shown in the following tables.

Table 3-22: WUSB UWB_link_A: Transfer Rate vs. Distance (I)

	Transfer Rate (Mbps) vs. Distance						
	0.3 m	**1 m**	**2 m**	**3 m**	**4 m**	**5 m**	**6 m**
HD Tach	51.2	51.2	52	43.2	47.2	47.2	36.8
Host to device	50.4	50.4	50.4	44.8	44.8	44	36.8
Device to Host	49.6	49.6	49.6	41.6	44	43.2	38.4

Table 3-23: WUSB UWB_link_A: Transfer Rate vs. Distance (II)

	Transfer Rate (Mbps) vs. Distance							
	7 m	**8 m**	**9 m**	**10 m**	**11 m**	**12 m**	**13 m**	**14 m**
HD Tach	33.6	40.8	36	36	24	28.8	33.6	24
Host to device	30.4	32.8	36	32.8	18.4	26.4	23.2	16
Device to Host	32.8	37.6	34.4	34.4	20	30.4	24.8	24

Table 3-24: WUSB UWB_link_B: Transfer Rate vs. Distance (I)

	Transfer Rate (Mbps) vs. Distance						
	0.3 m	**1 m**	**2 m**	**3 m**	**4 m**	**5 m**	**6 m**
HD Tach	52	52	52	52	52	48	43.2
Host to device	28	28	27.4	27.6	24.4	28	24.8
Device to Host	49.6	48	49.6	46.4	43.2	46.4	41.6

Table 3-25: WUSB UWB_link_B: Transfer Rate vs. Distance (II)

	Transfer Rate (Mbps) vs. Distance							
	7 m	**8 m**	**9 m**	**10 m**	**11 m**	**12 m**	**13 m**	**14 m**
HD Tach	44	39.2	32	28.8	24	24	22.4	24.4
Host to device	23.2	23.2	22.4	20.8	17.6	15.2	15.2	20
Device to Host	39.2	39.2	34.4	28.8	22.4	20.8	20.8	26.4

Analyzing the obtained results, it can be concluded that, as expected, the longer the distance between host and device is, the lower the transfer rate is (for both writing and reading). It is also noticed an asymmetric read versus write performance in the UWB_link_B. UWB_device_B is an USB flash drive and unlike other architectural elements in the memory hierarchy, storage devices based on flash memory suffer from write performance that can be orders of magnitude slower than read performance. Over the past year significant improvement in USB flash device access speeds has been observed, probably due to enhancements in controller implementation and increased buffering on the devices. Current Wisair's implementation is sensitive to low performance storage devices. Future implementations are designed to remove these exaggerations of the underlying protocol.

Concerning HD Tach, it should be noted that it uses its own low level drivers to measure and it provides "burst" and "sequential" results. File transfer under Windows uses fixed 64k block accesses to USB storage devices. The files themselves may be stored in random fragments on the media, limiting consecutive location access to the media.

3.3.2 Point to multipoint

3.3.2.1 Wireless USB Adapter Set (based on WSR601 single chip from Wisair)

3.3.2.1.1 Set-up

The set-up assembled to evaluate a point to multipoint configuration using WUSB dongles provided by Wisair is depicted in Figure 3-18. The equipment used to carry out these measurements is the following:

- UWB dongles: 2 WUSB adapter sets from Wisair (2 HWA and 2 DWA)
- Host laptop
- UWB_device_A: HD
- UWB_device_B: pendrive

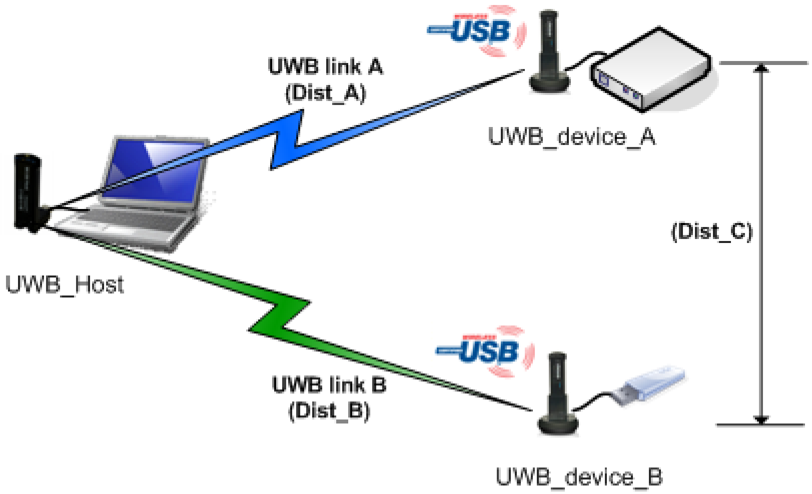

Figure 3-18: WUSB adapter set: point to multipoint measurement set-up

In the set-up, 2 WUSB devices have been connected to the same WUSB host, as shown in the snapshot of Wisair's Wireless UWB manager (Figure 3-19). This operation allows the simultaneous connection of the UWB host with both devices (device_A and device_B).

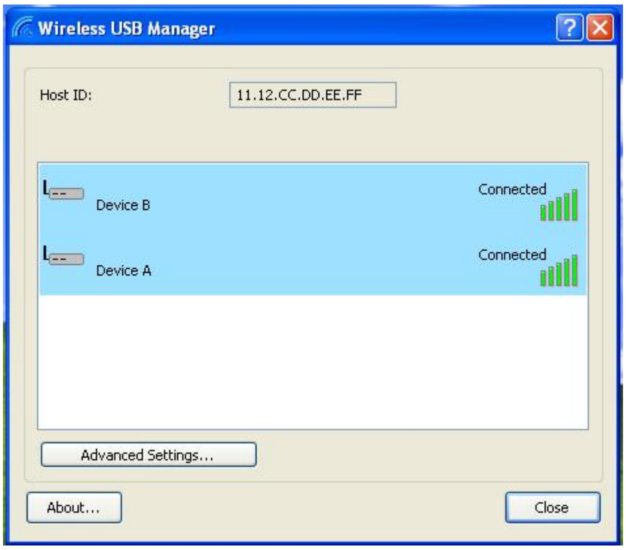

Figure 3-19: Wireless USB Manager (from Wisair) with 2 active WUSB devices

3.3.2.1.2 *Test variables*

- Influence of TFC configuration
    - Although in Europe, currently, it is only allowed the UWB transmission at TFC7 (channel number 15), the system performance has been tested using TFC5 and TFC6. TFC7 uses only WiMedia Band #3, whereas TFC5 and TFC6 use Band#1 and Band#2, respectively.
- Distance between host and device (each link)
    - UWB_Host and UWB_device_A: Dist_A
    - UWB_Host and UWB_device_B: Dist_B

- Distance between links: Dist_C

3.3.2.1.3 Test parameters

- Link throughput using:
    - HD Tach, a software program that measures the HD transfer rate (read speed), has been selected to calculate the effective transfer rate
    - Measurement of the instantaneous transfer rate between storage devices
- Hard disk connection error when the WUSB link fails.

3.3.2.1.4 Test results

The performed tests are summarised in the following list:

1. **Test 1A**

- UWB_link_A: UWB_Host → UWB_device_A file transfer rate
- UWB_link_B: HD Tach on UWB_device_B

2. **Test 1B**

- UWB_link_A: UWB_device_A → UWB_Host file transfer rate
- UWB_link_B: HD Tach on UWB_device_B

3. **Test 2A**

- UWB_link_A: HD Tach on UWB_device_A
- UWB_link_B: UWB_Host → UWB_device_B file transfer rate

4. **Test 2B**

- UWB_link_A: HD Tach on UWB_device_A
- UWB_link_B: UWB_device_B → UWB_Host file transfer rate

5. **Test 3A**

- UWB_link_A: UWB_Host → UWB_device_A file transfer rate
- UWB_link_B: UWB_Host → UWB_device_B file transfer rate

6. **Test 3B**

- UWB_link_A: UWB_device_A → UWB_Host file transfer rate
- UWB_link_B: UWB_device_B → UWB_Host file transfer rate

Table 3-26: Summary of tests

		Scenario 1 Dist_A=1m Dist_B =1m Dist_C=1m	**Scenario 2** Dist_A=1m Dist_B =10cm Dist_C=1m	**Scenario 3** Dist_A=1m Dist_B =1m Dist_C=10cm
Test 1A	UWB_link_A: Transfer rate UWB_Host→UWB_device_A	40 Mbps	41.6 Mbps	40 Mbps
	UWB_link_B: HD Tach UWB_device_B	39.2 Mbps	40.8 Mbps	39.2 Mbps
Test 1B	UWB_link_A: Transfer rate UWB_device_A→UWB_Host	41.6 Mbps	41.6 Mbps	41.6 Mbps
	UWB_link_B: HD Tach UWB_device_B	42.4 Mbps	42.3 Mbps	43.2 Mbps
Test 2A	UWB_link_A: HD Tach UWB_device_A	44.8 Mbps	45.6 Mbps	45.6 Mbps
	UWB_link_B: File transfer rate UWB_Host→UWB_device_B	26.4 Mbps	26.4 Mbps	26.4 Mbps
Test 2B	UWB_link_A: HD Tach UWB_device_A	43.2 Mbps	43.2 Mbps	44 Mbps
	UWB_link_B: File transfer rate UWB_device_B→UWB_Host	41.6 Mbps	40.8 Mbps	41.6 Mbps
Test 3A	UWB_link_A: File transfer rate UWB_Host→UWB_device_A	20 Mbps	24.2 Mbps	20 Mbps
	UWB_link_B: File transfer rate UWB_Host→UWB_device_B	14.18 Mbps	14.4 Mbps	13.7 Mbps
Test 3B	UWB_link_A: File transfer rate UWB_device_A→UWB_Host	40.8 Mbps	40.8 Mbps	41.6 Mbps
	UWB_link_B: File transfer rate UWB_device_B→UWB_Host	39.5 Mbps	39.5 Mbps	42.7 Mbps

Table 3-27: Summary of tests (II)

		Scenario 4 Dist_A=1m Dist_B =3m Dist_C=4m	**Scenario 5** Dist_A=5m Dist_B =5m Dist_C=1m	**Scenario 6** Dist_A=8m Dist_B =3m Dist_C=5m
Test 1A	UWB_link_A: Transfer rate UWB_Host→UWB_device_A	41.6 Mbps	40.8 Mbps	40.8 Mbps
	UWB_link_B: HD Tach UWB_device_B	36.4 Mbps	38.4 Mbps	40.8 Mbps
Test 1B	UWB_link_A: Transfer rate UWB_device_A→UWB_Host	40 Mbps	37.6 Mbps	38.2 Mbps
	UWB_link_B: HD Tach UWB_device_B	40 Mbps	39.2 Mbps	40 Mbps
Test 2A	UWB_link_A: HD Tach UWB_device_A	44.8 Mbps	40 Mbps	40 Mbps
	UWB_link_B: File transfer rate UWB_Host→UWB_device_B	22.4 Mbps	21.6 Mbps	24.2 Mbps
Test 2B	UWB_link_A: HD Tach UWB_device_A	40.8 Mbps	36.8 Mbps	38.4 Mbps
	UWB_link_B: File transfer rate UWB_device_B→UWB_Host	39.2 Mbps	34.4 Mbps	34 Mbps
Test 3A	UWB_link_A: File transfer rate UWB_Host→UWB_device_A	24 Mbps	22.4 Mbps	20 Mbps
	UWB_link_B: File transfer rate UWB_Host→UWB_device_B	13.6 Mbps	13.5 Mbps	14.3 Mbps
Test 3B	UWB_link_A: File transfer rate UWB_device_A→UWB_Host	39.2 Mbps	34.4 Mbps	35.2 Mbps
	UWB_link_B: File transfer rate UWB_device_B→UWB_Host	39 Mbps	27.1 Mbps	28.4 Mbps

3.3.2.1.5 Conclusion

In general, the performance of the point to multipoint configuration based on the Wireless USB adapter set from Wisair has been satisfactory. The overall throughput is better than the produced over a single link.

The worst results are obtained for Test 3A, independently of the scenario, where the UWB_Host transfers information at the same time to UWB_device_A and UWB_device_B. The host (laptop/drivers and HWA/WUSB protocol) manages the connection. What takes longer is the write process on the devices. The overhead associated with the laptop accessing files on its local file system should be similar in both the “host to device - write” (Windows reading from its local file system and writing to the device) and ‘device to host (read)’ (Windows reading from the device and writing to its local file system) cases.

Knowing that the overall behaviour of the Wireless USB protocol during read and write access to USB devices is similar, without analyzing traces of both the Wireless USB protocol and the driver interactions, the Windows file system could have some dependency between parallel write accesses to two devices. The slower UWB_device_B then adversely affects the access to UWB_device_A.

It can also be highlighted that for a fixed dist_A=1m, dist_B and dist_C have no influence on the transfer rate from the UWB_Host to the UWB_device_A. In general, the performance is more dependent on the type of devices involved in the communications (host/device) than the distances between devices.

As previously commented, the influence of the available TFC has also been evaluated. As a conclusion, no throughput variations have been detected when changing the UWB transmission frequency.

4 Higher layer requirements for heterogeneous networks

4.1 All-IP Heterogeneous Access Networks

In the last few decades, the proliferation of fixed and mobile access technologies and networks has provided a large choice to the network operators to offer a variety of services. These emerging access technologies and networks complement each other and offer different data rates and coverage that captures the needs and requirements of mobile users. For instance, the new generation of wireless networks such as Wi-Fi, WiMAX, UWB, etc. offers high data rates at low cost but does not guaranty a global coverage and high mobility. In contrast, the traditional and advanced cellular networks such as GSM/GPRS and UMTS provide wide area coverage and high mobility at high cost but do not offer high data rates.

As it is stated in many works that can be found in the literature [10]-[14], next-generation wireless systems (4G) are envisioned to have an IP-based infrastructure with the support of heterogeneous access technologies. Different access technologies such as cellular, cordless, WLAN, short-range connectivity, and wired systems will be combined on a common platform to complement each other optimally for different service requirements and radio environments. It appears that any near-term pervasively wireless communication system is likely to be a hybrid, with high bandwidth “islands” within buildings and public places (i.e. airports, shopping malls...) and lower bandwidth in-between spaces. In this context, UWB arises as a potential access technology providing very high data rate access in short-range picocells.

It is expected that in future scenarios users will be able to choose from a wide range of services from various access networks. In a heterogeneous network it is possible to use a combination of several networks, each of which is optimized for some particular service. This results in a system that delivers each service via the network that is most efficient for that service.

In such a diverse environment, the concept of being always connected becomes always best connected. This refers to being not only always connected, but also being connected in the best possible way by exploiting the heterogeneity offered by the access networks in order to experience a large variety of network services. Moreover, mobile hosts are being increasingly equipped with multiple interfaces capacitating access to different wireless networks subject to network availability, device characteristics and the applications used, all of which introduces the need for network interoperability in this heterogeneous environment via a common IP-based core network.

Internet protocol (IP) provides a universal network-layer protocol for wireline packet networks, and is viewed as an attractive candidate to play the same role in wireless systems. IP provides a globally successful open infrastructure for creating and providing services and applications. All-IP wireless networks will enable the abundant applications and software technologies developed for wired IP networks to be used over wireless networks. With IP as the common network layer protocol, an IP-based mobile device (with multiple radio interfaces or software defined radio) could roam between different wireless systems [15].

IP is the best interoperability solution for fixed networks, but faces several challenges in mobile networks. Communication over wireless links is characterized by limited bandwidth, high latencies, high bit-error rates and temporary disconnections that must be dealt with by network protocols and applications. In addition, protocols and applications have to handle user mobility and the handoffs that occur as users move from cell to cell in cellular wireless networks.

Reliable transport protocols such as TCP have been tuned for traditional networks made up of wired links and stationary hosts. TCP performs very well on such networks by adapting to end-to-end delays and packet losses caused by congestion. TCP provides reliability by maintaining a running average of estimated round-trip delay and mean deviation, and by retransmitting any packet whose acknowledgment is not received within four times the deviation from the average. Due to the relatively low bit-error rates over wired networks, all packet losses are correctly assumed to be because of congestion.

In the presence of the high error rates and intermittent connectivity characteristic of wireless links, TCP reacts to packet losses as it would in the wired environment: it drops its transmission window size before retransmitting packets, initiates congestion control or avoidance mechanisms and resets its retransmission timer. These measures result in an unnecessary reduction in the link's bandwidth utilization, thereby causing a significant degradation in performance in the form of poor throughput and very high interactive delays.

In order to solve this problem, several strategies are proposed in the literature, such as caching packets and performing local retransmissions across the wireless link by monitoring the acknowledgments to TCP packets generated by the receiver (snoop) [16] or modifying TCP implementation to distinguish wireless packet losses from congestion packet losses [17]. Anyway, it is clear that error correction, acknowledgement and retransmission schemes should be implemented in the wireless link in order to minimize packet losses and provide support to TCP/IP.

Another problem of using TCP/IP in wireless networks is related with routing data between the wired network and the wireless devices [18]. Designed before hosts moved, the existing protocols are ill-suited for highly mobile nodes, as IP address is not only used to uniquely identify a host, but also to route traffic through the network as it identifies the network that the host belongs to. As a host moves from one network domain to another, it must change its address to one belonging to the new network, as rebuilding and redistributing the necessary routing information would be prohibitively expensive. But ongoing or incoming connections will be addressed to the host's home network.

Mobile IP is the general term for several proposed solutions to this problem. It uses a level of indirection to forward packets to correct temporary addresses. Each mobile host has a unique home address. As the mobile moves through the network, the control protocol notifies the gateway managing its home address of the terminal's current temporary address. Packets sent to the home address are automatically forwarded to this address by the gateway. When mobility is localized within an administrative domain (micromobility), optimized solutions can be applied to reduce the signalling load, delay and packet losses associated to the handover [14].

Therefore, one of the research challenges for next generation all-IP-based wireless systems is the design of intelligent mobility management techniques that take advantage of IP-based technologies to achieve global roaming among various access technologies. To make this roaming seamless, the integration and interoperation of heterogeneous mobility management techniques with efficient support for both intra- and interdomain roaming are required.

4.2 Wireless access to IP networks

The integration of UWB or any other wireless system as an access technology to an all-IP Heterogeneous Network faces a number of challenges [13]:

- Reliability and fault tolerance: TCP/IP was designed for wired networks, where no errors are likely to occur in the transmission and losses are assumed to be due to congestion. In contrast, wireless transmissions are subject to errors due to noise, interference, fading... In order to provide a similar performance to wired access, efficient coding of the signal to minimize the bit error rate and frame loss detection and retransmission schemes to minimize packet losses must be provided. Furthermore, the system should minimize potential failures and allow a fast recovery after temporary disconnections.

- Security: Wireless networks present unique security challenges due to the loss of protection provided by wires and shielding. Therefore, a higher level of security is required to assure confidentiality and integrity of the information.

- Quality of service: Access technology should provide mechanisms to provide the quality of service required by higher layers, such as IP or application layer.

- Mobility: One of the main advantages of wireless access technologies over wired access is that it supports users' mobility. Horizontal and vertical handover are required with minimum handover latency and packet loss.

In the following subsections it will be analysed how the WiMedia PHY and MAC layers and higher layer protocols such as WLP and WUSB face this challenges.

4.2.1 WiMedia PHY and MAC support

Following, it is analysed how the WiMedia Standard ECMA-368 [3] meets each one of the requirements previously enumerated:

- Reliability and fault tolerance: WiMedia PHY provides frequency-domain spreading, time-domain spreading, and forward error correction (FEC) coding for optimum performance under a variety of channel conditions. The FEC used is a convolutional code with coding rates of 1/3, 1/2, 5/8 and 3/4. At MAC level, the PLCP header including MAC and PHY headers is protected by a header check sequence (HCS) and a shortened Reed-Solomon code, while the Frame Payload is protected by a frame check sequence (FCS). It also provides three types of acknowledgements to enable different applications, namely No-ACK, Immediate-ACK and Block-ACK. If the source device does not receive the requested acknowledgement, then it may retransmit the frame or it may discard the frame.

- Security: WiMedia security is separated into two parts [19]. Association is performed at the application layer for the first-time setup and is protocol-specific. Wireless USB and WLP have custom association protocols that provide security for their respective needs. One of the most important aspects of association is that all WiMedia products require permission from the user before they are allowed to connect with other products. Once products have been set up, ongoing operational security is provided by the WiMedia Common Radio Platform.

The WiMedia standard specifies the operational security mechanisms. It defines two levels of security: no security and strong security protection. Security protection includes data encryption, message integrity, and replay attack protection. Secure frames are used to provide security protection to data frames as well as selected control and command frames. Secure frame counters and replay counters are set up on a per-temporal key basis to guarantee message freshness. 128-bit symmetric temporal keys are employed based on AES-128 with CCM to provide payload encryption and message integrity code (MIC) generation.

The standard further specifies a 4-way handshake mechanism to enable two devices to derive their pair-wise temporal keys (PTKs) while authenticating their identity to each other. A secure relationship between two devices is established following a successful 4-way handshake, which is conducted based on a shared master key. In addition, means for the solicitation and distribution of group temporal keys (GTKs) for protecting multicast and broadcast frames are provided.

- Quality of service: WiMedia MAC provides prioritized contention access for quality of service provision depending on traffic class, and reservation for end-to-end quality of service provision.

The WiMedia MAC sublayer provides prioritized schemes for isochronous and asynchronous data transfer to ensure Quality of Service. To do this, a combination of Carrier Sense Multiple Access (CSMA) and Time Division Multiple Access (TDMA) is used. A Distributed Reservation Protocol (DRP) is used to reserve the medium for TDMA access, while Prioritized Contention Access (PCA) is provided using a CSMA scheme. The mapping of IP traffic classes or end-to-end QoS requirements to the provided PCA and DRP schemes depends on the adaptation layer (WUSB, WLP...).

The PCA mechanism provides differentiated contention access to the medium for four access categories (ACs), which are mapped from eight user priorities, of frames buffered in a device for transmission. A device employs a prioritized contention procedure for each AC to obtain a transmission opportunity for the frames belonging to that AC using the PCA parameters associated with that AC. The DRP enables devices to reserve one or more medium access slots that the device can use to communicate with one or more neighbours. All devices that use the DRP for transmission or reception shall announce their reservations in their beacons.

- Mobility: WiMedia do not specify how mobility is handled, although the MAC sublayer is designed to enable mobility, such that a group of devices may continue communicating while merging or splitting from other groups of devices. Periodic beacon transmission enables device discovery, supports dynamic network organization, and provides support for mobility. Nevertheless, handover should be handled by higher layers, i.e. adaptation layer or IP layer. Consequently optimized micromobility strategies should be implemented in order to minimize the latency and packet losses due to handover. Furthermore, the integration of multiple access technologies in heterogeneous access networks requires the implementation of solutions for supporting macromobility and intersystem handover, i.e. Mobile IP.

In general, the WiMedia Standard provides the means to support access to IP networks, although they must be handled by the higher layers. In the following section, the adaptation layer designed in order to converge to TCP/IP platforms, WLP, is described. As it is widely extended in commercial UWB developments, the Support of IP network access with WUSB is also analysed.

4.2.2 WiMedia logical link control protocol (WLP)

WiMedia logical link control protocol (WLP), formerly referred to as WiMedia Network protocol adaptation layer or WiNet, is a protocol adaptation layer (PAL) that builds on the WiMedia UWB common radio platform to augment the convergence platform with TCP/IP services [20]. It acts as the interface between higher-layer networking protocols and the WiMedia media access controller (MAC).

4.2.2.1 Protocol

WLP defines a logical link control layer networking protocol for the WiMedia radio platform to model the behaviour of an IEEE 802 network [21]. This facilitates easy migration of applications compatible with an IEEE 802 environment to a WiMedia environment with few or no changes. For example, a TCP/IP protocol stack designed for an IEEE 802.3 (Ethernet) environment will work with a WiMedia environment. WLP protocol preserves the IEEE 802 headers to facilitate the design of bridges between a WiMedia network and other IEEE 802 or compatible wired or wireless networks [22].

Since WLP is designed for TCP/IP, it maintains support for the routable nature of Internet applications, meaning that WLP packets contain a device address as well as a network address. Mobile WLP devices are designed to communicate with the Web using standard Internet routers. WLP is a true peer-to-peer protocol, meaning that devices may communicate with each other directly. This facilitates the creation of ad-hoc wireless personal area networks for mobile devices and applications.

In WLP, bridging to other networks is based on IEEE 802.1D. WLP provides control messages that allow devices to select the level of bridge-forwarding services that are desired. Bridge service requests allow a device to designate which packets should be filtered based on protocol identifiers and multicast addresses. WLP also allows devices to omit the 802 headers for more efficient data transfer if the packets are destined for WiMedia wireless network.

4.2.2.2 Packet format

WLP frames are delivered to the WiMedia MUX service as MUX payloads. The MUX header for all WLP frames is the WLP Protocol ID. The format of a standard data frame is illustrated in Figure 4-1.

octets: 1	1	6	6	2	N
WLP Frame Type (=0)	WSS tag	Destination Address	Source Address	Type/Length	Client Data

Figure 4-1: WLP standard data frame format

The total length of the WLP header is 16 octets. The WSS tag field is set to a value used by the transmitting device to identify the WSS for the data frame. The Destination Address field is set to the EUI-48 of the ultimate destination of the frame. The Source Address field is set to the EUI-48 of the original source of the frame. The Client Data field contains the payload of the frame as received from the WLP client.

As it can be observed in Table 4-1, maximum transmission unit (MTU) for client data is reduced from 4095at the MAC service access point to 4048 at the WLP client. Therefore, maximum throughput will be further reduced in at least 1.15% per cent considering a full occupation of the data units (for smaller data units, the throughput reduction due to the overhead would be more important).

Table 4-1: MTU calculation

mMaxFramePayloadSize	4095 octets
MAC security header and MIC	20 octets
MUX Header	2 octets
WLP standard data frame header	16 octets
Margin for future expansion	9 octets
MTU for Client Data	4048 octets

4.2.2.3 Power management

Another major feature is a new advanced hibernation algorithm, which makes use of mechanisms already built into the MAC. While the MAC has an information element that announces when a device will hibernate, there is no way for a set of devices to coordinate their sleep cycles. WLP defines a local cycle, which allows a device to announce when it will be active. It further defines a global cycle, which is used to synchronize neighbours' local cycles. This hibernation scheme allows devices to conserve power when their data transfer requirements are low. WLP was designed from first principles to run in a battery powered environment and it provides a firm foundation for extending internet connectivity to battery powered devices.

4.2.2.4 QoS support

WLP supports two types of quality of service (QoS) provisioning via two medium access mechanisms in the WiMedia MAC, namely DRP (Distributed Reservation Protocol) and PCA (Prioritized Channel Access). For applications with traffic characteristics that are known and service quality requirements that are precisely specified, the reservation-based medium access mechanism, DRP, supports parameterized QoS. For applications with traffic characteristics and service quality requirements that are unknown or unspecified, the contention-based medium access mechanism, PCA, supports prioritized QoS. Legacy applications that do not have specified traffic characteristics or user priority use the AC_BE access category of PCA to obtain medium access with a corresponding user priority of *best effort*.

If an IPv4 or IPv6 packet is to be transmitted using PCA, the transmitting device shall assign a user priority based on the packet's DS field as shown in Table 4-2.

Table 4-2: DS field mapping for IP packets

DS field (in hex)	User Priority
0x38-0x3F	7
0x30-0x37	6
0x28-0x2F	5
0x20-0x27	4
0x18-0x1F	3
0x10-0x17	2
0x08-0x0F	1

If a WLP device supports higher-layer end-to-end QoS signalling protocols as a part of a larger network providing end-to-end QoS delivery, it should provide controlled load and guaranteed services. If a device supports Controlled-load or Guaranteed services, it shall use the distributed reservation protocol (DRP) to reserve medium time. Traffic characteristics and service quality of an application are encoded in the form of a Traffic Specification (TSPEC), based on which network resources, such as medium time, will be reserved to provide the QoS requested.

4.2.2.5 Security

WLP introduces the concept of a WiMedia Service Set or WSS which is a named group of devices that share a security relationship. A WSS provides a context for exchange of frames between devices. WSS was designed to make it easy to form secure ad hoc networks where devices can discover each other and form securely encrypted links.

A device can become enrolled in a WSS in one of two ways: it can enroll in an existing WSS or it can create a new WSS with new properties. In order to enroll in an existing WSS, a device must first discover the existence of another device accepting enrollment for that WSS. In case of a secure WSS, an association method must be used for the enrollment session. Through the association process, the different authentication and encryption keys and hash values are derived. Possible association methods include:

- Display association methods: These association methods use a numeric value generated and displayed by one device and entered by the user into the other to confirm enrollment.

- User-provided Password association method: This association method uses a password entered by the user into both the registrar and enrollee to authenticate enrollment.

- Numeric comparison association method: This association method authenticates the identity of the registrar and the enrollee by asking the user to visually compare and accept a short number that is displayed on both the registrar and the enrollee.

Once the device has enrolled in the WSS and prior to exchanging data frames with a neighbour within the WSS, a device shall connect to the neighbour. If the WSS is secure, a device shall always send a connection frame as a MAC secure frame. This requires that a device use the 4-way handshake as defined in the WiMedia MAC specification to establish a secure relationship and generate a PTK for use with the target device for this WSS. For this process, the device shall use the WSS master key. A device shall also distribute a GTK for protecting WSS broadcast traffic, as defined in the WiMedia MAC specification. Once the device has established a connection to a target device in a secure WSS, MAC secure frames shall be exchanged as defined in the WiMedia MAC specification.

4.2.3 Wireless USB

Wireless USB (WUSB), also referred to as Certified Wireless USB by the USB Implementers Forum, is the wireless extension to USB that supports robust high-speed wireless connectivity by utilizing the common WiMedia MB-OFDM Ultra-wideband (UWB) radio platform as developed by the WiMedia Alliance [23].

The Wireless USB Promoter Group was formed in February 2004 to define the Wireless USB specification and in May 2005 it announced the completion of the Wireless USB specification. First commercial products hit the market in mid-2007 and products from different vendors are available, including WUSB adapters, hubs, hard disk drives and notebooks with embedded WUSB. Currently, WUSB is the main service implemented utilizing UWB, and almost all the WiMedia UWB developing companies focus on this standard.

The WUSB standard [24] is interfaced directly into the WiMedia protocol, already at the MAC layer level. The WUSB standard is not above the WiMedia MAC, rather, it replaces some parts of it: The WUSB standard requires to follow the WiMedia MAC standard as far as the channel access protocols, requiring standard beaconing and reservations (WUSB and similar protocols have a special type of DRP, but it follows the same rules as other DRPs), but the Data management and transfer protocols of the WUSB differ from the WiMedia standard.

The main characteristics of the WUSB are described below.

4.2.3.1 Topology

A WUSB system consists of a host and some number of devices all operating together on the same time base and the same logical interconnect. The WUSB topology is a star, as shown in Figure 4-2, the host is located at the centre of the network, and the devices are at the nodes. Data is only sent to the host or from it, and not directly between devices. A group of physical-devices containing a host and its devices are called a cluster. WUSB hosts can support up to 127 devices.

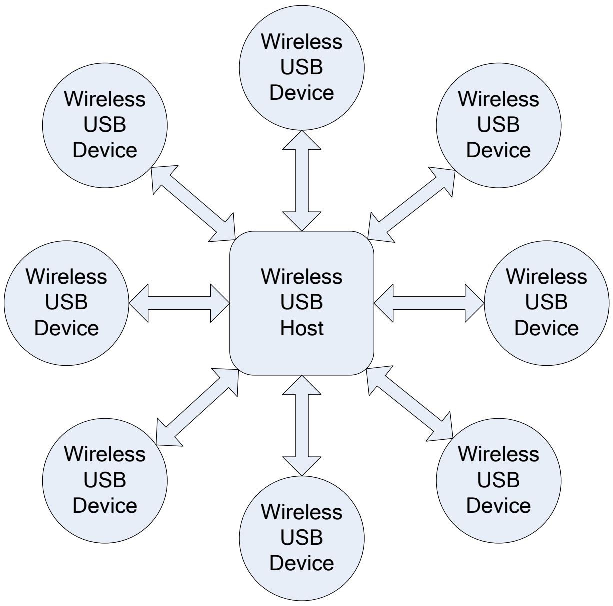

Figure 4-2: WUSB topology

In relation to USB, a new device class called Wire Adapter is defined. This device class describes a standard way for a device of one USB type (wired or wireless) to connect devices of other type. A Host Wire Adapter acts as the host for a Wireless USB system and provides a way to upgrade an existing PC to have Wireless USB capability. A Device Wire Adapter acts as a host for a wired USB system and allows wired USB devices to be connected wirelessly to a host PC.

4.2.3.2 WUSB Management – Host responsibilities

While the WUSB devices do create their own beacons, their operation is actually controlled by the host. The host decides on all the communication characteristics (some of the host decisions are based on negotiations with the device \ device driver, and in some cases – the host may have only one choice to decide upon), for example:

- The Channel (frequency band group, and the Frequencies set and time interleaving),
- The DRP reservations,
- The internal cluster timings
  - When each data packet shall be sent.
  - When Acknowledgment shall be sent.
- The number of packets in a burst.
- The size of the data packets per each packet (but only if supported by the device).

- The data rate per each packet burst.
- The transmit power per each packet burst.

4.2.3.3 Data Access – TG, MMC, Bursts and Burst Acks

Wireless USB retains the same concepts as wired USB such as Endpoints, Pipes and Transfer types. Like wired USB, all WUSB devices are accessed by a USB address that is assigned when the device is attached and enumerated. A device Endpoint is the terminus of a communication flow between a host and a device. Each Wireless USB device additionally supports one or more pipes through which the host may communicate with the device.

Wireless USB is a polled, TDMA based protocol similar to wired USB. Like wired USB, each transfer logically consists of three 'packets': token, data and handshake. WUSB maps the USB 2.0 transaction protocol onto the TDMA Micro-scheduling feature. WUSB defines a WUSB Channel which is encapsulated within a set of MAC Layer superframes via a set of MAC Layer MAS reservations (DRPs), as it is shown in Figure 4-3. This encapsulated channel provides the structure that serves as the transmission path for data communications between a host and devices in a WUSB Cluster. The WUSB provides low latency and fine grained bandwidth control, allowing the host to rapidly and efficiently change the amount of channel time allocated to individual function endpoints.

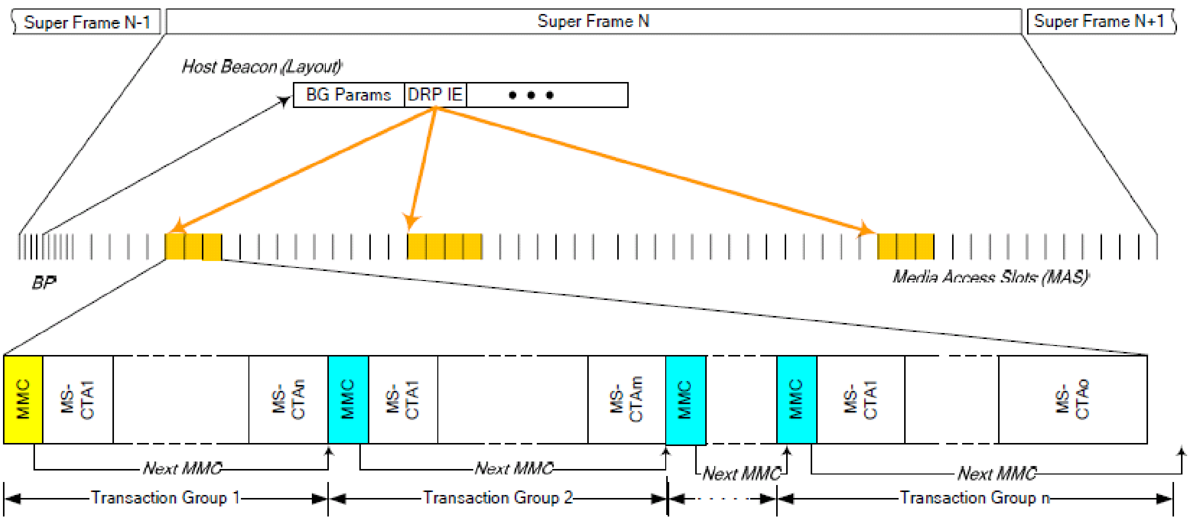

Figure 4-3: WUSB Channel encapsulated within MAC Layer superframes

Within the context of the WUSB application, the micro-scheduled sequence is called a Transaction Group (TG). The structure of a TG is shown in Figure 4-4. The Wireless USB protocol broadcast USB Token (equivalents) in the MMC (Micro-scheduled Management Command) and utilizes TDMA timeslots for Data and Handshake phases. In order to increase the efficiency, host combines multiple token information into a single MMC and multiple data packets can be sent during a transaction's data phase. The general term for this capability is a Burst Mode Data Phase. A WUSB host determines how individual transactions are scheduled into individual transaction groups in order to satisfy the needs (and priorities) of the applications controlling the devices in the WUSB Cluster.

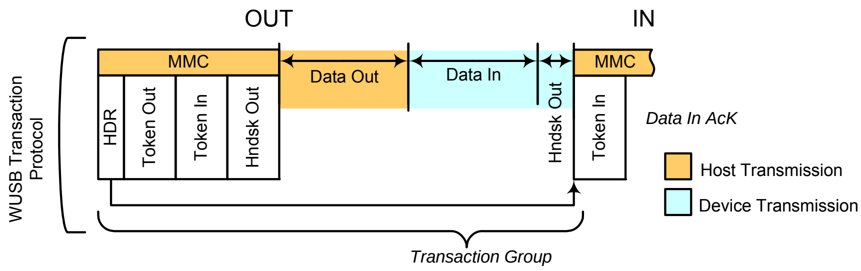

Figure 4-4: WUSB Transaction Group structure

A TG must have an MMC (Micro-scheduled Management Command), in which the Host defines all the relevant parameters mentioned in 4.2.3.2. The MMC duration varies based on the data content of the MMC, a typical value would be about 25µSec. Note that the MMC also contain a section for Acknowledgment of all incoming data packets. Finally, in each MMC, the timing of the next TG (the start of the next MMC) is defined.

After the MMC, the Host transmits the data it should send to all other devices, after that, the devices send their data and then the devices send their acknowledgments for the data sent previously. This arrangement is intended to minimize the flow direction reversals (changes from Tx to Rx and vice versa) of both Host and devices. Inter-slot time between consecutive transmit slots is equal to MIFS, inter-slot time between consecutive device transmit slots is equal to MIFS plus a guard time and flow direction turnaround time is equal to SIFS plus a guard time.

Because of the higher error rate characteristic of wireless communications, Wireless USB protocol defines different mechanisms for error handling. These mechanisms include handshakes on data delivery and retry of failed transfers, as well as device specific amounts of buffering to allow devices some measure of control on the overall reliability. The Acks format is always a Burst Ack, with variable memory size of up to 32 packets. The Acks may also indicate a flow control situation. As error handling is already performed by WUSB, the WUSB protocol exclusively utilizes a MAC Layer No-ACK policy.

Additionally, WUSB allocates specific ‘management’ channel time (Device Notification Time slots, DNTS) for asynchronous, device initiated communications. This asynchronous upstream (i.e. Device to Host) communication is used for signalling connect, remote-wake and other events.

4.2.3.4 Packet format

WUSB uses the packet (frame) formats defined in the WiMedia standard. WUSB packets which originate or terminate on a function endpoint must include a WUSB application header. The WUSB header serves several purposes one of which is to carry Endpoint Number addressing information. The length of the WUSB header is different depending on the value of the packet ID. Isochronous data phase data packets have an additional variable length header section following the common Wireless USB header. WUSB packet format is shown in Figure 4-5.

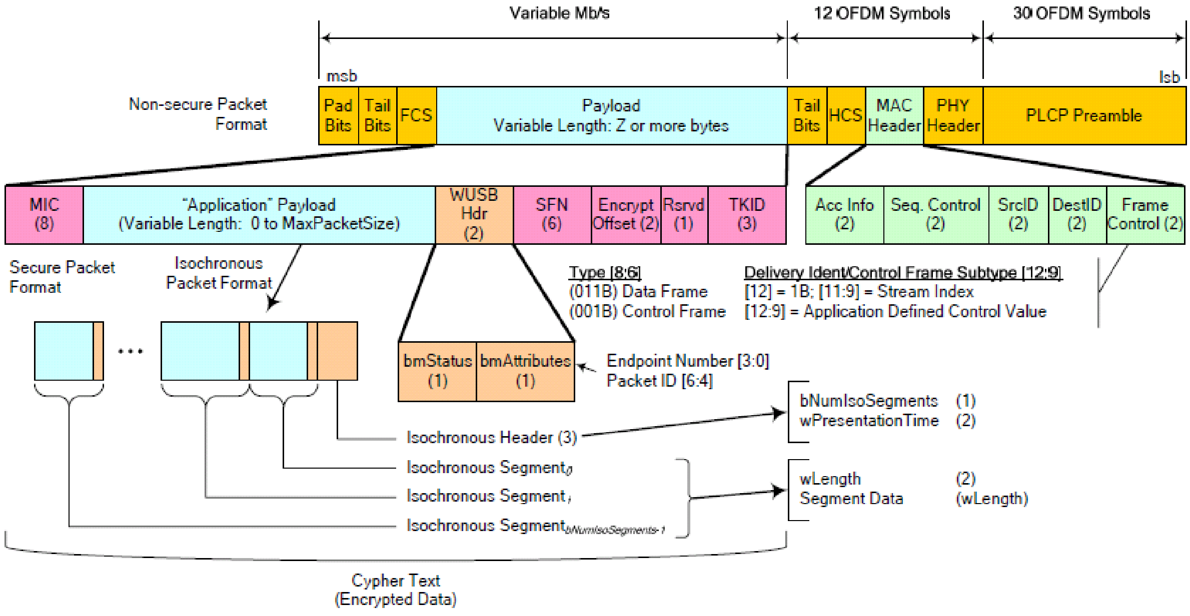

Figure 4-5: WUSB packet format

There are four basic packet types used to communicate information in the WUSB protocol:

- The MMC packet. MMC packets use the Application-defined Control Frame format defined in the MAC Layer standard, do not include a WUSB header and must be transmitted at the most reliable bit transfer rate. MMC packets are always transmitted using secure packet encapsulation, with the host using the WUSB Group Key to generate the MIC.
- Protocol data packets. Protocol data packets are encoded as Data Frame in the MAC header, must include the WUSB header and must be transmitted using secure packet encapsulation unless explicitly specified otherwise. Protocol data packets can be transmitted at any of the implementations supported bit transfer rates
- Protocol handshake packet. Protocol handshake packets are encoded as Data Frame in the MAC header, must include the WUSB header, must be transmitted using secure packet encapsulation unless explicitly specified otherwise and must be transmitted at the most reliable bit transfer rates.
- Device notification packets. Device notification packets are encoded as Data Frame in the MAC header, can only be transmitted by a device and are transmitted using secure packet encapsulation unless explicitly specified otherwise.

4.2.3.5 Higher layer – USB 2.0 Transports

The WUSB supports any USB2.0 traffic over it. An example of a typical application is the MSD (Mass Storage Device) which includes its own higher layer protocol. Unfortunately, most of these protocols were optimized for USB2.0 and are not optimized for the WUSB standard, which often hampers the overall system performance much more then the over the air throughput limitations.

4.2.3.6 QOS types supported

The WUSB standard supports several data transfer types from the point of view of the QOS:

- Bulk transfers: Intended to support devices that want to communicate relatively large amounts of data at highly variable times where the transfer can use any available Wireless USB channel bandwidth. Provide access to the WUSB channel on a bandwidth available basis and guaranteed delivery of data but no guarantee of bandwidth or latency
- Interrupt transfers: Intended to support devices that want a high reliability method to communicate a small amount of data with a bounded service interval. Provide guaranteed maximum service period, retries during the service period if delivery failures occur and retry the next service period in case of multiple transfer failures during a service interval. In order to accomplish the low-latency, the host must poll the endpoint for data at the required poll rate.
- Isochronous transfers: Intended to support streams that want to perform constant rate, error tolerant, periodic transfers with a bounded service interval. Provide guaranteed bandwidth for transaction attempts with bounded latency, average constant data rate, retries during the service period if delivery failures occur and additional reliability during short term error bursts by adding delay to the stream. Defined by the requested bandwidth and service interval. Bandwidth in the WUSB channel is reserved to guarantee a transaction attempt and a certain number of retries each service period.

Control transfers are also defined for device initialization and logical device management. The WUSB system makes a "best effort" to support delivery of control transfers between the host and devices.

4.2.3.7 Security

All hosts and devices must support Wireless USB security. The WUSB security mechanisms are implemented using the security mechanisms of the WiMedia MAC Layer. The security mechanisms ensure that both hosts and devices are able to authenticate their communication partner (avoiding man-in-the-middle attacks) and that communications between host and device are private. The security mechanisms are based on AES-128/CCM encryption, providing integrity checking as well as encryption.

The security framework requires that the devices retain information about the host it was previously connected to (Connection Context). This context consists of three pieces of information: a unique host ID (CHID), a unique device ID (CDID) and a symmetric key (CK) that is shared by both parties. This key is used to re-establish the connection at a later date. The Connection Context may be initialized for new devices via out-of-band provisioning methods which establish on a device information about its intended host including the host's name (CHID) and a secret shared with for that host. New connections require some form of user-interaction.

A device that is looking to establish a connection with a known host locates a MAC layer channel which encapsulates the WUSB Channel being maintained by its intended host by capturing and processing MMCs in each observable WUSB Channel. Then it follows the MMC control stream looking for a DNTS opportunity to transmit a connect notification. When a host receives a connect notification, it allocates a Device Address and includes a connect acknowledgement IE in a subsequent MMC. On reception of the connect acknowledgement, the device updates its WUSB channel device address and proceeds through the Authentication process.

Authentication must be symmetrical between the host and device. WUSB security accomplishes this by using a 4-way handshake that allows the host and device to prove to each other they hold matching

CKs. The 4-way handshake also allows both parties to derive initial session keys from the CK without directly using the CK to encrypt transmitted messages. Once the host and device have completed mutual authentication, each has the proper session key for encrypting/decrypting protocol data and handshake packets.

4.2.3.8 Power management

Wireless USB defines mechanisms and protocols that allow hosts and devices to be as power efficient as possible. Devices have three general ways to manage their Wireless USB power consumption. The first is to manage power during normal operation by taking advance of the TDMA nature of WUSB protocol and opportunistically turning their radio off during periods when it is not needed. The second way is to have the device go to 'sleep' for extended periods of time but still stay 'connected'. In this case the device will not be responsive to any communications from the host. Devices must notify the host before sleeping. The third way is to disconnect from the host.

4.2.3.9 Additional differences of WUSB compared to the WiMedia MAC

The WUSB maximal data size in a packet is 3584 bytes and not 4096 bytes, since the WUSB adds an additional header as part of the data, and the basic WUSB packet sizes vary in integral multiples of 512 bytes.

4.2.3.10 WUSB as a network access protocol

As WUSB preserves the functionality of wired USB, the feasibility of using WUSB to provide IP network access is demonstrated, as there are already network access devices with USB interface such as 802.11 USB dongles or UMTS/HSDPA USB dongles. Only suitable software drivers should be developed in order to make the WUSB device appear as a network access interface to the operating system (OS) and be compatible with the OS's TCP/IP stack (i.e. Windows Sockets for Windows OS).

Although WUSB was not originally designed for IP network access, it accomplishes the requirements in terms of topology, high throughput, reduced overhead, reliability and security. Nevertheless, its performance will not be as optimum as other protocols specifically designed for network access, i.e. WLP. For example, concerning QoS, WUSB provides appropriate support to end-to-end QoS protocols for applications with traffic characteristics that are known and service quality requirements that are precisely specified, but lacks for support of prioritized class-based QoS protocols for applications with traffic characteristics and service quality requirements that are unknown or unspecified, such as DiffServ.

Another drawback for the use of WUSB for network access is the lack of support for mobility, as WUSB is aimed to static point-to-point or point-to-multipoint configurations. If a device wants to switch to another access point eventually using another physical channel, it should search for available WUSB channels on the different physical channels and then start a connection procedure which entails a not inconsiderable duration. Therefore, seamless handover will not be possible.

4.3 Mobility in heterogeneous networks

Next-generation wireless systems are envisioned to have an IP-based infrastructure with the support of heterogeneous access technologies. Next-generation wireless systems call for the integration and interoperation of mobility management techniques in heterogeneous networks.

Currently, there are various wireless technologies and networks that capture different needs and requirements of mobile users. For high-data-rate local-area access, UWB is a satisfactory solution. For wide-area communications, traditional and next-generation (NG) cellular networks may provide voice and data services. Since different wireless networks are complementary to each other, their integration will empower mobile users to be connected using the best available access network that suits their needs. The integration of different networks generates several research challenges because of the following heterogeneities:

- Access technologies: each network using different radio technologies may have overlapping coverage areas and different cell sizes, ranging from a few square meters to hundreds of square kilometres.
- Network architectures and protocols: each network will have different architectures and protocols for transport, routing, mobility management, and so on.
- Service demands: mobile users demand different services ranging from low-data-rate non real-time applications to high-speed real-time multimedia applications offered by various access networks.

The above intrinsic technology heterogeneities ask for a common infrastructure to interconnect multiple access networks. IP is recognized to become the core part of NG integrated wireless systems to support ubiquitous communications. For interoperation of different communication protocols, an adaptive protocol suite is required that will adapt itself to the characteristics of the underlying networks and provide optimal performance across a variety of wireless environments. Furthermore, adaptive terminals in conjunction with “smart” base stations will support multiple air interfaces and allow users to seamlessly switch among different access technologies.

4.3.1 Mobility management

In NG wireless systems there are two types of roaming for mobile terminals (MTs) [25].

- **Intrasystem** roaming refers to moving between different cells of the same system; mobility management techniques are based on similar network interfaces and protocols.
- **Intersystem** roaming refers to moving between different backbones, protocols, technologies, or service providers.

Mobility management (MM) contains two components: location management and handoff management.

Location Management enables the system to track the locations of MTs between consecutive communications. It includes two major tasks. The first is **location registration** or **location update**, where the MT periodically informs the system to update relevant location databases with its up-to-date location information. The second is **call delivery**, where the system determines the current location of the MT based on the information available at the system databases when a communication for the MT is initiated. Two major steps are involved in call delivery: determining the serving database of the called MT and locating the visiting cell/subnet of the called MT. The latter is also called **paging**, where polling messages are sent to all the cells/subnets within the residing registration area of the called MT.

When the service areas of heterogeneous wireless networks are overlapped, the design of location management techniques for intersystem roaming has the following challenges.

- Through which networks an MT should perform location registrations.
- In which networks and how the up-to-date user location information should be stored.
- How the exact location of an MT would be determined within a specific time constraint.

Handoff Management is the process by which an MT keeps its connection active when it moves from one access point to another.

Intrasystem handoff is the one of homogeneous networks. The need for intrasystem handoff arises when the signal strength of the serving base station deteriorates below a certain threshold value. The need for intersystem handoff between heterogeneous networks may arise in the following scenarios:

- When a user is moving out of the serving network and will enter another overlaying network shortly.
- When a user is connected to a particular network, but chooses to be handed off to the underlying or overlaid network for its future service needs.
- When distributing the overall network load among different systems is needed (this may optimize the performance of each individual network).

In order to support **MM in heterogeneous wireless networks**, several protocols are proposed for NG all-IP-based wireless systems. These solutions try to support mobility from different layers of the TCP/IP protocol stack reference model.

- **Network layer** solutions provide mobility related features at the IP layer. They do not rely on or make any assumption about the underlying wireless access technologies. Signalling messages for mobility purposes are carried by IP traffic.
- **Link layer** solutions provide mobility related features in the underlying radio systems. They ensure uninterrupted communications when MTs change positions within the scope of an access router.
- **Cross-layer** solutions are mainly proposed for handoff management. They aim to achieve layer 3 handoff with help from layer 2. By obtaining signal strength reports and movement detection information from the link layer in advance, the system can make better preparation for the network layer handoff so that the packet loss is eliminated and the handoff latency is reduced.

4.3.1.1 Network layer MM

Network layer mobility management solutions can be broadly classified into two categories: macro-mobility and micro-mobility management solutions.

One *domain* is an administrative body, which may include different access networks, such as UWB, 2G and 3G networks of one service provider.

The movement of mobile users between two network domains is referred to as macro-mobility. The movement of mobile users between two subnets within one domain is referred to as micro-mobility (see Figure 4-6).

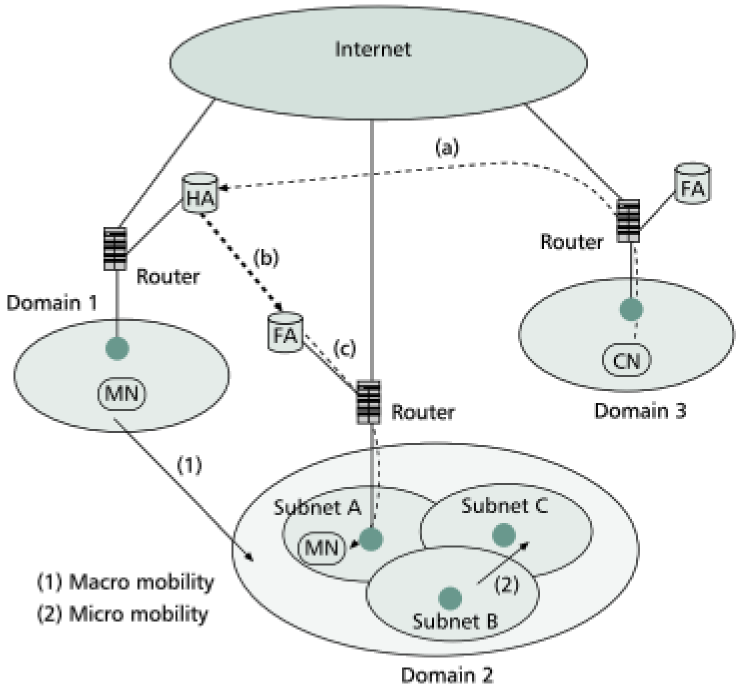

Figure 4-6: Mobile IP architecture

4.3.1.1.1 Macro-mobility MM

Mobile IP is proposed to solve the problem of node mobility by redirecting packets for the **mobile node** (MN) to its current location. MM is supported using the following procedures:

- *Agent discovery*: an MN is able to detect whether it has moved into a new subnet by periodically receiving messages broadcasted from each **foreign agent** (FA).
- *Registration*: when an MN discovers it is in a foreign network, it obtains a new care-of address (CoA). This CoA can be obtained by soliciting or listening for FA advertisements (an FA CoA), or contacting Dynamic Host Configuration Protocol (DHCP) or Point-to-Point Protocol (PPP) (a collocated CoA). The MN registers the new CoA with its home agent (HA). Then, the HA updates the mobility binding by associating the CoA of the MN with its permanent IP address.
- *Routing and tunnelling*: packets sent by a correspondent node (CN) to an MN are intercepted by the HA. The HA encapsulates the packets and tunnels them to the MN's CoA. With an FA CoA, the encapsulated packets reach the FA serving the MN, which decapsulates the packets and forwards them to the MN, as shown in steps a, b, and c in Figure 4-6. With a collocated CoA, the encapsulated packets reach the MN, which then decapsulates them.
- *Handoff Management*: when an MN moves from one subnet to another, the handoff procedure is carried out by the following steps:
    - o The MN obtains a new CoA when it enters a new subnet.

  - The MN registers the new CoA with its HA. The HA sets up a new tunnel up to the end point of the new CoA and removes the tunnel to the old CoA.
  - Once the new tunnel is set up, the HA tunnels packets destined to the MN using the MN's new CoA.
- *Paging*: In order to save battery power consumption at MNs, IP paging is proposed as an extension for Mobile IP. Under Mobile IP paging, an MN is allowed to enter a power saving idle mode when it is inactive for a period of time. During idle mode, the system knows the location of the MN with coarse accuracy defined by a paging area composed of several subnets. An MN in idle mode does not need to register its location when moving within a paging area. It performs location update only when it changes paging areas. When packets are destined to an MN in idle mode, they are terminated at a paging initiator. The paging initiator buffers the packets and locates the MN by sending out IP paging messages within the paging area. After knowing the subnet where the MN resides, the paging initiator forwards the data packets to the serving FA of the subnet and further to the MN. When an MN is in active mode, it operates in the same manner as in Mobile IP, and the system keeps the exact updated location information of the MN.

Mobile IP supports mobility across both homogeneous and heterogeneous systems. It is well suited for macro-mobility management, but less suited for micro-mobility management.

4.3.1.1.2 Micro-mobility MM

MNs usually move frequently between subnets of one domain. To reduce signalling load and delay to the home network during movements within one domain, many micro-mobility solutions have been proposed. They can be broadly classified into two groups:

- *Tunnel-based schemes* use local or hierarchical registration and encapsulation concepts to limit the scope of mobility-related signalling messages, thus reducing the global signalling load and handoff latency. Mobile IP regional registration (MIP-RR), hierarchical Mobile IP (HMIP), and intradomain mobility management protocol (IDMP) are tunnel-based micro-mobility protocols.
- *Routing-based schemes* maintain host-specific routes in the routers to forward packets. The host-specific routes are updated based on host mobility. Cellular IP (CIP) and handoff-aware wireless access Internet infrastructure (HAWAII) are routing-based micro-mobility protocols.

4.3.1.2 Link layer MM

Link layer mobility management solutions focus on the issues related to intersystem roaming between heterogeneous access networks with different radio technologies and different network management techniques. There are two issues critical for intersystem roaming: the air interface protocol and the mobile application part (MAP).

When an MT roams from one wireless access network to another that supports the same air interface and MAP, services are provided seamlessly. However, when the MAPs in the two systems are different, additional entities and signalling traffic are required for interworking and interoperation between dissimilar systems. Since each individual system has its own mobility management procedures, the new interworking entities should not replace existing systems, although they may affect some of the functions or signalling in the present systems.

There are several interworking entities proposed, such as the dual-mode home location register (HLR) for interworking between IS-41 and PCS1900, the gateway location register/boundary location register (GLR/BLR) for intersystem location management, the multitier HLR (MHLR) for a multitier PCS system, and the gateways in the integrated 3G/UWB system. All the proposed new interworking entities are connected to the mobility management entities in individual systems and provide the following functions:

- *Format transformation and address translation*: signalling messages, data packets, and addresses must be translated for communication between heterogeneous networks.
- *User profile retrieval*: a user profile is retrieved from an MT's home network for its communication in the new visiting network.
- *Signalling message transmission and connection setup*: the interworking unit acts as a gateway for message transmission and connection rerouting.
- *Mobility information related to intersystem roaming recording*: the mobility pattern of intersystem roaming needs to be recorded for future mobility management.
- *QoS negotiation*: QoS maintenance must be renegotiated when an MT moves into a new network.
- *Authentication between systems*: authentication is necessary for security reasons.

4.3.1.3 Cross-layer MM

As described previously, cross-layer solutions are mainly proposed for handoff management techniques. MIP handoff latency is composed of latencies for movement detection and registration. Micro-mobility solutions particularly achieve reduction in registration signalling delay, but fail to address the problem of movement detection delay. Cross-layer mobility management protocols reduce movement detection delay using link layer information, such as signal strength. Some algorithms use signal strength measurements directly to reduce handoff latency, while others use signal strength measurement for tracking the MNs and then use this tracking information to support low-latency MIP handoff.

4.4 Heterogeneous networks: the use case of security applications

As stated before, in the heterogeneous environment the always best connected concept will apply with a seamless communication from the user point of view. Users being in buildings, airports would be able to download data thanks to a very high data rate network such as UWB and outside would be able to be connected through a moderate data rate network such as UMTS. IP is the network layer that will allow the integration of all technologies and a global radio resources management will be applied through the different networks (UWB, WLAN, WiMAX) in order to guarantee an end to end QoS. This end to end QoS will be studied in the HDR UWB/WiMAX Gateway taking into account the different WiMAX profiles.

For security applications, users will not download data in buildings and will not be connected through all networks all the time; the purpose here is to have a picocell with HDR UWB or LDR UWB and to connect this network to another network for wider range coverage.

The scenario that has been already described is the following one:

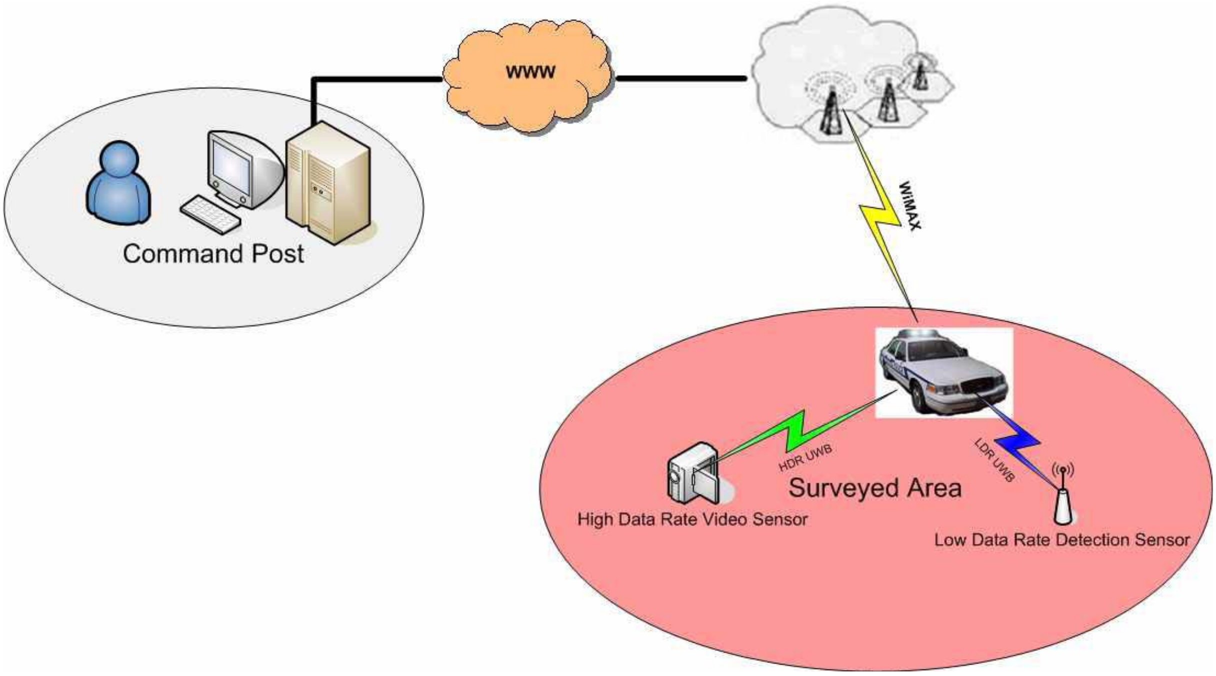

Figure 4-7: Heterogeneous networks scenario for security applications

In this scenario low data rate UWB sensors detect an activity which will wake up high data rate UWB radios connected to high definition video cameras.

In this context, the QoS has to be optimised for the whole network as described in the previous sections. However, another point has to be highlighted: the users are not downloading data. The video stream which is in a very high quality (HD) in order to be able to give all details of the scene has to be sent on a network having a data rate much less than the HDR UWB data rate. Optimised compression and video treatments have then to be used in order to send on the WiMAX network only the needed information to save the capacity. These topics will be studied in the scope of EUWB and compression algorithms will be added in the HDR UWB/WiMAX Gateway.

5 Conclusions

Next-generation wireless systems (4G) are envisioned to have an IP-based infrastructure with the support of heterogeneous access technologies. Different access technologies such as cellular, cordless, WLAN, short-range connectivity, and wired systems will be combined on a common platform to complement each other optimally for different service requirements and radio environments. In this context, UWB arises as a potential access technology providing very high data rate access in short-range picocells.

The only technology comparable to HDR UWB in terms of throughput is IEEE 802.11n, although complexity required to achieve the claimed maximum data rate of 600 Mbps would be very high as four antennas would be needed. Currently certified devices only use 2 antennas and feature physical data rates up to 300 Mbps. Moreover, due to PHY and MAC inefficiencies achievable throughput is approximately 50% of maximum physical data rate and throughputs of 110-130 Mbps have been experienced with current developments. In contrast, throughputs of 380 Mbps can be already achieved with available WiMedia commercial products. Furthermore, UWB offers lower complexity, cost and power consumption.

On the other hand, the main drawback of HDR UWB is its short range, limited to 15 meters for minimum data rate of 53.3 Mbps and just 3 meters for maximum data rate of 480 Mbps. Therefore, the use of HDR UWB as an access technology would be restricted to scenarios requiring a very high data rate and short-range (picocells). Some scenarios would include providing broadband Internet access and high definition video-streaming in airport departure lounges or providing fast music and video purchase on multimedia kiosks.

Theoretical results show that the WiMedia PHY and MAC add approximately a 20% of overhead for the maximum physical data rate and payload length, so throughput available is still 80% of the physical data rate, and a throughput of 380 Mbps can be achieved for 480 Mbps of physical data rate. Besides physical data rate, payload length is one of the key parameters concerning efficiency, as throughput decreases as payload length is reduced, but a longer payload increases packet error rate and reduces effective range. Therefore in some situations (long distance from access point, interferences...) it may be desirable to reduce physical data rate or/and payload size to improve packet error rate in exchange of throughput loss. Experimental results with DV9110M development kits confirmed the theoretical results, although maximum throughput could not be achieved as payload length on the kits is limited to 1512 bytes. Application level throughput for UDP/IP was also measured, which was very close to MAC throughput, although it was limited due to the 100 Mbps Ethernet connections to the kits.

Commercial WUSB devices from Wisair, i.e. WUSB adapters (dongles) have also been tested. Observed throughput was limited to 52 Mbps even for a physical data rate of 480 Mbps, as maximum reserved bandwidth for an isochronous connection is limited on WUSB standard in order to guarantee that available bandwidth is fairly shared among devices. This result is also in line with the manufacturer specifications. It was also shown that as expected range is limited to 3 m. for maximum data rate of 480 Mbps and 14 m. for minimum data rate of 53.3 Mbps. A point-to-multipoint configuration with two devices was successfully tested, which showed a higher aggregated throughput up to 85 Mbps, although it was sometimes limited by the writing speed of a USB memory stick (flash memory).

The integration of UWB into all-IP Heterogeneous Access Networks entails several challenges. Due to the characteristics of the wireless links (limited bandwidth, high latencies, high bit-error rates and temporary disconnections, medium accessibility, mobility...) some requirements must be fulfilled in order to provide wireless access to IP networks: reliability and fault tolerance, security, quality of service and mobility. WiMedia PHY and MAC offer some mechanisms to provide reliability, security and quality of service which are managed by the higher layers, i.e. protocol adaptation layers. WLP is specifically designed to provide compatibility with an IEEE 802 environment and TCP/IP services and consequently offers an optimum convergence with IP networks. Nevertheless, WLP is not very extended on commercial products, which mainly focus on WUSB applications. Although WUSB is not specifically designed for networking, it can also be used to provide IP network access with the appropriate software drivers.

On the other hand, due to the short range of UWB and the limited scope of WUSB applications, the existing standards do not provide much support for mobility. Furthermore, considering heterogeneous networks, mobility among different technologies and networks should be considered, i.e. macromobility or vertical handover. This is being subject of extensive research in the last few years and several solutions have been proposed, mostly based on Mobile IP. Consequently, much of the effort in the following period should focus on analysing and proposing suitable micromobility and macromobility solutions.

Another topic that will be studied in the next months will be the way to cope with the different data rates in a heterogeneous network. Indeed, as shown in the real tests performed with High Data Rate UWB devices, the real throughput at application layer can achieve 247 Mbps with DVK and 52 Mbps with WUSB. WiMAX radio data rate can be up to 23 Mb/s allowing an application data rate of 10 Mbps. One way would be to add innovative compression algorithms in the UWB/WiMAX Gateway. This will be studied as well as other solutions in order to solve this problem especially for the security applications.

References

[1] Zeisberg, S., Schreiber, V.: "EUWB - Coexisting Short Range Radio by Advanced Ultra-Wideband RadioTechnology", ICT Mobile and Wireless Communications Summit, Stockholm, June 2008, accepted for publication

[2] URL of EUWB consortium: http://www.euwb.eu

[3] Standard ECMA-368, "High Rate Ultra Wideband PHY and MAC Standard", 1st Edition, December 2005.

[4] N. Kumar, R.M. Buehrer, "The Ultra Wideband WiMedia Standard", IEEE Signal Processing Magazine, September 2008, pp. 115-119

[5] WiMedia Alliance, "WiMedia Ultra-Wideband: Efficiency Considerations of the Effects of Protocol Overhead on Data Throughput", January 2009.

[6] WiMedia Alliance White Paper, "UWB – Best choice to enable WPANs", January 2008.

[7] PULSERS PHASE II, D4.6 "System demonstrator report", June 2008

[8] EUWB, IR6.1.2 "Specification of commercial UWB platform integration in user devices", March 2009

[9] EUWB, IR6.2.4 "UWB in existing and future radio access network: coexistence aspects", June 2009

[10] Javaid U., Meddour D.E., Rasheed T.M, "Towards Universal Convergence In Heterogeneous Wireless Networks Using Ad-hoc Connectivity", 9th International Symposium on Wireless Personal Multimedia Communications (WPMC), San Diego, September 2006

[11] Alam, M. Z., Patra, C. C., Patra, C., and Sobhan, M. A. "Multiplexing Technique for All-IP 4G Heterogeneous Network". Proceedings of the 2009 Fifth Advanced international Conference on Telecommunications, May 2009.

[12] P. J. M. Havinga and G. Wu, "Wireless Internet on Heterogeneous Networks", Proceedings of Workshop on Mobile Communications in Perspective, Enschede (the Netherlands) 2001.

[13] S. Y. Hui and K. H. Yeung, "Challenges in the migration to 4g mobile systems," IEEE Communications Magazine, vol. 41, no. 12, pp. 54-59, 2003.

[14] I. F. Akyildiz, J. Xie, and S. Mohanty, "A survey of mobility management in next-generation all-IP-based wireless systems," IEEE Wireless Communications, vol. 11, no. 4, pp. 16-28, 2004.

[15] P. Agrawal, T. Zhang, C. J. Sreenan, and J.-C. Chen, "All-IP Wireless Networks", Guest Editorial in IEEE Journal on Selected Areas in Communications, Vol. 22, No. 4, May 2004.

[16] H. Balakrishnan, S. Seshan, E. Amir, Y H. Katz, "Improving TCP/IP Performance over Wireless Networks", In Proceedings 1st ACM International Conference on Mobile Computing and Networking (Mobicom), November 1995.

[17] K. Xu, Y. Tian, N. Ansari, "TCP-Jersey for wireless IP communications", IEEE Journal on Selected Areas in Communications 22 (4), pp.747-756. 2004

[18] R.H. Katz, "Adaptation and mobility in wireless information systems", IEEE Personal Communications. Vol. 1, No.1, pp. 6-17. 1994

[19] P. Hunt, "Understanding WiMedia Association models and security", RF Design, November 2006.

[20] URL of WiMedia Alliance: http://www.wimedia.org

[21] WiMedia Alliance, "WiMedia Logical Link Control Protocol", WLP Specification Approved Draft 1.0, August 2007.

[22] A. Berkema, "WiNet Basics", RF Design, November 2006.

[23] URL of WUSB within USB Implementers Forum: http://www.usb.org/developers/wusb/

[24] Wireless Universal Serial Bus Specification, Revision 1.0, May 12, 2005
[25] Ian F. Akyildiz, Jiang Xie, Shantidev Mohanty "A Survey of Mobility Management in Next-Generation All-IP-Based Wireless Systems", IEEE Wireless Communications, August 2004

Acknowledgement

The EUWB consortium would like to acknowledge the support of the European Commission partly funding the EUWB project under Grant Agreement FP7-ICT-215669 [1], [2].