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Abstract

This deliverable is aimed at providing the basis for the investigations on radio technologies in WP2, on the three types of systems considered: Wireless Local Area Networks (WLAN), Wireless Personal Area Networks relying on Ultra Wideband (UWB) technology below 10 GHz (WPAN-UWB) or at 60 GHz (WPAN 60 GHz).

The purpose of the document consists in defining performance and QoS targets for the radio technologies. In order to achieve these goals, the document first describes use cases and usage scenarios, mainly from work package 1 of the OMEGA project, but also from other relevant works specific to radio. The wireless standards and systems being already in use or under deployment are also presented to describe the radio technologies landscape for the project. From the analysis of the use cases and the capabilities of current wireless technologies, performance and QoS requirements are derived, setting targets for the investigations on radio technologies.

Keyword list

WLAN, WPAN, UWB, standards, QoS, requirement

Executive Summary

This deliverable is the first deliverable of work package 2 (WP2) on radio technologies and is intended to provide a basis for the technical work in this work package, which covers three main categories of technologies: Wireless Local Area Networks (WLANs), Wireless Personal Area Networks (WPANs) relying on Ultra Wideband (UWB) technology below 10 GHz (WPAN-UWB) or at 60 GHz (WPAN-60 GHz). The goal of this document is to provide technical requirements which will serve as guidelines for the studies on radio technologies and support the selection of the most appropriate one for OMEGA networks.

The deliverable is divided into three main parts. The first one extracts the main features and aspects relevant to the work in WP2 from the use cases and usage scenarios described in WP1. Then, the second chapter summarizes the technological landscape for radio technologies by a description of the existing technologies for each of the three radio systems. Finally, the third section derives technical and QoS requirements according to different criteria like throughput, cost and hardware.

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List of Acronyms

Acronym	Meaning
AC	Access Category
ACMA	Australian Communications and Media Authority
AIFS	Arbitration Interframe Space
AIFSN	Arbitration Interframe Space Number
ASK	Amplitude Shift Keying
ATM	Asynchronous Transfer Mode
AV	Audio Video
AVB	Audio Voice Bridging
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BP	Beacon Period
BPSK	Binary Phase Shift Keying
BT	Bluetooth
COTS	Commercially off-the-shelf
CRC	Cyclic Redundancy Check
CSMA/CA	Carrier Sense Multiple Access / Collision Avoidance
DAA	Detect And Avoid
DBPSK	Differential Binary Phase Shift Keying
DECT	Digital Enhanced Cordless Telecommunication
DCF	Distributed Contention Function
DCM	Dual Carrier Modulation
DIFS	Distributed Interframe Space
DFS	Dynamic Frequency Selection
DRP	Distributed Reservation Protocol
DSSS	Direct Sequence Spread Spectrum
DTP	Data Transfer Period
EAT	Electro-Absorption Transceiver
ECC	Electronic Communications Committee
EDCA	Enhanced Distributed Channel Access
EESS	Earth Exploration Satellite Services
EIRP	Equivalent Isotropic Radiated Power
ENOB	Effective Number of Bits
EVM	Error Vector Magnitude

FFT	Fast Fourier Transform
FCC	Federal Communications Commission
FDS	Frequency Domain Spreading
FEC	Forward Error Correction
FLANE	Fixed Local Area Network Extension
FS	Fixed Services
FZ	Frank-Zadoff
GMSK	Gaussian Minimum Shift Keying
GSM	Global System for Mobile Communications
HAN	Home Area Network
HDTV	High Definition Television
HSI	High Speed Interface
HRP	High Rate Physical Layer
HT	High Throughput
IEEE	Institute of Electrical and Electronics Engineers
IM-DD	Intensity Modulation Direct Detection
IPTV	Internet Protocol Television
ISI	Intersymbol Interference
ISM	Industrial, Scientific and Medical
ITS	Intelligent Transport Systems
ITU	International Telecommunication Union
LDC	Low Duty Cycle
LDPC	Low Density Parity Check
LIPD	Low Interference Potential Devices
LOS	Line Of Sight
LRP	Low Rate Physical Layer
LSB	Least Significant Bit
MAC	Medium Access Control
MAS	Medium Access Slot
MB	Multi-Band
MCM	Multipath Channel Margin
MCS	Modulation and Coding Scheme
MCSS	Multi-Carrier Spread Spectrum
MGWS	Multiple Gigabit Wireless Systems
MIH	Media Independent Handover
MIFS	Minimum Interframe Space

MIMO	Multiple-Input Multiple-Output
MPDU	MAC Protocol Data Unit
MSB	Most Significant Bit
MSDU	MAC Service Data Unit
MWFSG	Millimeter Wave band Frequency Study Group
NAS	Network Attached Storage
NF	Noise Figure
NLOS	Non Line Of Sight
NPRM	Notice of Proposed Rulemaking
Nss	Number of Spatial Streams
OCMC	Optically Controlled Microwaves Converter
OFDM	Orthogonal Frequency Division Multiplex
OOK	On-Off Keying
PAR	Project Authorization Request
PCA	Prioritized Contention Access
PER	Packet Error Rate
PHY	Physical Layer
PLCP	Physical Layer Convergence Protocol
PN	Personal Network
PLCP	Physical Layer Convergence Protocol
P-PAN	Private Personal Area Network
PPDU	PLCP Protocol Data Unit
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
QoS	Quality of Service
RoF	Radio over Fibre
RMS	Root Mean Square
RF	Radio Frequency
RS	Reed-Solomon
RX	Receiver
SAP	Service Access Point
SC	Single Carrier
SCBT	Single-Carrier Blocked Transmission
SIFS	Short Interframe Space
SISO	Single-Input Single-Output
SINR	Signal to Interference and Noise Ratio

SME	Small and Medium Enterprises
SOHO	Small Office – Home Office
TDMA	Time Division Multiple Access
TDS	Time Domain Spreading
TFI	Time Frequency Interleaved
TX	Transmitter
TXOP	Transmission Opportunity
UDA	Unused DRP Announcement
UDR	Unused DRP Response
UEP	Unequal Error Protection
UM	Usage Models
UMTS	Universal Mobile Telecommunications System
UWB	Ultra Wide Band
VCSEL	Vertical-Cavity Surface-Emitting Laser
VHT	Very High Throughput
VoIP	Voice over Internet Protocol
WAPI	Wired Authentication and Privacy Infrastructure
WCDMA	Wideband Code Division Multiple Access
WLAN	Wireless Local Area Network
WPA	Wi-Fi Protected Access
WPAN	Wireless Personal Area Network
WVAN	Wireless Video Area Network
WWRF	Wireless World Research Forum
ZPS	Zero Padding Suffix

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1 Motivation for the design and improvement of radio technologies for OMEGA networks

According to Steve Balmer we are heading for the fifth wave of PC revolution. Within seven years everybody will be able to access his personal documents any time and anywhere without knowing where they are located. The same evolution will take place inside the house of the future. For mobility while viewing documents, pictures, and videos a reliable wireless technology with sufficient bandwidth is essential. More detailed application scenarios are to be found in WP1.

Due to the diverse applications exhibiting very different requirements, smart clients with different or even adaptable radios will be used. Within OMEGA's radio work package, the following radio technologies will be investigated and assessed regarding their suitability to achieve OMEGA home network goals:

- WLAN 801.11n,
- WPAN UWB,
- WPAN 60GHz.

Key issues of these investigations will be the performance of these technologies to deliver Gbps throughput, QoS for applications such as voice and TV, energy efficiency for long uptime and achieving the European Code of Conduct on Energy Efficiency in Broadband Equipment. Furthermore, robust and reliable operation as well as affordable prices are important requirements.

The application scenarios and use cases derived in WP1 will provide a framework for the investigations on radio technologies. They will be used for setting directions and defining constraints.

1.1 Application scenarios and use cases

This section is aimed at providing a summary of the use cases and usage scenarios envisioned in WP1. These use cases and usage scenarios have been the topic of an internal document and will be made public in September 2008. From typical scenarios and needs in a Home Area Network (HAN), different situations can be identified, involving interactions between the terminals present in a HAN.

- Use case: Family

This use case is developed based on a family composed of two parents and two children, living within a home equipped with various devices, e.g. the operator gateway, a media server, screens, etc. The different usage scenarios include:

  - An "evening in family home": each family member is using different applications, involving different types of data streams: HDTV, music and video streaming, VoIP.
  - In the "Follow me" usage scenario, the user accesses content stored on the network wherever his location in the house may be, switching from one display to another while changing rooms.
  - In the "Welcome home" usage scenario, a family member uses a tactile screen to read and transmit different kinds of messages (video, audio, 3D).

- Use case: Home-working

This use case involves a two-storey house with a family composed of two parents and four children.

  - The first usage scenario, "Working in the evening", involves video conferencing in a home office while other family members are having leisure time (HDTV streaming, game, VoIP, etc) and Network Attached Storage (NAS) backups are performed periodically.
  - In the second usage scenario, "Thin client", the family is surfing the web and streaming music from a thin client device.

- Use case: Student (or more generally e-learning)

A student living in a small open-space apartment is the sole element of this use case, with fewer terminals than in the two previous ones. The usage scenario "Gaming with friends" involves file downloading for work on a university project and other network activities related to leisure activities such as audio streaming and online gaming.

- Use case: Single

In this fourth use case and related usage scenario, "Evening party", the single occupant of an apartment (larger than the previous use case, with more equipment) receives friends and they are simultaneously pursuing distinct activities, with different types of associated data streams (IPTV traffic, HDTV and images streaming, IP telephony and online gaming).

- Use case: Small Office – Home Office (SOHO)

The usage scenario here deals with a "SME", i.e. a small and medium-sized enterprise located in a two-storey house, equipped with terminals essentially dedicated to working activities (PCs, screens, etc). The types of data streams include video conference, file downloads, VoIP and streaming of different files (presentation, online demonstration and music).

- Use case: Home to Home

This last use case involves a family with two parents and a child, living in an apartment.

- In the first usage scenario, "Multi-home party", an HD video conference takes place, with exchange of HD video and audio stream between the operator's Home, with a Femtocell Voice Gateway and different devices in the flat. HD video is stored and streamed again at a later stage.
- In the second one, "Content synchronization", videos stored in the home NAS are accessed in a synchronized way from two different locations, with or without edition capabilities, in parallel to an audio conference.
- The last one, "Multimedia content sharing", implies access from a guest device to the PC (play control) and video streaming, with real-time content adjustments to the display.

Other generic use cases can be added, such as online gaming (the key here is low latency), support of the aging population (ambient assisted living, security, monitoring, health care, etc), or cloud computing. Cloud computing is a new label for simplification of the data centre by leveraging virtualisation technologies to reduce complexity.

- Cloud computing: Users have the possibility to use the offered (web) applications without taking care of the underlying technologies. Furthermore, the costs are reduced as hardware, software and maintenance is shared by several users. For this application the offered QoS is dependant on used or booked services and can differ from case to case.
- Data storage: Hosting companies offer their customers storage capacity which can be bought or rented to store data on virtual servers. Data operators "virtualize" the resources according to the customer requirements and the customers can then manage the virtual servers by themselves.

1.2 Consequence on performance and QoS targets for radio technologies

Some of the use cases defined by WP1 can be selected to serve as target for the work in WP2. The most relevant ones are:

- Family: The usage scenario "Evening in the family home" should be taken into consideration as it is very generic (high probability of occurrence) and implies traffic to various devices located in different rooms. Radio technologies will necessarily be involved (one of the terminal is a mobile for example). The "Follow me" scenario is also interesting as it implies accessing content stored in the network while moving in the house, and radio technologies are natural candidates. The third scenario, "Welcome home" is interesting because of the number and variety of types of data streams, with possibly high bit rate requirements.
- Home Working: The usage scenario "Working in the evening" is a good reference as it is demanding for the technologies of the home network, with various types of flows, bit rate requirements (up to 1 Gbps) and activity period (periodic downloading, peak activity for file downloading, etc). The usage scenario "Thin client" could also be considered as the user interface is a mobile one.
- SOHO: The concern behind this use case (and the associated usage scenario SME) is that it implies a large number of devices. Generally, in the commercial sector, radio technologies

(WLAN) are commonly used. The demanding performance requirements and relatively low sensitivity to costs makes it a good market entry sector.

From these use cases requirements result with respect to the technology constraints. In the following use cases, according to the recommendations of the ITU for assuring the Quality of Service within wired and wireless networks, are listed.

- Audio: The area of audio is divided into three sub-categories which will be given in more detail below.
  - Conversational Voice

    The requirements of conversational voice are very much influenced by the delay occurring in different ways of transmission. There are two distinct effects of delay. The first is the creation of echo in conjunction with two-wire to four-wire conversions or even acoustic coupling in a terminal. The second effect occurs when the delay increases to a point where it begins to effect conversational dynamics, i.e. the delay in the other party responding becomes noticeable. However, the human ear is highly sensitive to short-term delay variation (jitter). As a practical matter, for all voice services, delay variation due to variability of incoming packet arrival times must be removed with a de-jitterizing buffer.

    Requirements in terms of information loss are influenced by the fact that the human ear is tolerant to a certain amount of distortion within a speech signal. In IP-based transmission systems a prime source of voice quality degradation is due to the use of low bit rate speech compression codecs and their performance under conditions of packet loss.
  - Voice Messaging

    Requirements with respect to information loss are essentially the same as for conversational voice (i.e. dependent on the speech coder), except that there is higher tolerance for delay since there is no direct conversation involved. The main point is to check how much delay can be tolerated. There is no precise data on the tolerance of stimulus-response delay in telecommunications but a delay of a few seconds seems to be reasonable for these applications. The main issue seems therefore to be the user reaction to playback.
  - Streaming Audio

    Streaming audio is expected to provide better quality than conventional telephony. The main requirements in this case result from avoiding information loss in terms of packet loss. As there are no conversational elements in audio streaming the delay requirements as well as the voice-messaging requirements do not have to be considered very strictly.

- Video: The area of video is divided into two sub-categories which will be given in more detail below.
  - Videophone

    Videophone implies a full-duplex system intended to be used for conversation, carrying both video and audio. The same delay requirements as for conversational voice are to be met, i.e. no echo and minimal effect on conversational dynamics, with the added requirement that the audio and video must be synchronised within certain limits to provide "lip-sync".

    Also the human eye is tolerant to some loss of information and a transmission delay. Some degree of packet loss is acceptable depending on the specific video coder and amount of error protection used.
  - One-way video

    The main distinguishing feature of one-way video to videophone is that there is no conversational element involved, meaning that the delay requirement will not be so stringent, and can follow that of streaming audio.
- Data: The prime requirement for any data transfer application is to guarantee zero loss of information. For the data transfer the delay does not have to be taken into consideration as it is not generally noticeable to the user, although a limit on synchronisation between media streams in a multimedia session (e.g. audio in conjunction with a white board presentation) is required. The different applications therefore tend to distinguish themselves on the basis of the delay which can be tolerated by the end-user from the time the source content is requested until it is presented to the user.

Performance targets for audio and video applications, as well as data applications, are summarized in table 1-1 and table 1-2. These tables are extracted from an ITU document [ITUTG1010] on performance targets for QoS for multimedia applications, and will be a starting point for the work in WP2. Some of these figures will obviously be updated in the next months in the course of the work in WP2, to reflect the more ambitious use cases considered.

Table 1-1: Performance targets for audio and video applications

Medium	**Application**	**Degree of symmetry**	**Typical data rates**	**Key performance parameters and target values**		
				One-way delay	**Delay variation**	**Information loss (Note 2)**
Audio	Conversational voice	Two-way	4-64 kbps	<150 ms preferred (Note 1) <400 ms limit (Note 1)	< 1 ms	< 3% packet loss ratio (PLR)
Audio	Voice messaging	Primarily one-way	4-32 kbps	< 1 s for playback < 2 s for record	< 1 ms	< 3% PLR
Audio	High quality streaming audio	Primarily one-way	16-128 kbps (Note 3)	< 10 s	<< 1 ms	< 1% PLR
Video	Videophone	Two-way	16-384 kbps	< 150 ms preferred (Note 4) <400 ms limit		< 1% PLR
Video	One-way	One-way	16-384 kbps	< 10 s		< 1% PLR

NOTE 1 – Assumes adequate echo control.

NOTE 2 – Exact values depend on specific codec, but assume use of a packet loss concealment algorithm to minimise effect of packet loss.

NOTE 3 – Quality is very dependent on codec type and bit-rate.

NOTE 4 – These values are to be considered as long-term target values which may not be met by current technology.

Table 1-2: Performance targets for data applications

Medium	Application	Degree of symmetry	Typical amount of data	Key performance parameters and target values		
				One-way delay (Note)	Delay variation	Information loss
Data	Web-browsing – HTML	Primarily one-way	~10 KB	Preferred < 2 s /page Acceptable < 4 s /page	N.A.	Zero
Data	Bulk data transfer/retrieval	Primarily one-way	10 KB-10 MB	Preferred < 15 s Acceptable < 60 s	N.A.	Zero
Data	Transaction services – high priority e.g. e-commerce, ATM	Two-way	< 10 KB	Preferred < 2 s Acceptable < 4 s	N.A.	Zero
Data	Command/control	Two-way	~ 1 KB	< 250 ms	N.A.	Zero
Data	Still image	One-way	< 100 KB	Preferred < 15 s Acceptable < 60 s	N.A.	Zero
Data	Interactive games	Two-way	< 1 KB	< 200 ms	N.A.	Zero
Data	Telnet	Two-way (asymmetric)	< 1 KB	< 200 ms	N.A.	Zero
Data	E-mail (server access)	Primarily one-way	< 10 KB	Preferred < 2 s Acceptable < 4 s	N.A.	Zero
Data	E-mail (server to server transfer)	Primarily one-way	< 10 KB	Can be several minutes	N.A.	Zero
Data	Fax ("real-time")	Primarily one-way	~ 10 KB	< 30 s/page	N.A.	$<10^{-6}$ BER
Data	Fax (store & forward)	Primarily one-way	~ 10 KB	Can be several minutes	N.A.	$<10^{-6}$ BER
Data	Low priority transactions	Primarily one-way	< 10 KB	< 30 s	N.A.	Zero
Data	Usenet	Primarily one-way	Can be 1 MB or more	Can be several minutes	N.A.	Zero
NOTE – In some cases, it may be more appropriate to consider these values as response times.						

Some use cases can also set specific requirements:

- File Transfer:

This application likely requires high peak throughputs but will not have any real-time constraints. Several applications can fall into this category, like wire replacements (connections between PC, printers, cameras, displays, TV sets, etc.) and NAS backup. With the increasing number of devices present within the home, wireless solutions become necessary to get rid of the clutter of cables to interconnect these different devices. There is also a large number of storage devices (USB keys, hard disk drives, etc.) and users want to access their content easily and rapidly.

Other aspects could be important, such as easy discovery of the devices (devices can rapidly interconnect to each other without requiring too much user assistance, etc.).

- Gaming

Very low latency is a key for gaming applications. The players are expecting a high reactivity.

These applications will follow the general trend regarding video applications and increasing use of HD content. This will also drive up the requirements regarding data rates. More sophisticated graphics or the use of 3D imaging will also influence the requirement for higher throughputs.

Games involving user-generated content will also set requirements on symmetric data rates.

- Aging

A strong requirement on devices for this application area is that they should be easy to use.

- Cloud computing

The cloud is often understood to be a public network, usually assumed to be the internet, where the services it can provide are more important to the user than the underlying technologies used to achieve the requested functions.

- Applications for cloud computing expand rapidly as connectivity costs fall.
- The location of infrastructure in areas with lower costs of real estate and electricity are a very important advantage of cloud computing.
- Most of the IT clouds are heterogeneous systems, while ensembles are a pool of homogeneous systems within a cloud which are compatible with one another. These ensembles allow for mobility of the software stack between physical servers by integration through virtualisation and management software.

In particular due to applications like high-definition video transmission and file transfer, there are growing demands for multi-gigabit wireless transmission. Traditionally, UWB has been considered to realize such gigabit short-range transmission. The IEEE 802.15.3a was formed to come up with these social demands; however it could not make it due to the conflict between two major parties. As an alternative, 60 GHz WPAN systems have gained attention. The standardization activities are being performed in several groups and industrial consortiums, representatively IEEE 802.15.3c, ECMA and Wireless HD. Brief introduction to these standardization activities will be given in section 2.3.2. Table 1-3 summarizes the application definitions in the IEEE 802.15.3c usage model document.

Table 1-3: Application definitions issued from IEEE 802.15.3c Task Group [TG3c06, 1]

Application	Load	Data type	BER	Asymmetry
HD video streaming	0.05 – 3.2 Gbps	Isochronous	10^{-12} – 10^{-11}	Yes
File transfer	0.1 – 2 Gbps	Asynchronous	10^{-6}	No
Wireless docking station and desktop	0.1 – 3.2 Gbps	Isochronous/ Asynchronous	10^{-12} for Iso. 10^{-6} for Asy.	Yes
Gaming	0.05 – 1 Gbps	Isochronous		No
Short-range backhaul	0.156 – 2.5 Gbps	Asynchronous	10^{-6}	No
Ad-hoc	0.1 – 1.6 Gbps	Asynchronous	10^{-6}	No
Wireless Gbps Ethernet	0.5 – 1.0 Gbps	Asynchronous	10^{-6}	No

2 Radio technologies landscape

Mechanisms and algorithms at the PHY layer are investigated and implemented to enable convergence at the radio layer, improving the coexistence and cooperation of radio technologies and to increase the data rates. State-of-the-art WLAN (mainly IEEE 802.11n) and WPAN (UWB and 60 GHz) systems will be used as a basis for this work. Improvements will be proposed and studied. Performance and complexity assessments will be conducted, in order to evaluate the benefits and gains of each technique.

Link adaptation techniques form a major part of this work, as they are required to facilitate adjustments of the home network topology to real-time traffic and moving devices. They can also bring significant benefits in making efficient use of scarce spectrum resources. Furthermore, the reliability of the transmission will be improved and enhanced.

The three types of radio technologies investigated have not reached similar level of maturity and status. A technology such as WLAN already has a history of standards and systems deployed, while WPAN systems using 60 GHz bands have not passed the first IEEE standardization phase yet. WPAN UWB systems have an intermediate status. This section is aimed at providing an overview of the status of each technology.

2.1 WLAN

Different WLAN standards have been specified. The most important ones are specified in the IEEE 802.11 standard family, which defines the medium access control (MAC) and the physical layer (PHY). In order to ensure interoperability of WLAN products based on the IEEE 802.11 specifications, the Wi-Fi Alliance develops test procedures and conducts Wi-Fi certification of wireless devices that implement these IEEE 802.11 specifications. Often, Wi-Fi is used as a synonym for WLAN standards and technologies.

The following subsections give a short overview on the legacy standard and the amendments which are primarily focussed on the PHY.

2.1.1 IEEE 802.11

The legacy standard for WLAN was approved in July 1997. Originally. it defined three different PHYs supporting data rates up to 2 Mbps in the 2.4 GHz ISM (Industrial, Scientific and Medical) band.

In 2007, a new version was released, which integrated all approved amendments at that time and omitted the obsolete parts. Currently, maintenance changes are accumulated.

2.1.2 IEEE 802.11a

This amendment was approved in September 1999 and products began to be shipped to the market in early 2002. It defined an additional PHY based on OFDM, so that data rates up to 54 Mbps are supported. The PHY operates in the 5 GHz band, which provides 19 non-overlapping 20 MHz channels in Europe.

2.1.3 IEEE 802.11b

This amendment was also approved in September 1999 and products began to be shipped to end markets in early 2000. It operates at data rates up to 11 Mbps in the 2.4 GHz ISM band. In 2001, a corrigendum of this amendment was released.

2.1.4 IEEE 802.11g

In 2003, IEEE released a new amendment called 802.11g, which specified several PHYs in the 2.4 GHz band and supports data rates up to 54 Mbps. Most of the WLAN products available today are based on this amendment.

2.1.5 IEEE 802.11n

In January 2004, the IEEE announced that it had formed a new 802.11 task group to develop a new standard for wireless networking. The major objective of 802.11n is to increase the throughput. It is aimed to provide a physical data rate of up to 600 Mbps. The launch of this standard has been delayed several times, because of a failure of the IEEE members to agree on a number of final details of the standard. It is planned that the standard will be released in September 2009. However, this has not stopped products being brought to market. Several “pre-n” products, designed around what the suppliers believe will be the final standard, are available since mid-2006.

2.1.5.1 PHY layers

As a final 802.11n amendment or corresponding requirements do not exist yet it is up to the implementation of a radio chipset to fulfil the necessary system specifications with minimal cost overhead. The target for the final OMEGA radio PHY is to implement it into a 65 nm or 45 nm CMOS technology.

Key targets for the OMEGA radio prototype:

- Single chip radio with embedded power amplifier.
- Radio chip only with PCI interface for a baseband processor.

Collaborative Coexistence with Bluetooth (BT) devices shall be supported (BT device connected on same board). Synchronized BT coexistence shall be supported according to 802.15.2. RF Frontend control for BT coexistence shall not be supported.

Non collaborative coexistence shall be supported (device not connected on same board):

- Microwave oven
- DECT
- Bluetooth
- Amateur radio
- Cellular radio

Table 2-1 and Table 2-2 give an overview about the different WLAN standards that will be supported by the OMEGA radio prototype, while Table 2-3 provides more details about IEEE 802.11n PHY functionalities.

Table 2-1: WLAN PHY standards supported by the OMEGA radio prototype

Standard	F_0 [GHz]	Transmission method	Modulation	Data sub-carriers	Bandwidth [MHz]	Coding Rates	Air Rate [Mbps]
802.11a	5	OFDM	BPSK, QPSK, 16-QAM, 64-QAM	48	20	1/2, 2/3, 3/4	<= 54
802.11b	2.4	DSSS	DBPSK, DQPSK, CCK		20		1 2 5.5 /11
802.11g	2.4	OFDM	BPSK, QPSK, 16-QAM, 64-QAM	48	20	1/2, 2/3, 3/4	<= 54
802.11n	2.4/5	OFDM	BPSK, QPSK, 16-QAM, 64-QAM	52 or 108	20 or 40	1/2, 2/3, 3/4, 5/6	<= 600*

**: IEEE 802.11n draft includes possible air rates up to 600 Mbps but the corresponding transmission modes are not implemented yet*

Table 2-2: Further standards/drafts supported by the OMEGA radio prototype

802.11k	Radio Resource Measurement of Wireless LANs
802.11w	Protected Management Frames
802.11v	Wireless Network Management
802.11u	Wireless Interworking with External Networks
802.11h	Spectrum Management in 5 GHz range

802.11j	5 GHz operation in Japan
802.11e	MAC enhancements for QoS
802.11i	Enhanced Security Mechanisms
802.11d	Regulatory Domain Update
802.15.2	**Coexistence of WPANs and WLANs**
CCX v1-5	Cisco Compatible Extensions
Wi-Fi Alliance	WPA/WPA2
GB 15629.11-2003	**Wired Authentication and Privacy Infrastructure (WAPI)**
802.21	Media Independent Handover (MIH)
802.1	Audio Voice Bridging (AVB)

Table 2-3: Main characteristics of IEEE802.11n

Frequency of operation	2.4 GHz and 5 GHz
Channel bandwidth	20 MHz, 40 MHz
Modulation scheme	OFDM 20 MHz mode: FFT size = 64, 52 data subcarriers out of 56 available subcarriers 40 MHz mode: FFT size = 128, 108 data subcarriers out of 114 available subcarriers
Error-correcting codes	Convolutional coding (Mandatory) LDPC coding (Optional)
MIMO techniques	Direct Mapping (Mandatory) Spatial Spreading/Expansion (Mandatory) Space-Time Block Coding (Optional) Transmit Beamforming (Optional)
Number of spatial streams	From 1 spatial stream to 4 spatial streams
Compatibility	Interoperability with 802.11a and 802.11g Coexistence with 802.11b

2.1.5.2 *Efficiency Improvements in the IEEE 802.11n MAC enhancement*

The basic IEEE 802.11 transmit mechanism limits the maximum achievable transmission rate due to its high constant-size overhead per transmitted frame. To evaluate the impact of the overhead, especially concerning the new Modulation and Coding Schemes (MCSs) introduced with IEEE 802.11n, we calculate the throughput and the efficiency of the MAC protocol in the single-link as following:

$$throughput = \frac{l}{\lceil (l+o+s+t)/N_{DBPS} \rceil \times d_{OFDM} + d_{PHY} + d_{DIFS} + d_{BO} + d_{SIFS} + d_{ACK}} \quad \text{[bps]}$$

$$efficiency = \frac{throughput}{N_{DBPS} / d_{OFDM}}$$

With

- l: frame length [b]
- o: MAC header size [b]
- s: PHY service bits [b]
- t: PHY tail bits [b]

- N_{DBPS}: Number of data bits per OFDM symbol
- d_{OFDM}: Duration of one OFDM symbol
- d_{PHY}: Duration of PLME header and preamble
- d_{DIFS}: Duration of DIFS
- d_{BO}: Average backoff duration
- d_{SIFS}: Duration of SIFS
- d_{ACK}: Duration of ACK

Figure 2-1 shows the efficiency of the MAC using the highest Modulation and Coding Scheme (MCS) of IEEE 802.11a, i.e. 64QAM R=3/4 with a gross rate of 54 Mbps. These results can be extended by assuming an infinite gross rate in Figure 2-2. Even with this rate, the maximum achievable throughput at the MAC SAP is limited by the packet size to 111 Mbps.

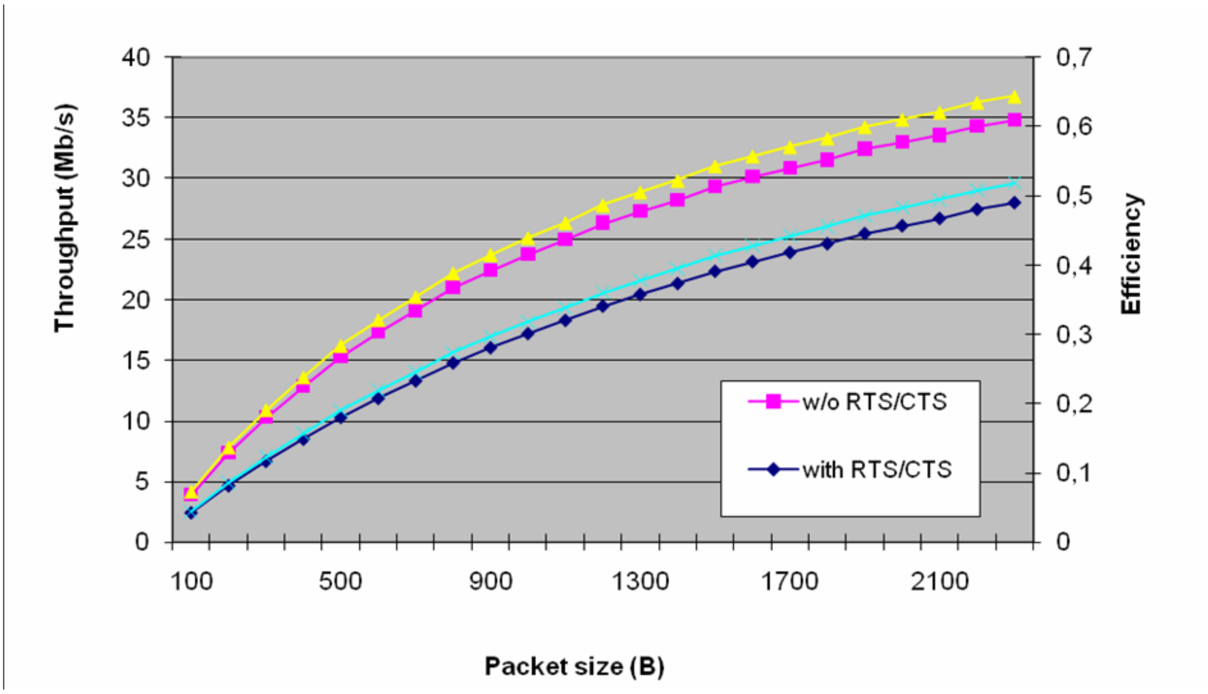


Figure 2-1: Throughput and efficiency of IEEE 802.11a, 64QAM ¾, varying packet size

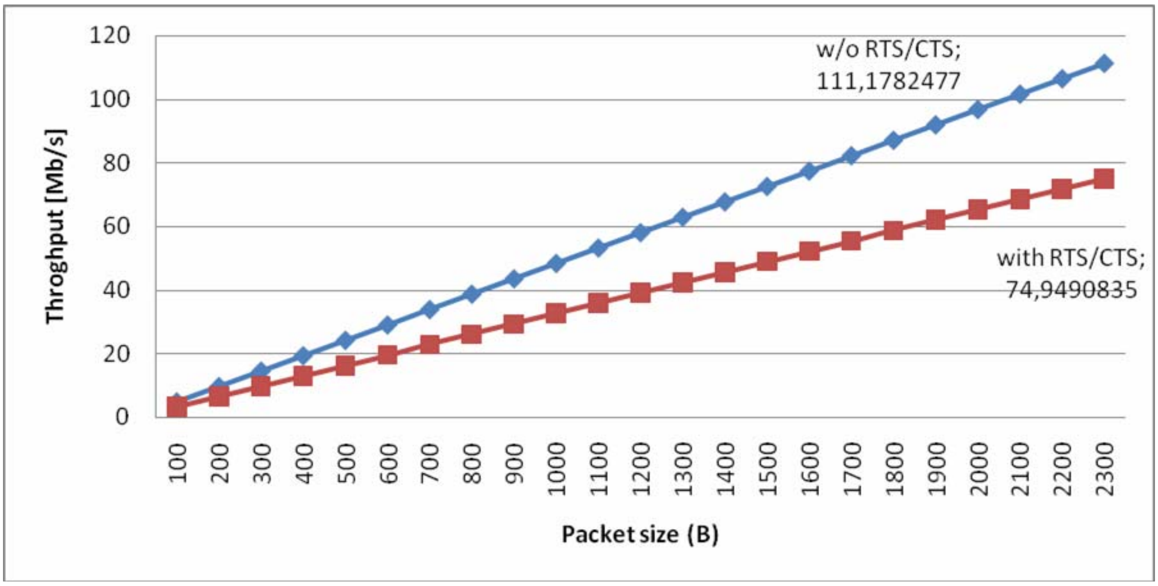


Figure 2-2: Throughput of an imaginary physical layer with infinite gross data rate

Therefore, methods are required to lower the amount of overhead per transmitted packet, which results mainly from the collision avoidance of the IEEE 802.11 Distributed Contention Function (DCF). Thus, IEEE 802.11n proposes methods that allow multiple consecutive frame transmissions if a single contention for the channel has been won, extending the Transmission Opportunity (TXOP) principle from IEEE 802.11e. Instead of separating the transmitted packet from each other, they are aggregated into one single packet train, so that the transceiver needs to do one backoff operation only. Inside the train, MPDUs are separated by MPDU delimiters which contain a defined delimiter marker, the length of the next MPDU and its CRC. Therefore, if interference during the transmission makes one single MPDU undecodeable, the receiver can search for the next correct delimiter marker and receive the remaining MPDUs successfully. By extending the maximum allowable number of Bytes per PPDU, the efficiency of the IEEE 802.11n MAC is increased heavily.

Together with the frame aggregation, a block acknowledgement scheme is introduced that allows for indicating the successfully/erroneous received MPDUs within one single data transmission.

Table 2-4 : IEEE 802.11n MAC functionalities introduced to improve efficiency

Efficiency Improvements in IEEE 802.11n	
Frame Aggregation	Multiple frames can be concatenated and transmitted in one channel access, saving backoff, preamble, PLME header etc.
Block Acknowledgement	Multiple frames can be acknowledged using a single ACK frame, indicating the successful/failed frames in a bitmap

2.1.6 Other collaborative work on WLAN systems

Other collaborative projects deal with WLAN systems, aiming at the design and/or improvement of WLAN systems, such as HOMEPLANE.

The overall goal of the HOMEPLANE project is to develop a homogeneous concept for the wireless integration of multimedia components within residential environments.

Today, the consumer experiences a vast number of devices suitable for digital information processing and digital multimedia. Up to now, the convergence of technologies is not yet fulfilled and a convenient solution is still missing. For this reason, existing services and products are impractical and less attractive. On the other hand, the technical progress provides various inexpensive solutions for this purpose. However, the adaptation of such solutions to the requirements of a homogeneous residential networking scenario is still missing.

The HOMEPLANE project aims to solve this problem by developing concepts that ensure the interoperability of different devices and by creating a user-friendly platform for home media networking.

An import task of this project concerns the enhancement of IEEE 802.11 based WLAN for multimedia applications. As confirmed by a user study, the wireless interconnection of multimedia devices is generally preferred. The increased flexibility of usage and the absence of additional cabling are very convenient. Users also expect the wireless network to be as reliable as cable. Nevertheless, currently available solutions are not well suited for this application scenario. In order to cope with this, newly created concepts to enhance the potential of the physical and MAC layers used within IEEE 802.11 based networks are simulated and implemented into the whole system.

The HOMEPLANE project funded by the BMWi (German Federal Ministry of Economics and Technology) is focused on the “Consumer Electronic” field of innovation within the scope of the “NextGenerationMedia” submission. Besides the Dortmund University of Technology, the European Microsoft Innovation Center, AllTec GmbH (succeeding Lintec IT AG), the Institute for High Performance Microelectronics (IHP) and SIEMENS AG cooperate in this project.

Among the projects in the FP7 framework, the MIMAX project [MAG, WP3.1, 06] MAGNET IST-507 102, WP3 Internal Report, "IR3.1.1, "Radio-engineering for optimisation of PAN devices", November 2006.

[MIMAX] (Advanced MIMO systems for maximum reliability and performance) intends to develop low power and ultra compact MIMO transceiver, reconfigurable to adjust to the applications and channel conditions, and target not only UMTS but also WLAN applications.

2.1.7 Perspective

2.1.7.1 Spectrum issues

The introduction of new modes with larger bandwidth (40 MHz) in IEEE 802.11n is one of the means enabling higher throughputs. Nevertheless, the number of terminals operating in the allowed frequency bands, especially at 2.4 GHz, is growing and it will probably become progressively more difficult to use the modes with a double bandwidth.

In the perspective of the evolution of WLAN systems towards higher data rates, larger bandwidths will become necessary. If saturation of 2.4 GHz frequency bands is confirmed in the coming years, this will restrict the use to frequency bands at 5 GHz (or higher) for higher throughputs.

2.1.7.2 IEEE 802.11VHT

As the IEEE 802.11n Task Group is finishing the work towards a standard, a new draft is coming closer to ratification, several companies involved in WLANs are looking ahead towards evolution of this standard. The race to higher throughputs is still driving data rates to higher levels, and targets such as 1 Gbps, which was considered as unrealistic not so long ago, are now becoming more concrete objectives. Wireless transmission of uncompressed HDTV and large-volume file exchange are good examples for such high data rate applications. Moreover, an increasing number of systems are now competing for these applications: millimetre-wave WPAN systems are clearly focusing on multiple gigabits applications and the corresponding group at IEEE (IEEE 802.15.3c) is finalizing a standard with modes up to at least 1.5 Gbps (see section 2.3.2). The competition is therefore becoming fiercer in the home network, and the WLAN community has also started to position WLAN systems to avoid being outdated in the area of very high throughput systems.

A first initiative was raised at the March 2007 IEEE meeting. The creation of a new study group on Very High Throughput (VHT) systems was proposed. This new study group started working in May 2007 on the preparation of a Project Authorization Request (PAR) and 5 Criteria (founding documents of an IEEE Task Group) by analysing the use cases, technology trends, spectrum and regulatory opportunities. They will work on editing the PAR and 5C documents in the first semester of 2008 in order to prepare the Task Group phase, targeting the first meeting of the Task Group in November 2008. The objective consists in having a standard approved by end 2010, with deployment in 2012.

Two frequency bands are proposed, a first one targeting the < 6 GHz band and a second one for the wide 60 GHz band. During January 2008 meeting straw polls were carried out to decide the frequency bands to be considered and the study group objectives concerning both PAR and 5C. It was then decided that the VHT study group would lead to the creation of two Working Groups, each one dedicated to a frequency band (< 6 GHz or 60 GHz) and targeting specific PAR and 5C. Discussions are going on concerning the status (amendment or new standards) of these future standards, but the latest discussions tend to show that they would be both amendments to the IEEE 802.11 standard. The question concerning a solution that would allow a dual-band operation is still open.

Both VHT Task Groups should unofficially begin at July 2008 meeting and officially at November 2008 meeting, waiting for the approval of IEEE executive Committee.

2.2 WPAN-UWB

2.2.1 Regulation

As UWB systems use a large bandwidth, they employ parts of spectrum that are shared by other services or systems, which led to difficulties to define a frequency regulation for UWB systems.

The decision from the FCC (Federal Communications Commission), the US regulation body, to authorize UWB transmission for communication systems in the 3.1 – 10.6 GHz frequency band, with a power level limit set to -41.3 dBm/MHz, was the starting point for UWB development. The FCC [FCC] is an independent United States government agency, directly responsible to the Congress. The FCC was established by the Communications Act of 1934 and is in charge of regulating interstate and international communications by radio, television, wire, satellite and cable. The FCC's jurisdiction covers the 50 states, the District of Columbia and U.S. possessions. FCC is directed by five commissioners appointed by the President and confirmed by the Senate for 5-year terms, except when filling an unexpired term.

The spectral mask raised controversy in other countries, as some coexistence studies revealed interferences with other communication systems. There have been intensive discussions within European regulation bodies to define suitable power levels for UWB transmissions in order to protect existing services like UMTS, GSM, WLAN, Fixed services, Fixed Satellite Services, but also future services to be deployed, like WiMax and future mobile systems. The availability of UWB chipsets in the US put pressure on the European regulation bodies to issue a first decision, in order to avoid the invasion of unauthorized and potentially interfering systems on European market. The Electronic Communications Committee (ECC) published a first decision in March 2006 [ECC06].

- in the frequency band 6 – 8.5 GHz, the ECC decided that High Data Rate and Low Data Rate UWB can be introduced in accordance with the ECC emission mask (-41.3 dBm/MHz)
- in the frequency band 3.1 – 4.8 GHz, several possibilities were kept under investigation:
    - Introduction of UWB techniques with mitigation techniques (Detect And Avoid) with -41.3 dBm/MHz as power spectral density limit.
    - In frequency band 4.2 - 4.8 GHz, temporary solution for UWB application to use this band until 2010/2012 without mitigations techniques. This solution is called phased approach.
    - Introduction of UWB low data rate with mitigation techniques such as limitation of duty cycle LDC 5% per second and 0.5% per hour

The first two solutions remained under discussions until the end of 2006. Indeed, in the low frequency band 3.1 - 4.8 GHz, further investigations on mitigation techniques and additional coexistence tests have been required before reaching a decision. The main systems requiring protection are WiMax systems and radar. After having authorized the use of the 6-8.5 GHz band with the March 2006 decision, the ECC reached a new decision in December 2006 and officialized it in February 2007 [ECC07], settling the case of the 3.1 – 4.8 GHz band.

The 4.2 – 4.8 GHz band is considered for future mobile applications, justifying the cut-off deadline set by the EU. Figure 2-3 to Figure 2-5 summarize these decisions.

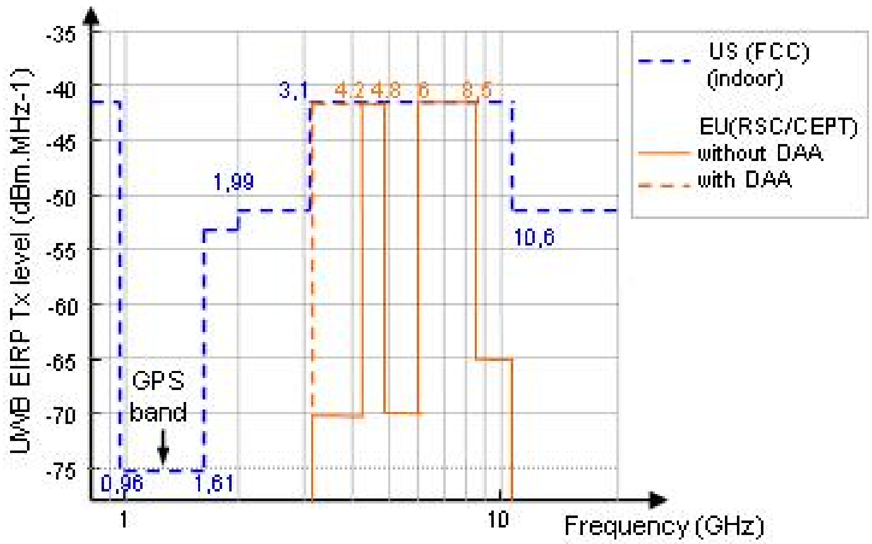


Figure 2-3: Spectrum mask in EU before December 31st, 2010

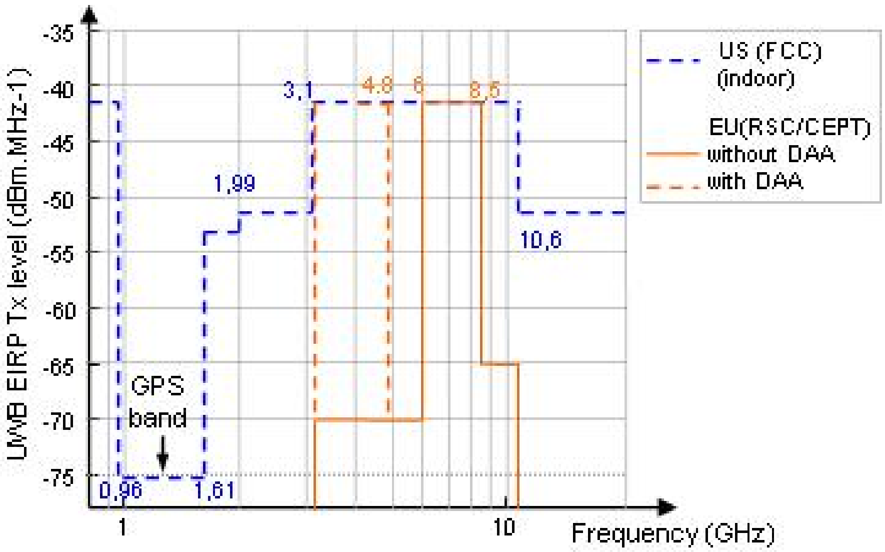


Figure 2-4: Spectrum mask in EU after December 31st, 2010

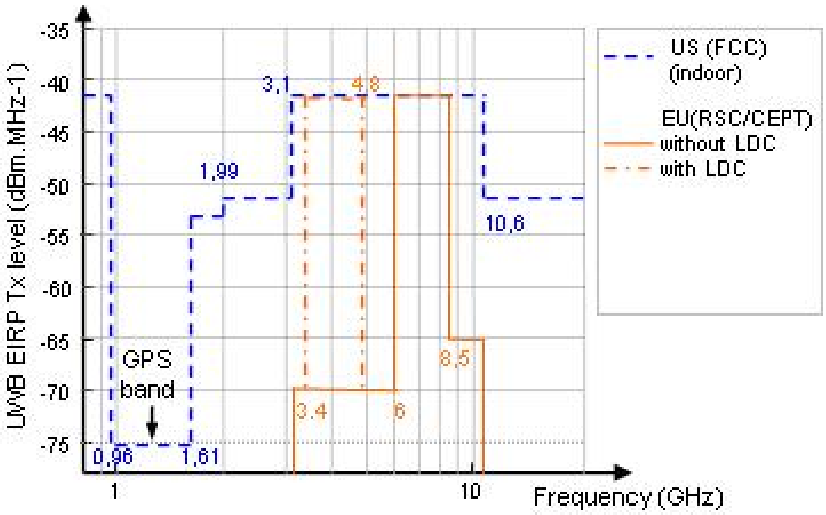


Figure 2-5: Spectrum mask with Low Duty Cycle (LDC) restrictions

Similar decisions have been taken or are under process by regulation bodies in other countries. Japan regulation authority (MIC) was the first to issue a regulation which is close to the European one. UWB transmissions will also be allowed in the upper band at -41.3dBm/MHz power level, but at a different frequency band: 7.25 - 10.25 GHz instead of 6 - 8.5 GHz. In the lower band, UWB transmission at power level -41.3 dBm/MHz will be authorized without mitigation techniques (DAA: Detect And Avoid) until the end of 2008. In the remaining of the lower band (between 3.4 and 4.2 GHz), UWB transmission will be authorized either at -41.3 dBm/MHz power level with DAA, or at -70dBm/MHz without DAA. These conditions will also be applied to the 4.2 – 4.8 GHz band starting from 2009. Similar decisions are underway in Korea and China.

2.2.2 Standardization

2.2.2.1 PHY

For supporting the immense rise in the consumer electronics market the need for streaming e.g. uncompressed HDTV between set-top-boxes and presentation displays, increases. The WiMedia 2.0 specification is targeting gigabit throughput, which requires further enhancements on the PHY and MAC layers. For improving the transmission performance and the overall system efficiency Low-Density Parity-Check (LDPC) codes can be used. Furthermore, this implementation renders several blocks of the physical layer unnecessary, e.g. interleaving, diversity spreading/combining and Dual Carrier Modulation.

The WiMedia PHY uses a Multiband-OFDM transmission scheme with a frequency range from 3.1 GHz to 10.6 GHz. The spectrum is divided in 14 bands, each with a bandwidth of 528 MHz. Those bands form six band groups in total.

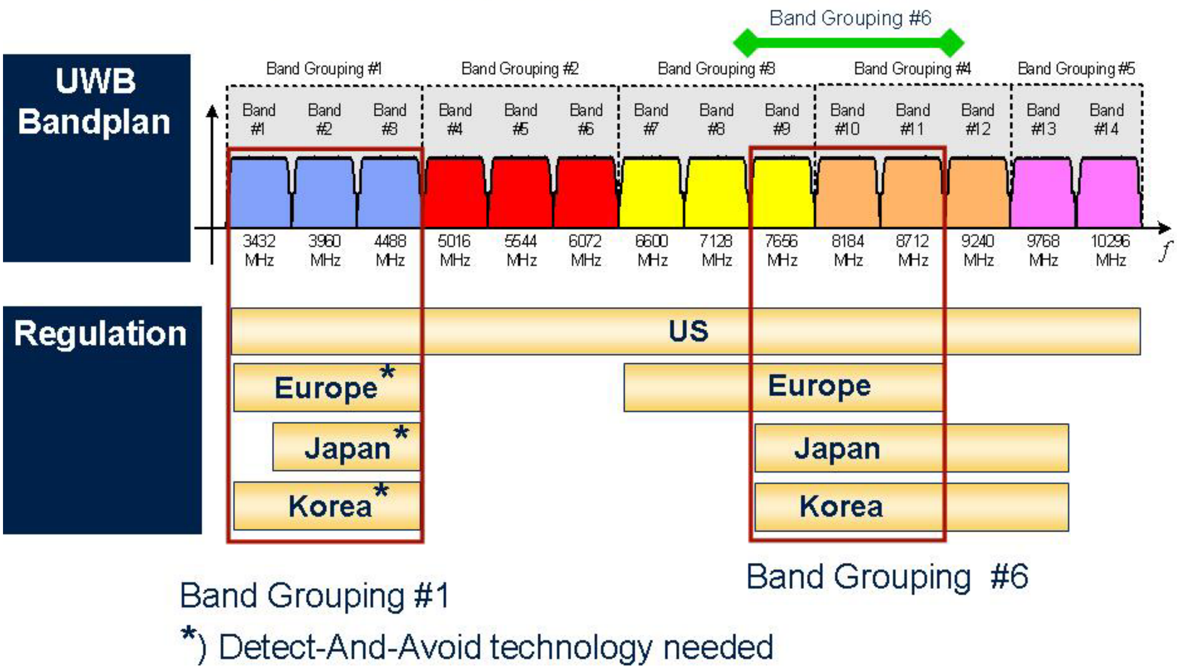


Figure 2-6: UWB Band plan versus world-wide Regulation

The WiMedia PHY offers data rates between 53.3 Mbps and 480 Mbps as listed in Table 2-5. They result from the use of different code rates, spreading and modulation techniques. The corresponding PHY block structure is based on Orthogonal Frequency Division Multiplexing (OFDM) and depicted in Fig. 2-7. Each OFDM symbol consists of 128 subcarriers with a spacing of 4.125 MHz fitting into one band. In the overall symbol duration of 312.5 ns a zero padding suffix (ZPS) of 70.08 ns is included to mitigate intersymbol interference (ISI). The OFDM parameters of WiMedia are summarized in Table 2-6.

The subcarriers can either be modulated by QPSK symbols or a novel modulation scheme called dual carrier modulation (DCM) for the higher data rates. For each group of four bits, DCM produces two data symbols from different 16-QAM constellations with suitable mappings and transmits them at distant subcarriers. In addition to the diversity gain, DCM promises a slight coding gain in comparison to QPSK modulation.

The large bandwidth offers the possibility to exploit diversity. Therefore, diversity spreading can be applied at the transmitter. In the case of frequency domain spreading (FDS) QPSK symbols are repeated within one OFDM symbol at two distant subcarriers, whereas for time domain spreading (TDS) they are spread over two consecutive OFDM symbols.

Table 2-5: Supported WiMedia data rates

Data rate (Mbps)	Mod.	Code Rate	FDS	TDS
53.3	QPSK	1/3	YES	YES
80	QPSK	1/2	YES	YES
106.7	QPSK	1/3	NO	YES
160	QPSK	1/2	NO	YES
200	QPSK	5/8	NO	YES
320	DCM	1/2	NO	NO
400	DCM	5/8	NO	NO
480	DCM	3/4	NO	NO

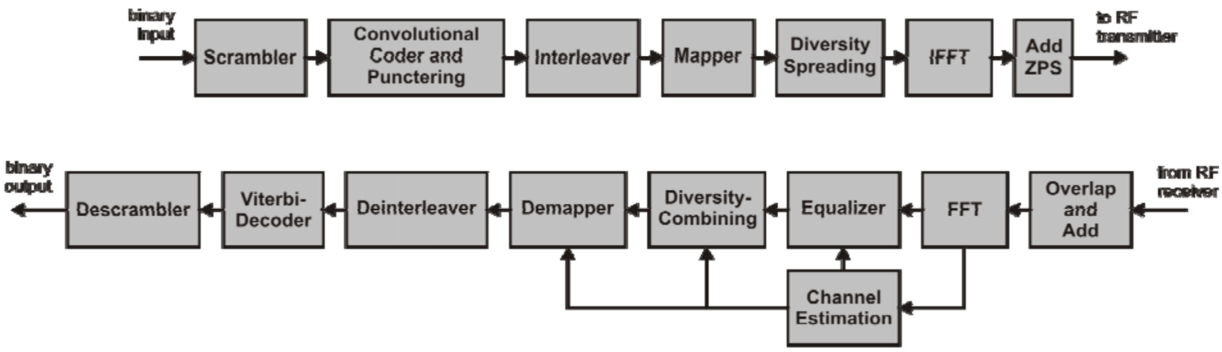


Figure 2-7: WiMedia PHY

Table 2-6: WiMedia OFDM parameters

Parameter	Value
Sampling frequency	528 MHz
Number of subcarriers (FFT size)	128
Number of data subcarriers	100
Number of pilot subcarriers	12
Number of guard subcarriers	10
Total number of subcarriers used	122
Subcarrier frequency spacing	4.125 MHz
OFDM symbol duration	242.42 ns
Zero-padded suffix duration	70.08 ns
Total symbol duration	312.5 ns

Among other characteristics, it should be noted:

- Transmit centre frequency and symbol clock frequency tolerance: ± 20 ppm

- Relative constellation RMS error (=EVM):

  Up to 200 Mbps: -17 dB

  Beyond 200 Mbps: -19.5 dB

  Measure over a minimum of 100 packets with at least 30 symbols each

- RX sensitivity levels are described in Table 2-6.

Table 2-7: Minimum Rx sensitivity levels for WiMedia MCS

Data Rate (Mbps)	53.3	80	106.7	160	200	320	400	480
Min. Rx Sensitivity (dBm)	80.8	78.9	77.8	75.9	74.5	72.8	71.5	70.4

These values are related to link budget assessments defined in the section 3.4 with a BER set to 10^{-6}.

- Phase noise contribution to EVM: -30 dBc

$$\phi_{err} = 10^{\frac{EVM}{20}} \qquad t_{j\,\text{int}} = \frac{\phi_{err}}{2 \cdot \pi \cdot f_{LO}}$$

EVM of -30 dBc → 1.8 deg phase error

→ 1.1 ps integrated RMS jitter @ 4488MHz (Band Group 1)

→ Estimated -100 dBc/Hz of in-band PLL phase noise

2.2.2.2 WiMedia MAC for UWB Networking

Designed for high-speed, short range communication infrastructureless networks, the WiMedia MAC differentiates itself from the traditional centralized WPAN systems, e.g., Bluetooth and IEEE 802.15.3, by using a synchronized and distributed scheme. In a WiMedia system, the channel time resource is organized into fix-length superframes, which comprise 256 Medium Access Slots (MASs). Each MAS lasts for 256 µs. At the beginning of each superframe a Beacon Period (BP) consisting of n MASs is allocated for all devices to exchange beacons, as shown in Figure 2-8. It is mandatory for every device to send its beacon in the BP of each superframe. Beacons are used for maintaining the system synchronization, learning the network topology and coordinating the channel accesses. Channel time other than the BP is used for data transfer, namely Data Transfer Period (DTP), which is also shown in Figure 2-8.

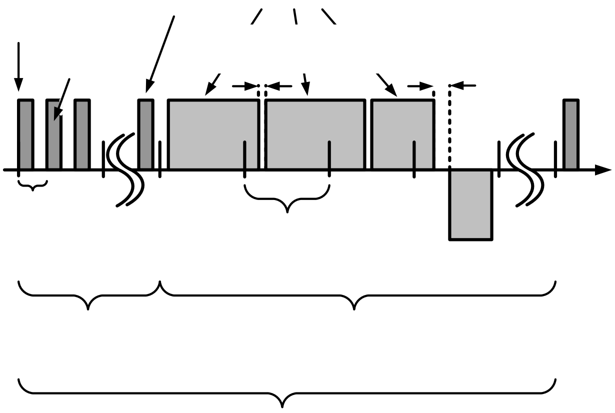


Figure 2-8: WiMedia Superframe structure

To combine the efficiency of TDMA based systems with packet based technology, the WiMedia system introduces the Prioritized Channel Access (PCA) and the Distributed Reservation Protocol (DRP). While the first one is well known from the contention based Enhanced Distributed Channel Access (EDCA) defined in IEEE 802.11e, the latter one is based on an advanced reservation scheme providing collision free channel access.

<u>Prioritized Contention Access (PCA)</u>

The PCA is very similar to the EDCA. It is a contention based Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) scheme relying on a prioritized backoff procedure. The PCA mechanism provides differentiated, distributed contention access to the medium for four access categories (ACs) of frames buffered in a device for transmission. A device employs a prioritized contention procedure for each AC to obtain a transmit opportunity (TXOP) for the frames belonging to that AC using the PCA parameters associated with that AC. Table 2-8 shows how the four ACs are mapped from eight user priorities.

Prior to every transmission attempt a device has to sense the channel as idle for a static period called Arbitration Interframe Space (AIFS). Afterwards, it has to keep on sensing the channel for multiples of the slot time (9 µs). The amount of slot times is a random number drawn from a uniformly distributed interval of (0, CW). The initial value of CW is CWmin. The duration of AIFS depends on the value of AIFSN, which depends on the access category, like CWmin and CWmax. Whenever the device senses the channel as idle it decreases its slot counter by one. If the slot counter reaches zero the device may start to transmit, as shown in Figure 2-9. If the device senses the channel as busy, it freezes its slot counter. After the channel is sensed as idle for an AIFS period again, the backoff procedure resumes counting down the remaining slots. With every failed transmission a device doubles its CW to reduce the probability of a collision with other devices. Table 2-9 shows the WiMedia PHY related parameters used by PCA.

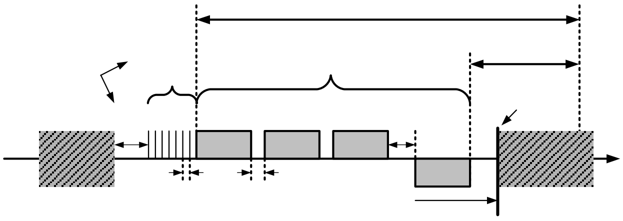


Figure 2-9: Principle of PCA

Table 2-8: PCA QoS Parameters supported by the WiMedia MAC

User Priority	AC	CWmin	CWmax	TXOPLimit	AIFSN
1	Background	15	1023	1 frame	7
2	Background	15	1023	1 frame	7
0	Best effort	15	1023	1 frame	4
3	Best effort	15	1023	1 frame	4
4	Video	7	511	1024µs	2
5	Video	7	511	1024µs	2
6	Voice	3	255	256µs	1
7	Voice	3	255	256µs	1

Table 2-9: Interframe spaces defined for the WiMedia MAC

Interframe Space	Value
Minimum Interframe Space (MIFS)	1.875 µs
Short Interframe Space (SIFS)	10 µs
Arbitrary Interframe Space (AIFS)	SIFS + AIFSN * slot time (9 µs)

Distributed Reservation Protocol (DRP)

The DRP provides a collision free channel access. It announces future transmissions and thus allows devices to coordinate their channel access. Through beaconing, devices sharing the same BP can learn the MAS occupation status and make their own reservation. The reservation is announced by the owner device in its beacon and identified with the start MAS number and the duration in unit of MASs.

The WiMedia MAC supports hard or soft reservations. A hard reservation enables the device owning the MASs to start its transmission immediately at the beginning of the reserved MASs, since all other devices must complete their transmissions a SIFS plus a guard interval before the reserved MAS. The reserved MAS itself may be used solely by the reserving device and its communication partners. No other transmission is permitted during that period. The Unused DRP Announcement (UDA), Unused DRP Response (UDR) frame exchange provides unused duration of a hard reservation to other devices.

For less strict demands on QoS support, DRP specifies soft reservation. In a soft reservation the PCA is used. Only the owner of the reservation can access the medium after sensing the channel idle for a AIFS period of the highest priority and without performing any backoff. The purpose of soft DRP is that, if the owner of the reservation does not fully use the reserved MASs, other devices can still share the unused MASs using PCA access.

Devices can negotiate reservations either by explicitly exchanging specific command frames or by implicitly including the intended reservation information in their beacon frames. Once a DRP session has been established both the sender and the receiver have to inform their neighbors about the reservation by including the reservation information in their own beacon frames, as depicted in Figure 2-10.

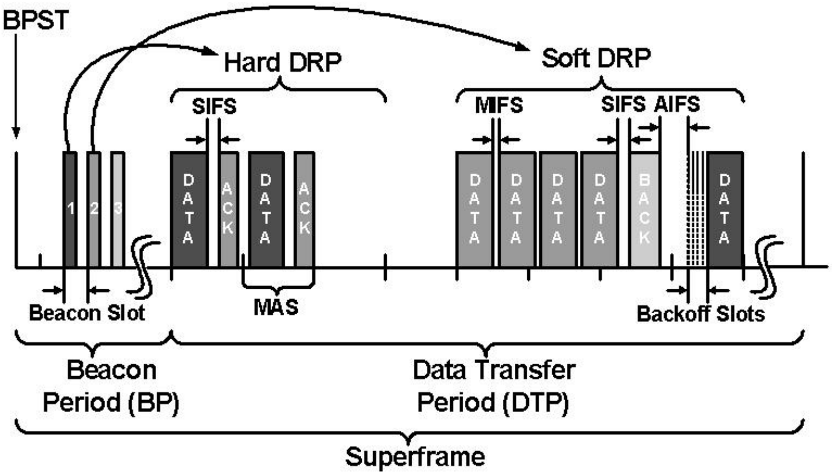


Figure 2-10: The contention free DRP principle

Transmission Opportunities (TXOPs)

Regardless if a device accesses the channel via PCA or DRP, the duration of every frame exchange sequence is bounded by the TXOPLimit. For Transmission Opportunities (TXOPs) gained via DRP the TXOPLimit equals the duration of the reserved MASs. For PCA channel access the WiMedia standard defines the TXOPLimit per priority. However, the duration of a TXOP gained under PCA is further restricted by the closest DRP reservation, since no PCA transmission may delay or foreshorten any DRP reservation. When accessing the medium with PCA or making a new DRP reservation, a device has to respect all existing reservations. Besides these limitations, all decisions regarding the data exchange are solely up to the transmitting device.

Acknowledgement Policies & Interframe Spaces

The WiMedia MAC defines three Acknowledgment (ACK) policies:

- No-ACK
- Immediate ACK
- Burst ACK.

Each directed frame carries an "ACK policy" field in the frame control field inside the MAC header, to allow the receiver to use the desired one. With No-ACK policy no ACKs are generated at all. As shown in Figure 2-11(a), with Immediate ACK (Imm-ACK) policy each successfully received Mac Protocol Data Unit (MPDU) is acknowledged after a Short Interframe Space (SIFS) period by the receiver. The SIFS period is needed for transceiver turnaround and frame checking. It is used in between every frame exchange. With Burst ACK (B-ACK), a burst of frames up to the burst ACK buffer size can be transmitted before the receiver is requested for a burst ACK frame, see Figure 2-11(b). According to the information contained in the burst ACK frame from the receiver, the transmitter can retransmit the missed frames or go on with the new ones as long as the burst ACK buffer size is not exceeded.

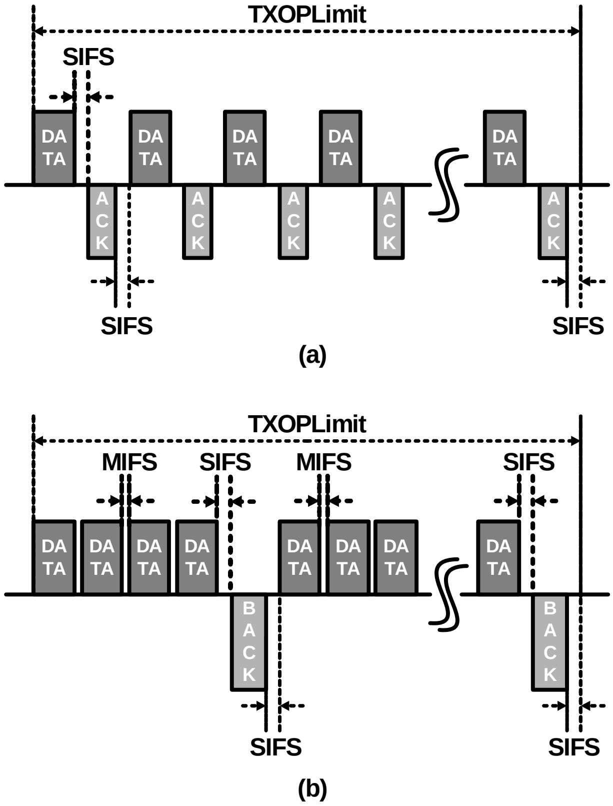


Figure 2-11: ACK Mechanisms: (a) Imm-ACK (b) Burst ACK

When No-ACK or Burst ACK policies are used, numbers of frames can be transmitted in a row, namely burst, without turning around the transmission direction. The Minimum Interframe Space (MIFS), which is shorter than the SIFS interval due to the absence of transceiver turnaround time, is used in between the consecutive burst frames, see Figure 2-11(b). The value of MIFS and SIFS are given in Table 2-9.

Frame Aggregation

In the WiMedia system, every device may benefit from frame aggregation. Frame aggregation concatenates subsequent frames into a single MAC Protocol Data Unit (MPDU) payload. However, the aggregated frame is subject to the same maximum size as any data frame payload. The aggregated frame structure is illustrated in Figure 2-12, where the processed MAC Service Data Units (MSDUs) are padded to 4 octet boundary and attached with a common header holding the length information of each MSDU and the number of aggregated MSDUs. To prevent the excessive delay for the MSDUs, a release timer is set according to the oldest MSDU in the aggregated frame. The aggregated frame is processed as a single indivisible entity, in term of acknowledgement and retransmission.

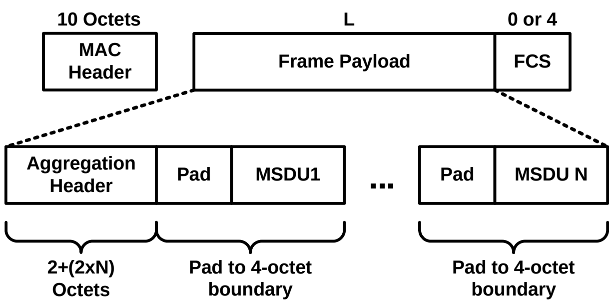


Figure 2-12: Frame aggregation

2.2.3 Other collaborative work on WPAN-UWB systems

The **RNRT BILBAO project (ANR – French Government) [2006-2008]** [PPCM, 07] deals with UWB transmissions through the optical fibre considering UWB RF signals operating in 3.1-10.6 GHz. Two kinds of multiband signals have been considered, an OFDM based transmission using WiMedia signal and a single carrier transmission proposed by Mitsubishi. The project proves the feasibility of UWB radio over fibre transmissions in order to extend the radio coverage of WPANs. Intensity Modulation Direct Detection (IM-DD) technique is mainly implemented to transmit optical signals (see section 2.3.3).

The **IST-FP6 UROOF project** [UROOF] [2006-2008] addressed the challenging problem of low-cost and high performance conversion of high data rates modulated communication signals from optical domain (over single mode and multimode fibre) to radio frequency domain to perform RoF (Radio over Fibre) transmissions in indoor environments. UROOF focus on photonic components for transmission of Ultra-wideband (UWB) radio signal over hybrid wireless/fibre networks. Three novel photonic components are considered, namely Optically Controlled Microwaves Converter (OCMC), Photonic mixer and enhanced Electro-Absorption Transceiver (EAT). The OCMC will be further investigated to allow working prototypes.

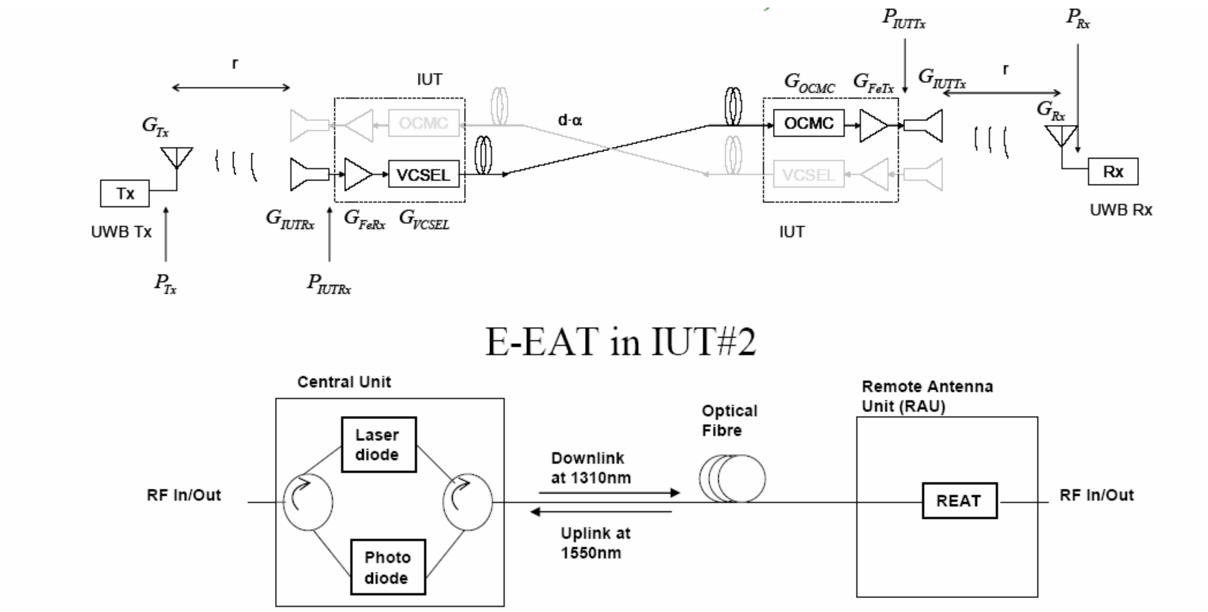


Figure 2-13: OCMC based UROOF technology for UWB-RoF transmissions

The second approach in UROOF is addressing optimized EAT transceiver for UWB operation. Additionally, innovative VCSEL technologies will be explored for low cost UROOF applications. These components are used to develop new devices which, in turn, are utilized to develop new systems and applications. Advanced applications are turned towards security and extended MIMO concepts.

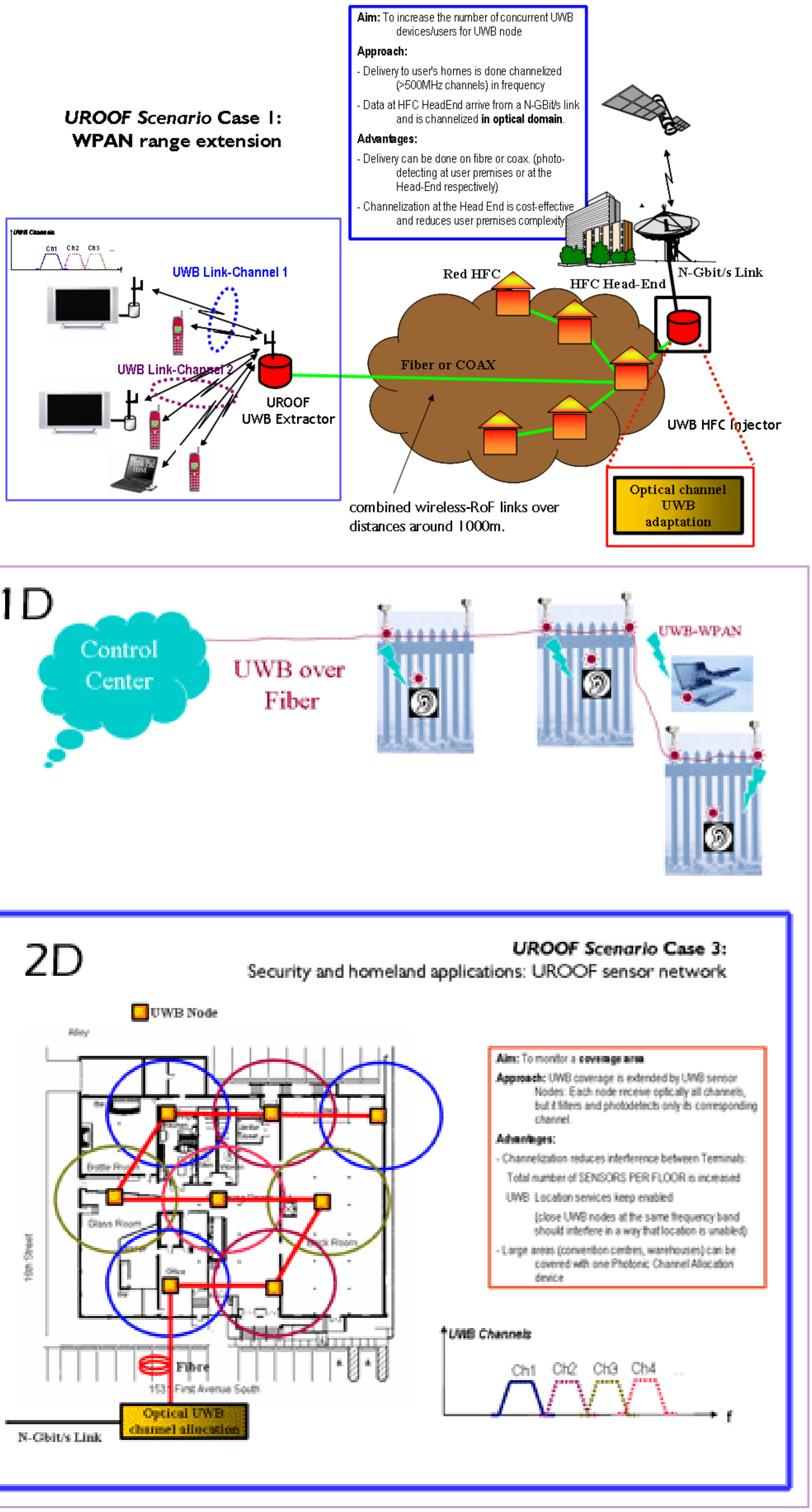


Figure 2-14: UROOF scenario for security applications

Among the FP7 projects portfolio, EUWB project [EUWB] (Coexisting Short Range Radio by Advanced Ultra-Wideband Radio Technology) is a project focused on system studies based on UWB systems and applications to four areas: intelligent home environment, public transportation, automotive environment and next generation of heterogeneous public access network. The project will capitalize on the existing and extensive research already carried on UWB technology and focus on improvements area such as cognitive techniques to facilitate coexistence, intelligent multiple antennas, localisation and tracking or multiband/multimode operation concepts.

Another project, labelled UCELLS [TG11n03] TG11n Usage models, 11-03-0802-23-000n, 2003.

[UCELLS] (Ultra-wide band real-time interference monitoring and CELLular management Strategies), aims at developing a UWB cellular architecture based in picocell clustering of UWB transmitters, in order to provide pervasive UWB connectivity in home or office buildings. They intend to employ standard low-cost UWB transceiver, and offer Gbps connectivity. Spectrum management strategies and interference monitoring techniques will be proposed to enable piconet clustering of UWB transmitters. A photonic analog-to-digital converter will be developed as the core element of the UCELLS UWB spectral management strategy.

2.3 WPAN-60 GHz

2.3.1 Regulation

Regulation issues within the 57-66 GHz allowing exempted license band use, result from

- FCC 15.255 requirements in USA,
- CEPT Recommendation TR 22-03 [CEPT90], ERC Report 25 ETSI DTR/ERM document [ETSI06] in Europe and the ECC report 114 [ECC_114, 07]
- Millimeter Wave band Frequency Study Group (MWFSG) in Korea. MWFSG allocated the 57-64 GHz to indoor WPANs with a maximum transmitter power set to 10 dBm
- In Japan, the frequency band is translated on 59-66 GHz with similar radiated power limitation One frequency channel is limited below 2.5 GHz bandwidth.
- In Australia, regulations are edited by the Australian Communications and Media Authority group ACMA.

Figure 2-15 supplies world-wide allocation of the 60 GHz band issued from Europe, Australia, Japan, Korea and Canada for wireless applications. For WPAN applications, a typical average radiated power set to 10 dBm is usually recommended.

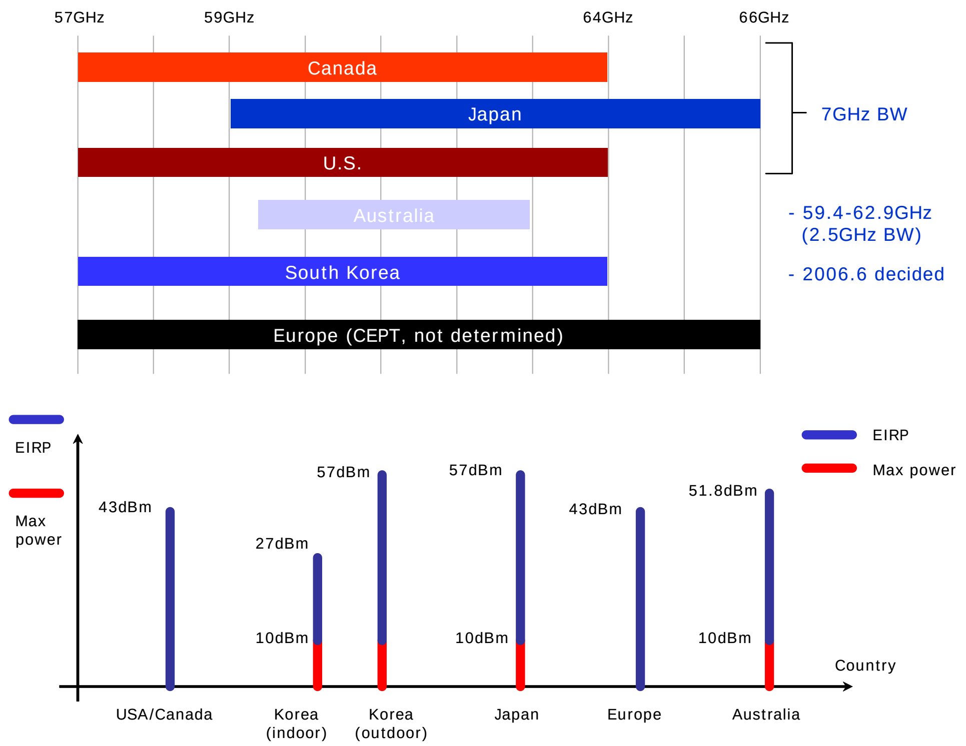


Figure 2-15: Frequency regulation of 57-66 GHz band

2.3.1.1 *Regulatory standardization groups in Europe*

Table 2-10 provides discussion statements related to European regulatory issues connected to MultiGigabit Wireless Systems (MGWS). Discussions around the use of 71-76 GHz and 81-86 bands are also considered for MGWS and Fixed Local Area Network Extension (FLANE) applications.

Table 2-10: ECC WG statements.

Standardization group	Reference document	Scope	Decision date	Statement
ECC Spectrum Engineering Working Group (WG SE) Meetings SE18&19	Report 113 and 114	Technical conditions for MGWS vs. Fixed Services (FS) deployment at 60 GHz	Sept 2007-Sept 2008	Possible consideration of regulatory issues is pending, guidance from WG FM in the band 57-66 GHz based on ECC Report 114 and ECC Report 113
ECC WG SE Meetings SE19&20	Revision of ECC REC(05)07	Technical conditions for FS deployment inside 71-76/81-86 GHz	Sept 2007-Sept 2008	The link with WI SE21_11 to be resolved through liaison with SE21
ECC WG SE Meeting SE24_26	012SE(08)	WLAN on board of aircrafts in the band 5725 to 5875 MHz	2008 2009	Impact analysis. Response based on background as given in document 012SE(08)
ECC Frequency Management Working Group (WG FM)	TR-22-03, ERC Report 25 ETSI DTR/ERM	Summary of WG FM discussions		

In 2007, following the ECC WG SE_24 meeting held in September 2007, it was decided to translate the 7 GHz exempted licence band into 59-64 GHz and consider the use of 57-59 GHz band. This decision results from the high Oxygen absorption in the 57-64 GHz which is foreseen as an advantage in frequency reuse of resource allocation between adjacent WPAN cells. The oxygen absorption decreases from 64 to 66 GHz RF band.

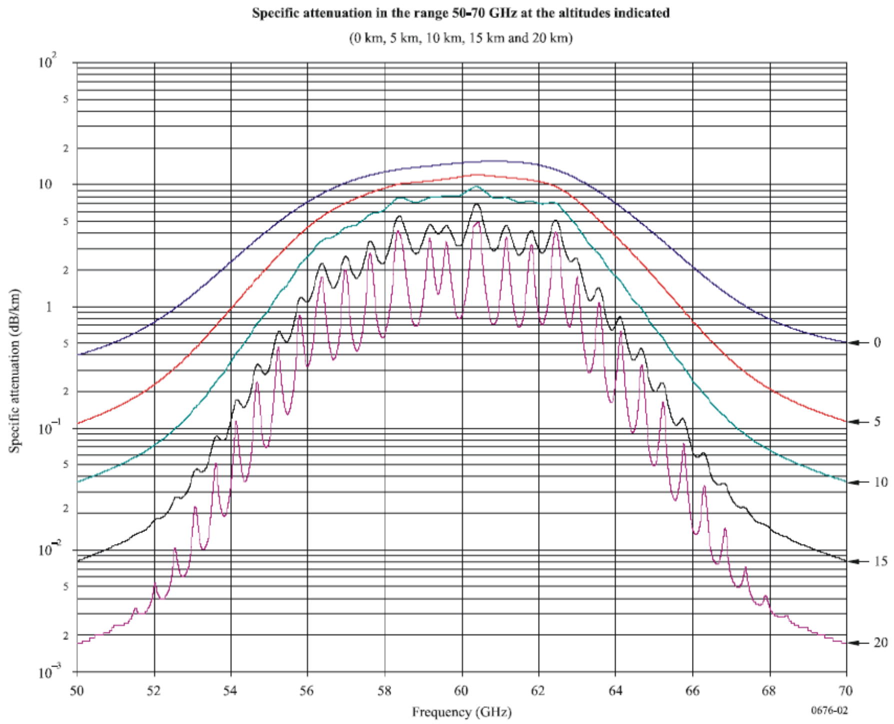


Figure 2-16: **Specific Oxygen Attenuation (dB) – Recommendation ITU-R P.676**

The summary of recent decisions issued from report 114 is given in the next paragraph.

Report 114 Summary [ECC_114, 07]

This study was carried out in order to determine the technical and operational requirements to be associated with deployment of MGWS in Europe. The compatibility study was initiated in response to the requirements for MGWS deployment specified in ETSI TR 102 555 [ETSI_MGWS]. The report considered frequency range 57-66 GHz for MGWS deployment, excluding the compatibility with Intelligent Transport Systems (ITS) in 63-64 GHz, which is a subject studied in a different ECC Report 113.

<u>Compatibility findings</u>

Three of the existing services in the subject band were identified for detailed compatibility analysis.

Frequency band	**Required separation distances with offset angles of 5-15^0 (see section 4 for details) (m)**		**Critical scenario**
	MGWS WLAN/WPAN	**MGWS FLANE**	
57-59 GHz	330-18	1250-700	Point-to-point FS -> FLANE
59-63 GHz		1250-2500 (Note)	Radar -> FLANE
63-64 GHz	Subject of a separate study, see ECC Report 113		
64-66 GHz	670-33	2800-750	FLANE -> Point-to-point FS

Note: side-lobe gain of 10 dBi applied for radar antenna, two values represent two directions of interference.

Regarding the critical case of MGWS-FS co-existence, it appears that indoor WLAN and WPAN applications of MGWS may be deployed in 57-59 GHz and 64-66 GHz without significant risk of interference to Point-to-point FS/High density FS links, whereas deployment of FLANE may require taking some precautionary provisions in both considered bands, to ensure co-existence with the Point-to-point FS links.

No compatibility problems between MGWS and Earth Exploration Satellite Service (EESS) in the frequency range 57- 59.3 GHz were identified since the density of MGWS transmitters that would be needed to exceed the EESS interference limits is comfortably above expected MGWS deployment densities, also noting that the real tolerable density of WLAN/WPAN deployment will be much higher due to additional attenuation provided by indoor deployment.

Discussion of regulatory options requiring further consideration

Analysis of the results of compatibility studies suggests that the introduction of various applications in MGWS family across the range 57-66 GHz[1] may not be resolved through a single cut regulatory solution, therefore this report outlines some ideas that could be used to develop appropriate regulatory framework for introduction of MGWS.

The first obvious observation is that the very different compatibility results for FLANE as opposed to WLAN & WPAN applications of MGWS call for different regulatory considerations, which are discussed below.

It should be also noted that introduction of different types of MGWS applications (that might be both mobile and fixed) may need an update of the current service allocations in the ECA (ERC Report 25).

MGWS WLAN/WPAN

It may be safely assumed that MGWS WLAN & WPAN applications would be deployed pre-dominantly indoors leading to overall low risk of interference. Therefore it would appear that WLAN & WPAN applications might be allowed to be deployed across entire frequency range 57-66 GHz on the licence-exempt provisions with emission limitations considered in this study, based on current TR 102 555 (+40 dBm EIRP, etc.) [ETSI_MGWS].

Possible technical measures to ensure indoor usage and to give additional degree of interference protection could include obligations for integral antennas.

It was also noted that some kind of Dynamic Frequency Selection (DFS)/Detect And Avoid (DAA) mechanism may be introduced to ensure intra-system co-existence between WLAN/WPAN installations, which would also provide additional mitigation of inter-service interference, but practical implementation and feasibility of this measure was not further considered in this report as this was felt being outside the mandate of this study.

2.3.1.2 Regulatory standardization groups in Canada and USA

In USA and Canada, regulations are harmonized in accordance with the U.S. FCC Part 15.255 requirements in response to the NPRM (Notice of Proposed Rulemaking) in ET Docket 94-124, addressing the 57.05-64 GHz to unlicensed wireless applications with a 7 dBm/MHz spectrum mask. All edited documents are listed on the website http://infoserver.fcc.gov/Document_Indexes/2008_annual_index.html

Some relevant documents are listed in the Table 2-11.

Table 2-11: 60 GHz FCC statements

		Reference documents
Millimeter Wave Communications Working Group ("MWCWG")	59-64 GHz band for FLANE	FCC-97-267
Millimeter Wave Communications Working Group ("MWCWG")	46 GHz and 76 GHz RF bands use for vehicle radar systems	FCC-97-267
FCC Broadband Forum	RoF using 60 GHz air interface	"The Benefits of 60 GHz Unlicensed Wireless Communications" C. Coh *http://www.ydi.com*

2.3.1.3 Regulatory standardization groups in other regions

In Australia, the Australian Communications and Media Authority (ACMA) authorize unlicensed frequency bands for Low Interference Potential Devices (LIPDs) in the 59.4-62.9 GHz with a maximum peak transmitter

[1] The conclusions referring to "entire range 57-66 GHz" are without prejudice to situation in 63-64 GHz which is subject of a separate study

power set to 10 dBm. An international regulation harmonization is required between these regions. The most restrictive band allocation is due to ACMA specifications.

In Japan, the 59-66 GHz is dedicated to unlicensed low power radio stations with a maximum antenna gain set to 47 dBi and an occupied bandwidth up to 2.5 GHz.

In Korea, the Millimeter Wave band Frequency Study Group (MWFSG) allocated the 57-64 GHz to indoor WPANs and Point to Point outdoor radio links with a maximum transmitter power set to 10 dBm.

Allocations in other parts of the world

It should be noted that US/Canada and Korea allocated the band 57-64 GHz for licence exempt applications similar to MGWS. Similar allocation in Japan for licence-exempt operation is in 59-66 GHz, whereas in Australia it is in 59-63 GHz.

2.3.2 Standardization

To come up with social and technical demands for gigabit WPAN applications, there are several trials to have a standard for 60 GHz WPAN systems. In this document, three major activities are introduced.

On a first hand, IEEE (Institute of Electronics and Electrics Engineering) and ECMA International are trying to develop a standard for a 60 GHz-band PHY and MAC layers, targeting different applications. On a second hand, Wireless HD is an industrial consortium of several major consumer electronics companies whose goal is to enable 60 GHz wireless connectivity for streaming high-definition video signals. It is important to note that companies involved in Wireless HD consortium have promoted their solutions in the IEEE 802.15.3c standard so that it is now defined as one of the transmission modes in IEEE standardization draft.

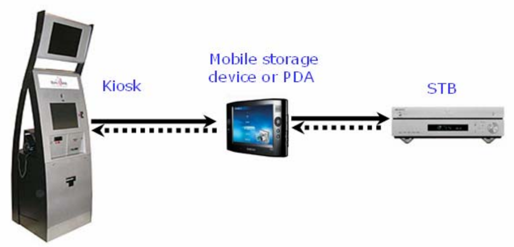
2.3.2.1 IEEE 802.15.3c

The IEEE 802.15.3 Task Group 3c (TG3c) was formed in March 2005 [WTG3c]. TG3c is developing an alternative millimetre-wave-based physical layer (PHY) for the existing 802.15.3 Wireless Personal Area Network (WPAN) Standard 802.15.3-2003 [WSt15] that uses frequencies around 2.4 GHz. IEEE 802.15.3c devices will operate in the 57-66 GHz unlicensed band presented in section 2.3.1. It should be the first IEEE standard addressing not only multi-gigabit wireless transmission but also millimetre-wave communication systems.

Thanks to high link capacity to reach several gigabit throughputs, many usage models (UM) for consumer applications have been presented in IEEE 802.15.3c standardization meetings. Through the long-time discussion and compromise, finally five usage models had been decided, which appear in [Wdoc3c] under reference (06/055r21). This document defines required data-rate/performance and millimetre-wave channel models which should be used for PHY evaluation/simulation. Eventually, two usage models (UM1 and UM5) remain as mandatory while the other three are optional. Mandatory UM are presented on Figure 2-17 for UM1 (uncompressed video streaming) and Figure 2-18 for UM5 (kiosk file-downloading). Both these mandatory usage models are based on point-to-point communication while optional UM define point-to-multipoint links. This classification means TG3c has rather focused on simple point-to-point communication without considering any MAC modification to support 60GHz high directivity antenna.

Environment	Throughput MAC SAP	Distance	Note
LOS/NLOS Residential	1.78Gbps for 1080i, 24bit, 60Hz 3.56Gbps for 1080p, 24bit, 60Hz	5m/10m	- P2P link - Asymmetric link

Figure 2-17: UM1 – Uncompressed Video Streaming



Environment	Throughput MAC SAP	Distance	Note
LOS Office	1.5Gbps burst 2.25Gbps burst	1m	- P2P link

Figure 2-18: UM5 – Kiosk File downloading

More than 20 proposals were presented and now merged into one standard draft. Three different transmission modes are currently defined in this draft. One is based on single carrier modulation which is called Single Carrier (SC) mode. The other two modes are High Speed Interface (HSI) mode and Audio/Video (AV) mode which have been designed on the basis of multi-carrier modulation.

Although these three different modes are basically different from each other, there is a common agreement that all TG3c devices are required to have the same channelization plan as shown in Table 2-12. From 57 GHz to 66 GHz, four independent channels were defined, centred respectively on frequencies of 58.32 GHz, 60.48 GHz, 62.64 GHz and 64.8 GHz. Within the range of unlicensed 60 GHz frequency band allocated by a governmental agency, a TG3c device chooses a channel while keeping the assigned centre frequency and maximum channel bandwidth.

Table 2-12: IEEE 802.15.3c channelization plan in 60 GHz

CHNL ID	Centre Frequency (GHz)	Low Frequency (GHz)	High Frequency (GHz)
1	58.32	57.24	59.40
2	60.48	59.40	61.56
3	62.64	61.56	63.72
4	64.80	63.72	65.88

- <u>SC Mode</u>

SC mode uses different Modulation and Coding Schemes (MCS) supporting PHY-SAP data rate from 50 Mbps to about 6 Gbps. As can be seen in Table 6-1 (see Annex 6), it defines many different modulations, pi/2 BPSK, GMSK, QPSK, 8-QAM, 16QAM, OOK and DRB according to different classes. Eleven forward error correction schemes are specified, based on RS (Reed-Solomon) channel coding or LDPC coding. Supporting RS block codes is mandatory whereas supporting LDPC block codes is optional. The overall PHY layer scheme for SC mode is summarized on Figure 2-19. The complete data rate dependent parameters are listed in Annex 6, in Table 6-1.

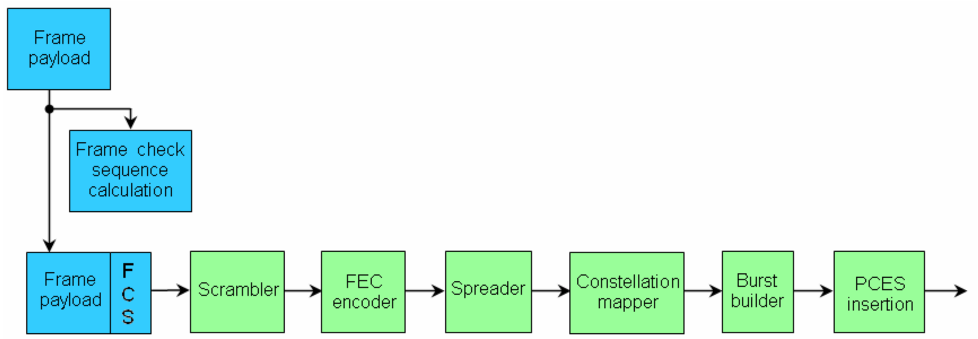


Figure 2-19: SC PHY architecture

- <u>HSI mode</u>

HSI mode supports data rates from 59 Mbps to 6.3 Gbps. It is designed for NLOS (Non Line Of Sight) operation and based on an orthogonal frequency domain multiplexing (OFDM) transmission with a sampling frequency of 2592 MHz and an FFT size of 512. As listed in Table 2-13, 336 sub-carriers are allocated for data subcarriers, 141 for guard subcarriers and 16 for pilot subcarriers which are used for coherent detection. For the UEP (unequalled error protection), different coding rates are applied to the MSB octets and LSB octets.

The default cyclic prefix length shall be set to 64. Supporting the length of 128 is left to optional one. The pilot channel estimation sequence (PCES) symbols can be periodically inserted in the OFDM symbols and used for channel re-acquisition or tracking.

Frequency domain spreading, QPSK, 16-QAM and 64-QAM modulation schemes, and forward error correction are used to support various data rates. Two FEC coding schemes are specified: an LDPC block code with coding rates of 1/2, 3/4 and 7/8, and a concatenation of the LDPC with an outer RS block code. The complete data rate dependent parameters are listed in Table 6-2 (see Annex 6).

The overall HSI PHY layer scheme is summarized on Figure 2-20.

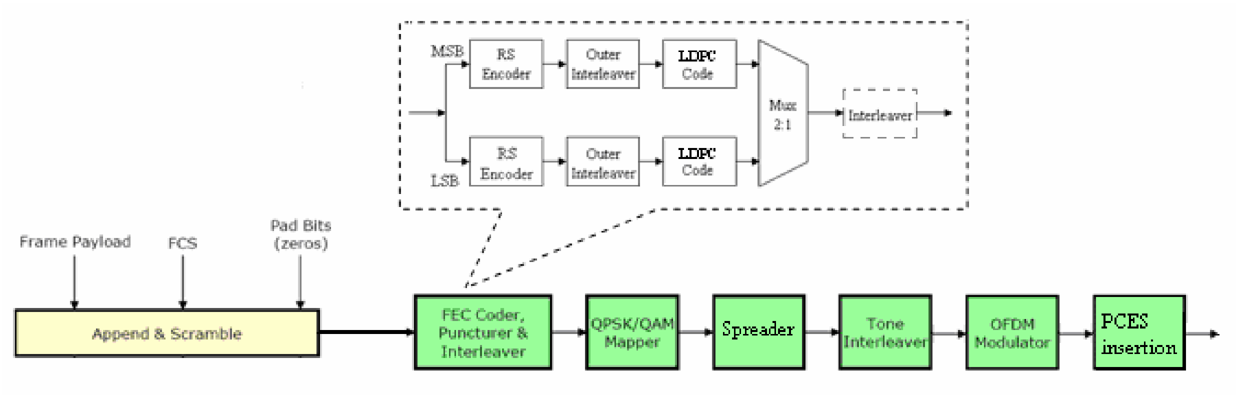


Figure 2-20: HSI PHY architecture

- AV mode

The AV mode is implemented with two PHY modes, the high-rate PHY (HRP) and low-rate PHY (LRP), both of which use OFDM transmission. Basically, the HRP modes use the channels defined in Table 2-12. In each of the HRP channels, three LRP channels are defined. In a piconet, only one HRP channel and one LRP channel is used at a time. Each of the LRP channels is defined relative to the centre frequency of the current HRP channel.

The HRP mode uses BPSK, QPSK and 16QAM modulation with an inner convolutional code and an outer RS code. The LRP mode is based on BPSK with repetition coding. The timing parameters corresponding to AV mode are listed in Table 2-13, the data rate dependent parameters in Table 6-2 (see annex 6).

The HRP permits to reach bit rates up to 4 Gbps thanks to beamformed directional link. LRP allows bit rates up to 10 Mbps in omni-directional link.

There are four classes of AV OFDM capable devices, corresponding to different kinds of LRP and HRP implementation (TX and/or RX).

A reference implementation of the HRP baseband is schematically illustrated in Figure 2-21.

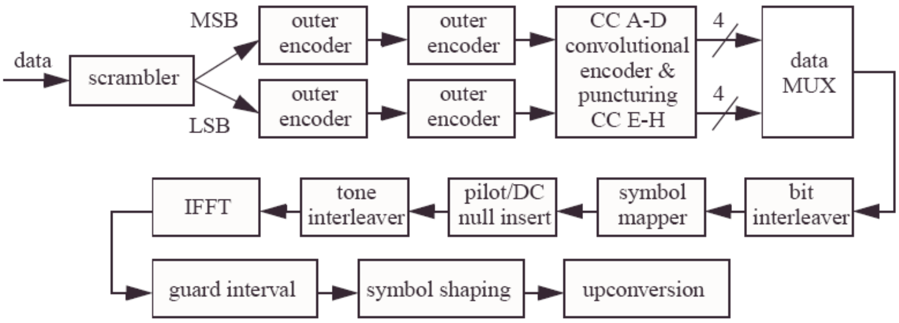


Figure 2-21: HRP reference implementation block diagram

A reference implementation of the LRP baseband is illustrated in Figure 2-22.

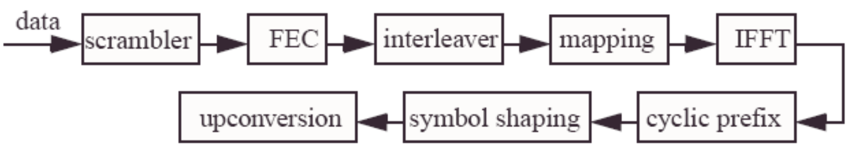


Figure 2-22: LRP reference implementation block diagram

Table 2-13: Timing related parameters for HSI and AV OFDM modes

Parameter	Description	Value			
		HSI		AV HRP	AV LRP
R_C	Sampling frequency (MHz)	2592		2538	92
T_C	Chip duration (ns)	0.395		0.394	10.8
N_{FFT}	FFT size	512		512	128
N_D	Number of data subcarriers	336		336	30
N_{DC}	Number of DC subcarriers	3		3	3
N_{CP}	Cyclic prefix length	64	128	64	28
D_F	Subcarrier frequency spacing (MHz)	5.06		≈ 5	2.48
T_{FFT}	IFFT and FFT period (ns)	197.53		202	403
T_{CP}	Cyclic prefix duration (ns)	24.69	49.38	≈ 25	88
T_{SYM}	Symbol duration (ns)	222.22	246.91	227	492

2.3.2.2 ECMA International

ECMA International TC48 [ECMA48] is trying to develop a standard for a 60 GHz PHY and MAC for WPAN applications. Major target applications are almost similar to those of IEEE 802.15.3c, however they have focused on single carrier modulations rather than multicarrier modulations including OFDM. Most of the PHY/MAC proposals that appear in ECMA draft standard were already submitted to IEEE 802.15.3c and partially included in the IEEE draft standard. However, it has several distinctive features including allowing channel-bonding, supporting spatial reuse with directional antenna and enhancing coexistence and interoperability between different types of devices.

The first draft standard (white paper) has been released in Feb. 2008. Now, TC48 is reviewing and trying to finish a first full draft standard for June 2008.

ECMA draft standard specifies four different frequency channels in the 57-66 GHz band. These channel allocations are similar to channelization plan of IEEE 802.15.3c (Table 2-12) except that the ECMA standard supports channel bonding between two adjacent channels. This is particularly attractive to support higher data-rate transmission with simple modulation.

The draft defines three types of devices according to PHY schemes and hardware complexities. These three types of devices interoperate with their own types independently and they can also coexist and interoperate with other types of devices. Thus, it offers a heterogeneous network solution that provides interoperability between all device types.

- Type A PHY

Target applications of Type A devices are high quality video streaming or packet transmission in 10m LOS/NLOS multi-path indoor environments. This device type is considered as the “high-end” – high performance device. Two types of PHYs are considered: single-carrier blocked transmission (SCBT) and OFDM modulations. Like the common mode in IEEE 802.15.3c, ECMA standard draft defines a mandatory mode based on SCBT to facilitate interoperability between Type A devices. This mandatory mode is different from that of IEEE 802.15.3c draft standard. Other SCBT modes and OFDM modes are optional.

All Type A devices support a flexible multi-segment frame format. This format allows the transmission of different MAC Protocol Data Units (MPDUs) using potentially different modulation and coding schemes within the same frame. It also enables flexible use and placement and/or length for frame check sums, midambles and antenna training sequence.

Like IEEE 802.15.3c, Unequal Error Protection (UEP) is provided through the use of multi-segment packets or specially designed modulation and coding schemes. In UEP modes, MSB and LSB of a video signal are separated and encoded by concatenated RS and eight parallel convolutional codes.

The SCBT has the option to use four different length of cyclic prefix (including no cyclic prefix) for frequency domain or time domain equalization. It supports pi/2 BPSK, QPSK, UEP-QPSK, pi/2-NS-8QAM - which is different from IEEE, 16QAM and UEP-16QAM. For low-level modulations such as BPSK and QPSK, concatenated RS and convolutional coding is used, whereas Trellis Coded Modulation (TCM) with RS coding is for high level modulations including 8-QAM and 16-QAM. Achievable data rate ranges from 0.4 Gbps to 6.1 Gbps. The mandatory common beaconing mode is based on pi/2 BPSK modulation supporting 0.4 Gbps. OFDM transmission schemes also use concatenated RS and convolutional coding with supporting UEP. A total of eight different data rates can be achieved using four different coding modes with QPSK and 16QAM modulation.

The modulation and coding for the discovery mode is similar to the common beaconing mode with the exception that a long adaptive spreading factor is used to increase time-bandwidth products. Device with a sector antenna use the beacons to select their sector. Phase-array antenna training is accomplished through the transmission of a negotiable number of Frank-Zadoff (FZ) sequences with a negotiable spreading factor. In open loop mode, the receiver responds with a similar set of FZ sequence. In closed loop mode, the receiver gives explicit feedback about the phase setting that the transmitter should use.

- Type B PHY

Type B PHY is a simplified single carrier transmission scheme with the common beaconing mode based on differentially encoded BPSK modulation (DBPSK). Application scenarios are video and data transmission over 1-3m LOS point-to-point links. This allows using either coherent or non-coherent BPSK detection and minimizes the implementation overhead to support interoperability with Type A devices. Two major difference between Type A and B to minimize the hardware complexity of a receiver are the modulation (DBPSK instead of pi/2 BPSK) and FEC (RS instead of concatenated RS and convolutional coding).

The type B does not support any cyclic prefix, neither the discovery mode used for antenna training. It has several optional modulations such as DQPSK, UEP-QPSK, OOK/4ASK and DRB which are also included in IEEE 802.15.3c. Flexible multi-segment frame formats and multiple sectors antennas remain as optional.

- Type C PHY

The simplest scheme in ECMA standard draft is a Type C which is based on ASK modulation. It supports very short LOS links less than 1m distance with very simple hardware structure. To have better power saving and channel uses, it has the optional function to support close-loop transmission power control. For managing devices and ensuring interoperability with Type A or Type B devices, the OOK with 2 symbol repetition is adopted for beacon mode. For hardware simplification, the type C device supports none of a multi-segment frame format, antenna training scheme, the convolutional coding and the UEP. It only uses RS coding for FEC.

- MAC layer

The ECMA TC48 MAC is based on the ECMA-368 MAC with necessary changes to support the 60 GHz communication with high directivity antenna.

A unified superframe structure

The superframe duration is composed of medium access slots (MASs) which is the smallest time unit a device can reserve for data transmission. Each superframe starts with Beacon Period (BP), which extends over one or more successive MASs. All devices transmit beacons in the BP using the mandatory mode with the exception of Type C operating slave mode.

Neighbouring discovery

Devices discover each other through exchange of beacons and polling frame in the Discovery Channel. Based on device types, a device follows different procedures with its own mandatory PHY modes. Neighbour discovery among heterogeneous devices is achieved through the transmission of polling frame on a master-slave basis

Beacon transmission

All devices except Type C operating slave mode broadcast beacons to all neighbours to exchange coordination information such as reservation of channel time or time synchronization. Unlike omni-directional beacon transmission in ECMA-368, beacons are transmitted using directional antennas to support simultaneous connections (thus maximizing spatial reuse). Devices transmit beacons in unique beacons slots within the BP of each superframe using the enhanced ECMA-368 Beacon Protocol. Since directional antennas are used to transmit beacons, a device might send more than one beacon as a single directional beacon might not be heard by all devices that the device needs to communicate.

Spatial reuse

Since beacons are transmitted with directional antennas, they are broadcasted over a more confined area, thus resulting in a smaller “interference zone”. Therefore, more links can be simultaneously established in limited area and resource, thus enabling the spatial reuse of the channel time.

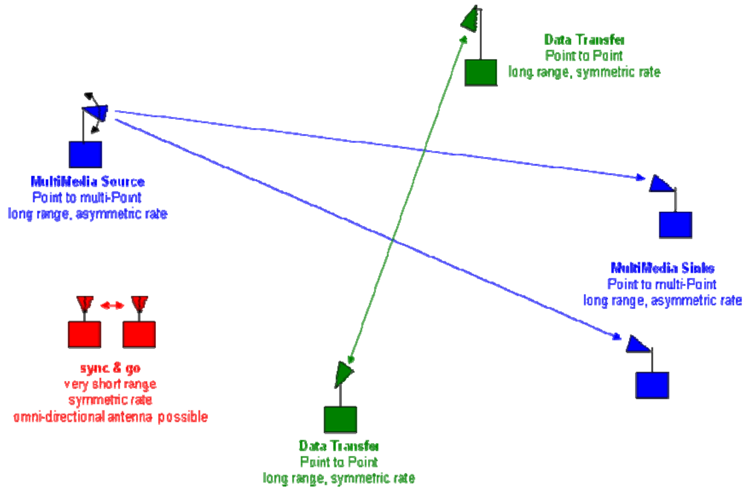


Figure 2-23: Spatial reuse

Spatial reuse is further maximized via a new reservation protocol. The new protocol is based on the ECMA-368 Distributed Reservation Protocol (DRP), which enables devices to reserve channel time that the device can use to communicate with one or more neighbours. To support simultaneous transmission using the existing DRP, devices that use the DRP for transmission or reception will include the antenna information such as beam number in the DRP IEs of their beacons. Devices that attempt to make new reservation will check both time and directionality of existing reservation via the information provided in the received DRP IEs.

Coexistence and interoperability

Although the coordination of channel usage among devices is achieved via exchange of beacons, devices of certain types may not be able to decode all beacons due to hardware or software limitation. To prevent potential interference from the devices with limited capabilities, devices of different types are given priorities in terms of sharing the channel with other devices. In general, a type C device is given the lowest priority, and thus has to surrender the channel usage to any type A or type B device whenever they are present. A type B can claim the ownership of a reservation and it made via the mode-A0 beacons so that a type A device will not interfere.

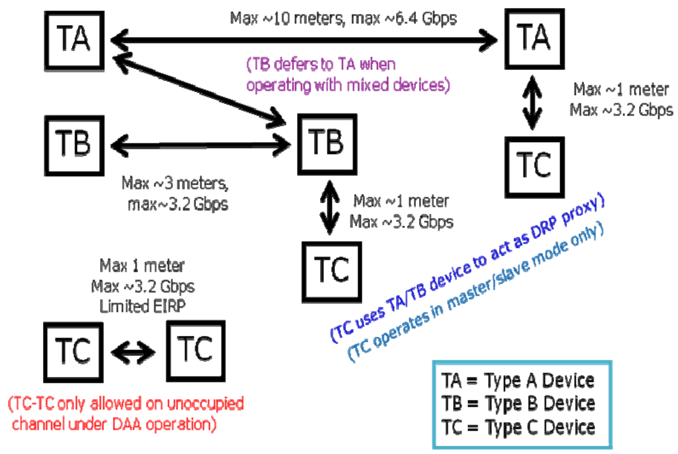


Figure 2-24: Coexistence and interoperability

To support data exchange between heterogeneous devices, devices establish a master/slave relationship via polling frames. In particular, a type A device will be the master of a type B or a type C device with which the type A communication and a type B will be the master of a type C. The master device is responsible for reserving the channel time and coordinating the communication via polling.

2.3.2.3 Wireless HD

Wireless HD is an industry-led effort aimed at defining a specification for the next generation wireless digital network interface specification for consumer electronics products. Its promoters are LG, Matsushita/Panasonic, NEC, Samsung, SiBEAM, Sony, Toshiba, and Intel. Many other companies are supporting Wireless HD as early adopters, such as Agilent, Nvidia Corporation, Philips Electronics, Pioneer, etc. The complete list of Wireless HD supporters is available on their official website [WiHD].

The Wireless HD specification defines a wireless video area network (WVAN) with the following characteristics.

- Stream uncompressed audio and video at up to 1080p resolution, 24 bit colour at 60 Hz refresh rates
- Deliver compressed A/V streams and data
- Advanced A/V and device control protocol
- Unlicensed operation at 60 GHz with typical range of at least 10 m for highest resolution HD A/V
- Smart antenna technology to enable NLOS operation
- Data privacy for user generated content.

Now, most part of wireless HD specification is included as one of the PHY modes (called AV mode) in IEEE 802.15.3c draft standard. Therefore, further explanation will be abbreviated.

2.3.2.4 Next Generation Millimetre-wave Specification (NGMS)

Intel announced its own standard of millimetre-wave for home network.

2.3.3 Other collaborative work on WPAN-60 GHz

Millimetre wave WPAN systems are designed since 1996 with the ACTS MEDIAN project and other projects. The figure below gives a summary of main European projects dealing with 60 GHz WPAN air interface systems.

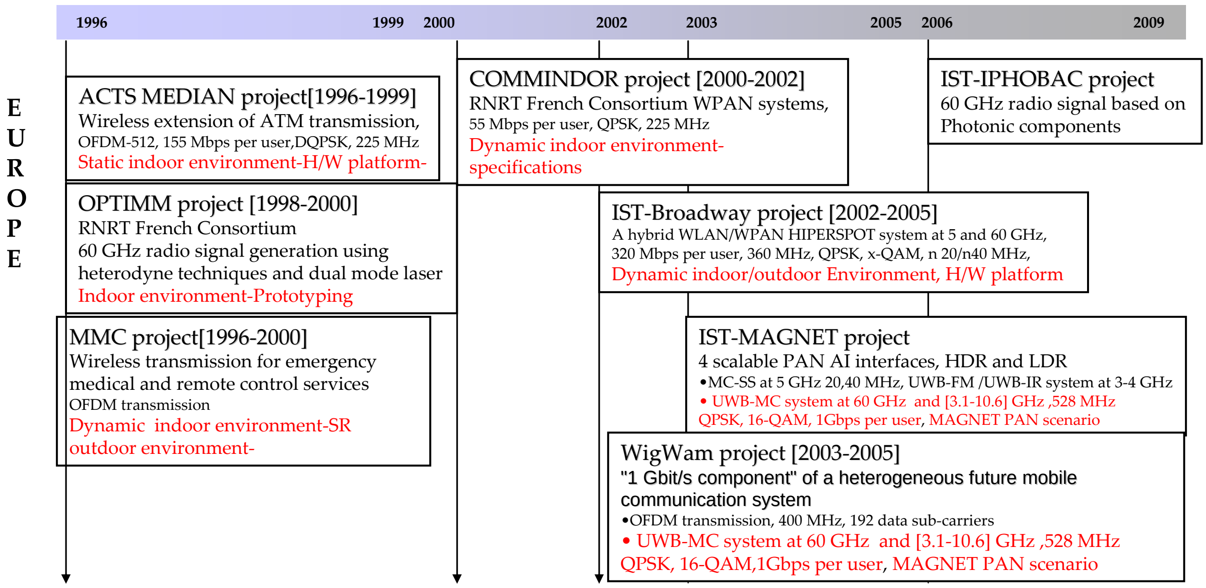


Figure 2-25: European project dealing with 60 GHz Air Interfaces

A large amount of research has been conducted in the ten past years in order to design optimum transmission systems using millimetre wave frequencies. Early activities targeted data rates in excess of 100 Mbps: the **ACTS MEDIAN project** (1996) [LC 96] designed an ATM-based WLAN, then the **IST BROADWAY project** [BROADWP3_02][CZMS,02] proposed a dual frequency WLAN/WPAN system using both 5 GHz and 60 GHz for WLAN and WPAN applications. A backward compatibility between Hiperlan2/IEEE802.11a and mm-Wave Broadway system was ensured considering sub-channel size multiple of 20/40 MHz and sub-carrier spacing multiple of IEEE802.11a sub-carrier spacing to cope with additional 60 GHz phase noise. The system offers data rates up to 360 Mbps to ensure a high capacity multi-user transmission.

The **RNRT COMMINDOR** (2002) project introduced the concept of time-variant environment with data rates up to 300 Mbps and sub-channels set to 200 MHz; performances were significantly improved in considering appropriate OFDM dimensioning [Si,05]. Mm-wave technology has been investigated and wideband antennas have been designed. Results conclude to the use of smart antennas to extend the radio coverage of mm-wave systems. Within the framework of COMMINDOR, antenna design and mm-wave technology have been also investigated to generate low cost 60 GHz RF stages.

More recently, mm-wave systems have been defined for WPAN applications within the framework of **FP6-IST MAGNET** project [MAG, WP3.2, 05] by considering UWB and WB transmissions based on high Spectrum Efficiency OFDM modes [Si,05] and dynamic interleaving process [SUM_1, 07] [SUM_2, 07] to cover data rates up to 1 Gbps and backward compatibility with WiMedia. The project used COMMINDOR results as technical background. The German **WIGWAM** Project [WIGWAM] initially targeted WLAN/WPAN systems with data rates of 1 Gbps in the 60 GHz band. In the course of the project, this aim was extended to multi-Gbps.

The IST-IPHOBAC project (2006-2009) [IPHOBAC] deals with photonic millimetre wave component developments and Radio Over Fibre Topologies to extend the radio coverage of 60 GHz WPAN systems using fibre transport of RF/IF/BB signals. Within this project, specified novel components are designed to enable 60 GHz radio generation, distribution via optical fibre. These photonic components include, very high speed modulators (EAMs), photodiodes and self pulsating lasers [IPHOD222, 07]. For telecom applications, The RF signal is either a 60 GHz transposed WiMedia signal or enhanced UWB-OFDM signal considering the FTR&D system denoted *Multiple RF band UWB-OFDM system with dynamic sub-carrier mapping allocation* [IPHOD222, 07]. The next step will consist in considering IEEE802.15.3c MGWS Air Interfaces in UWB-RoF systems. These studies will exploit close exchanges with the IST-FP7 OMEGA project launched in 2008 and FTR&D standardization activities in IEEE802.15.3c and WWRF activities.

The principle of RoF transmission based on Intensity Modulated and Direct Detection technique is illustrated on the next figure. On the basis of IM-DD, The RF signal modulates the current of a Laser-Diode to convert RF signal into optical signal transported through the fibre. At the end of the fibre, a photodetector detects the RF signal proportional to the optical signal.

The Techimages project (French Images and Networks competitivity pole) is focused on radio front-end and radio-optical interface developments. Within this project, where the 60 GHz radio waves were transported at an intermediate frequency over a point to point multimode optical fibre link, system design and architecture were demonstrated using commercially off-the-shelf (COTS) components. The design and modelling tools, which have been validated by experimental results within Techimages, will serve as a strong basis on which to construct a hybrid radio-optical system using novel components such as Si-Ge based phototransistors.

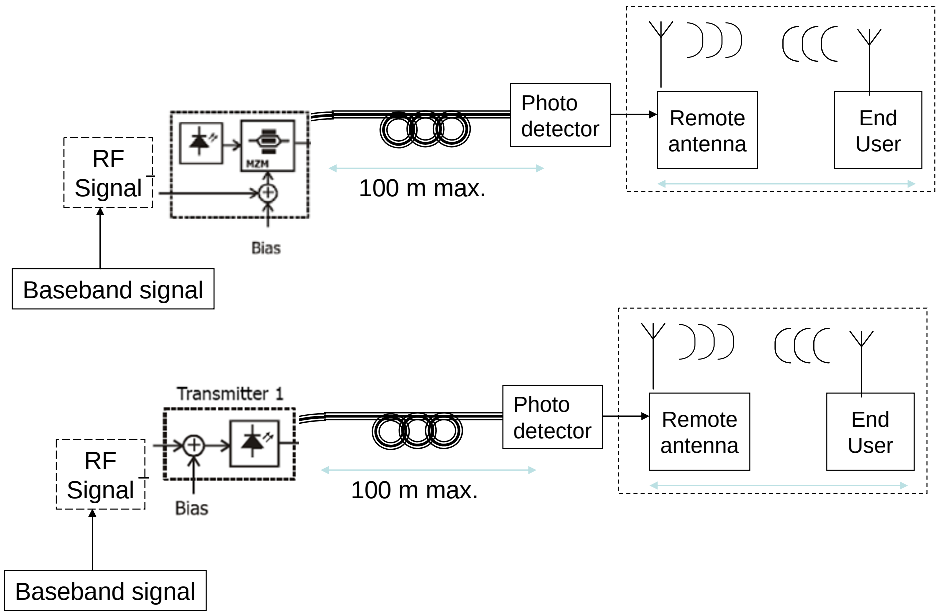


Figure 2-26: Typical RoF systems using IM-DD techniques

2.4 Initiatives on convergence among radio systems

2.4.1 WPAN Baseband compatibility

RF band scalability with a common baseband processing is mainly envisioned for UWB transmissions and connected to a dedicated scenario. A common baseband processing implies to have similar multipath propagation characteristics upon different RF bands that allow using the same baseband processing. As demonstrated in WWRF [WWRF_1, 07] and IST-IPHOBAC project [IPHOD222, 07] and recent technical papers [GSG,08], WiMedia and 60 GHz transposed WiMedia systems are alternatively implemented at the uplink and downlink transmissions to perform RF bands scalability as an extension to MultiBand (MB) processing. This dual band is foreseen to support asymmetric data rates and introduce diversity upon the radio link.

The concept of multiple RF bands using both 5 GHz and 60 GHz for WLAN applications has been firstly introduced through the IST Broadway project [BROADWP3_02] where a backward compatibility between Hiperlan2/IEEE802.11a and the mm-Wave Broadway system was ensured considering sub-channel size multiple of 20/40 MHz and sub-carrier spacing multiple of IEEE802.11a sub-carrier spacing to cope with additional 60 GHz phase noise. The system considers one scenario where similar OFDM time related parameters are used but the choice is rather oriented on baseband compatibility with 60 GHz sub-carrier spacing multiple of 5 GHz sub-carrier spacing. The system offers data rates up to 360 Mbps to ensure a high capacity multi-user transmission.

For WPAN applications, France Telecom introduced multiple RF bands UWB-OFDM PHY layer using a common baseband air interface for WPAN MultiGigabit Wireless Systems (MGWS) considering bandwidth size multiple of WiMedia ones [SUM_1, 07][SUM_2, 07][WWRF_1, 07]. First experiment propagation analysis in 57-66 GHz and 3.1-10.6 GHz justified a common baseband air interface for WPANs.

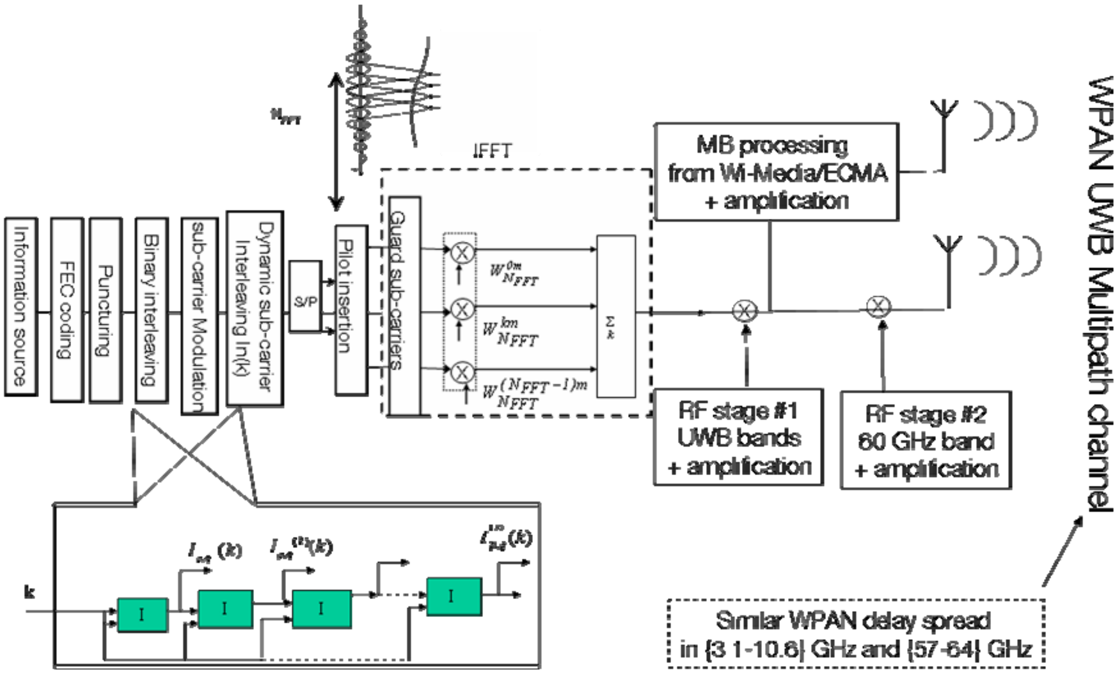


Figure 2-27: FTR&D Scalable RF UWB-OFDM system with dynamic sub-carrier mapping allocation

RF band scalability is motivated by data rate increase multiplied by a factor of 10 in the past ten years, and the progressive invasion of High-Definition (HD) content into various services. Recent usage models defined within the IEEE802.15.3c TG proves MGWS relevance for short range applications.

2.4.2 WLAN/WPAN convergence

The WPAN IST-MAGNET system (http://www.ist-magnet.org) designs a Personal Network (PN) concept where several PAN scenarios communicate together using flexible air interfaces and Personal Network federation (FEDNET) topologies. This concept aims at considering each user as a core-PAN enabled to establish several simultaneous communications with devices in its vicinity associated with a Private Personal Area Network (P-PAN) and ensures communications with other devices assigned to neighboured core-PAN denoted PANs scenarios. Several P-PAN and PANs may communicate using multi-PAN scenario with multiple air interfaces

Multiple WPAN air interfaces depending on desired data rates have been designed within the IST-MAGNET project, considering either UWB-FM transmissions for low data rates (100-300 kbps) or Multi-Carrier Spread Spectrum (MC-SS) techniques for high data rates up to 150 Mbps and WiMedia system [MAG, WP3.2, 05]. In this case, convergence is performed in the UCL convergence layer allowing several independent PHY layers. Efforts on convergence layers are now concentrated on UWB-FM and MC-SS MAGNET air interfaces.

2.5 Synthesis

These descriptions show that these three types of technologies, in spite of their different levels of maturity, can be seen as complementary technologies: they provide different coverages, throughputs, power efficiency levels, access mechanisms, etc. The following table summarizes these characteristics.

Table 2-14: Main characteristics of the three radio technologies

Usage	WPAN UWB	WLAN	WPAN 60 GHz
Standard	ECMA 368/369	802.11n	802.15.3c
Certification	WiMedia	Wi-Fi	/
Air rate	53.3-480 Mbps	up to 600 Mbps	>2 Gbps
Range	Up to 30 feet	Up to 300 feet	Up to 30 feet
Frequency	3 - 10 GHz	2.4 GHz & 5 GHz	60 GHz
Duplex	TDD	TDD	TDD
Bandwidth	528 MHz	20 or 40 MHz	2160 MHz
Baseband rate	528 Msps	20 or 40 Msps	2592 Msps (OFDM)
Modulation **Multiple access**	QPSK, DCM Multi-band OFDM TDMA/CSMA	BPSK, QPSK, 16QAM, 64QAM OFDM TDMA/CSMA	SC 2-4-8-PSK, GMSK, 16-QAM, OOK, CP-SC, OFDM
FFT size	128	64/128	512 128 (only LRP, AV OFDM)
Symbol duration for CP=1/4	303 ns	4 µs	48.38 ns
MIMO	no (RX diversity possible)	STBC/SDM, linear pre-coding, up to 4 antennas, Beamforming (option)	Switch Diversity, Beamforming
Coding	Convolutional, R=1/3, g=133, 165, 171	Convolutional, g=133, 171 R=1/2, 2/3, 3/4, 5/6 LDPC with block lengths 648, 1296, 1944	Reed-Solomon, Convolutional, LDPC
Product roll-out estimate	2007 (e.g. wireless USB)	Pre11n: 2007+	2009+

3 Derivation of technical and QoS requirements

Based on the use cases from one side, and the current status of the three radio technologies, some guidelines can be drawn on the technical work that will be led to meet the project's objectives. This section therefore summarizes the main requirements for suitable radio technologies for OMEGA networks. Standardization values are considered as first reference values, allowing air interfaces benchmarking with existing systems and highlight next enhanced proposals from the project. QoS is expressed in Packet Error Rate (PER) or Bit Error Rate (BER) targeted values associated with targeted data rates derived from usage models (see section 1.2).

Secondly, QoS and throughput requirements may be connected to WLAN/WPAN scenarios considering transmission medium constraints as multipath and pathloss conditions. This approach was firstly proposed within the IST-MAGNET project in mapping different pathloss models, air interfaces through several classes of data rates. This concept is adopted in the section 3.4.

3.1 Link Throughput

Link Throughput and QoS requirements vary with WPAN and WLAN applications. The reference systems are IEEE 802.15.3c and IEEE 802.11n systems.

3.1.1 WPAN

Highest data rates for WPAN should be obtained with WPAN systems using 60 GHz frequency band, and should be derived from IEEE 802.15.3c usage models detailed in [TG3c06, 1].

Consequently, data rates ranging from 50 Mbps to 6.3 Gbps shall be considered as reference values. They are derived from IEEE802.15.3c usage models and summarized in Table 3-1.

IEEE 802.15.3c data rates are spread over different classes of devices, depending on both applications and MCS. They result from recent contributions to the group in 2008 [TG3c08]. They are presented in Table 3-2 and Table 3-3. These solutions of MCS were adopted to fit different applications summed up in Table 3-1 with MCS modes, referring to IEEE document 06/055r22 [TG3c06, 1] and [TG3c08]. In Table 3-1 highlighted cells refer to mandatory usage models that all proposers shall use for their simulation analysis (see section 1.2).

Table 3-1: IEEE802.15.3c usage models [TG3c06, 1]

Application	Environment	MAC-SAP (Gbps)	Distance (m)	Notes
Uncompressed video streaming	NLOS, residential LOS, residential	1.78 3.56	5 10	
Multi uncompressed video streaming	LOS, residential NLOS, residential	1.75 0.62	5 5	Devices (TV) receiving video streaming must be 5m separated
Desktop office	NLOS, desktop LOS, desktop NLOS, office	3.56 0.25 0.5	1 1 5	Single direction (computer – TV) Average async. each direction Average async.
Conference ad hoc	LOS, office LOS, desktop LOS, office	1.75 0.0416 0.125	5 1 3	Single direction (computer – TV) Average async. each direction Average async. each direction for wireless bridge
Kiosk file downloading	LOS, office	1.5 - 2.25	1	Asymmetric upload/download

To answer these different applications, several modulation and coding schemes for single carrier or OFDM systems were proposed within TG3c and classified following their data rate (see Table 3-2), and different MCS were mapped to these classes of devices (see Annex 6).

Table 3-2: MCS categorization for SC mode (TG3c)

Class	Categorization
Common rate	Mandatory rate for all DEVs in SC PHY mode and PNC-capable OOK devices, and optional for other DEVs.
Mandatory low rate	Mandatory data transmission rate for all DEVs in SC PHY mode and PNC-capable OOK devices, and optional for other DEVs.
Class 1	Data rates at PHY-SAP < 1.5 Gbps
Class 2	1.6 Gbps < Data rate at PHY-SAP < 3 Gbps
Class 3	Data rates at PHY-SAP > 3 Gbps
Class 4	MCSs supporting OOK and DRB devices

3.1.2 WLAN

The same way as for WPAN, data rates for WLAN should be issued from IEEE802.11n and even IEEE 802.11vht:

- IEEE 802.11n: 600 Mbps
- IEEE 802.11 vht (< 6 GHz): 800 Mbps*
- IEEE 802.11 vht (60 GHz): 1 Gbps*

** These values correspond to the last known requirements for PAR and five criteria.*

In the case of IEEE802.11n version 3.0, targeted throughputs have been designed to assess reference power sensitivity of high throughput (HT) modes.

Targeted data rates are directly connected to the number of spatial streams (Nss) considered in MIMO configurations and the transmission bandwidth size set to 20/40 MHz.

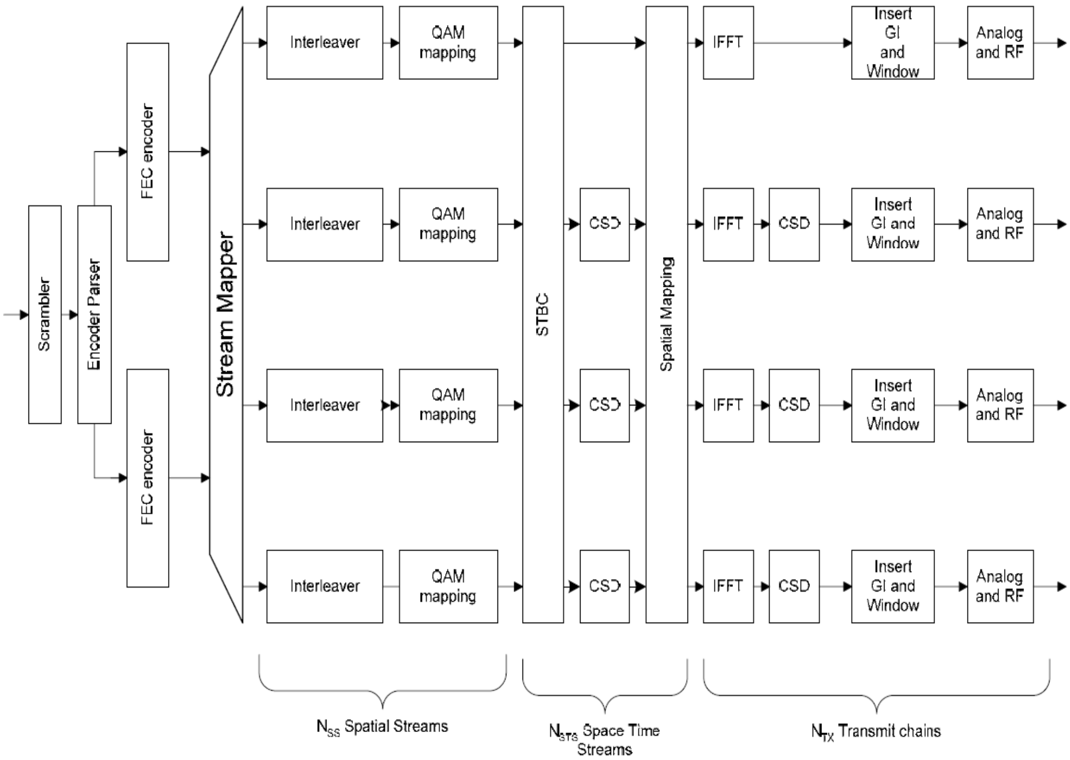


Figure 3-1: IEEE802.11n HT PHY layer design

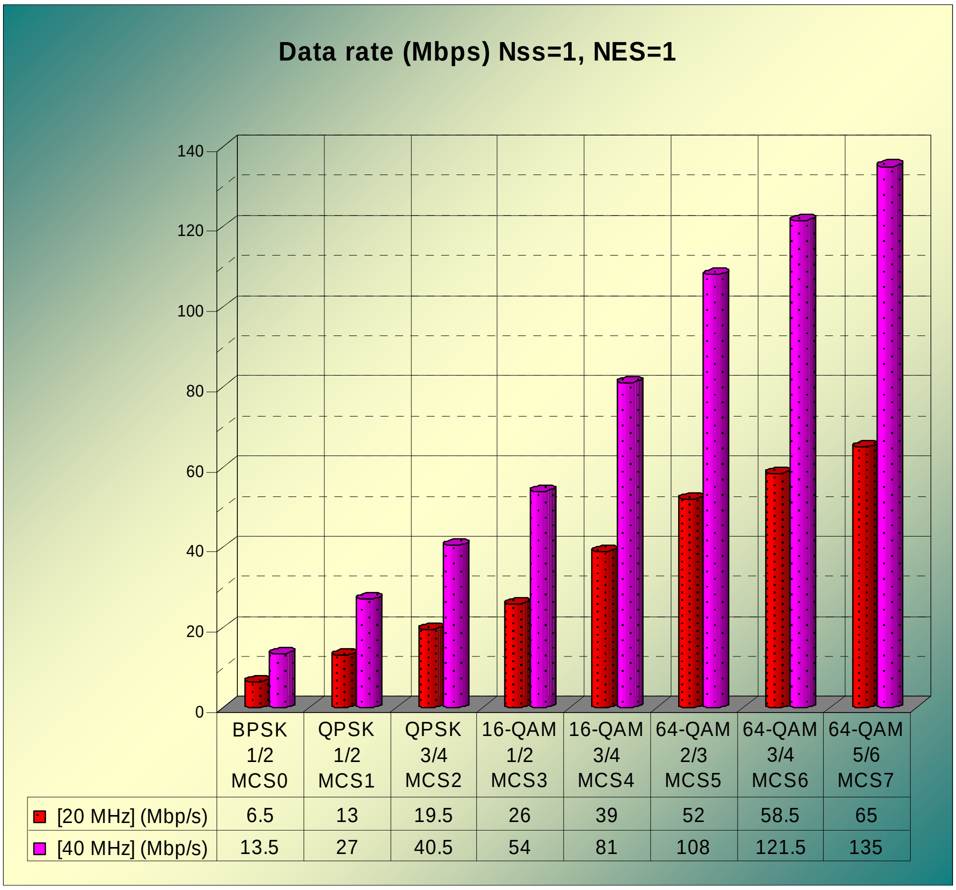
PSDU data rates are given by :

$$Du = \frac{\sum_{iss=1}^{Nss} N_{BPSC}(iss)\cdot r \cdot N_{SD}}{T_{SYM}} \qquad (3\text{-}1)$$

$$T_{SYM} = T_{GI} + T_{FFT}$$

N_{BPSC} (iss) is the number of bits per sub-carrier for the iss-th spatial stream (different modulations may be considered upon separate spatial streams), r is the code rate and N_{SD} is the number of data sub-carrier per OFDM symbol. T_{SYM} is the OFDM symbol duration including guard interval.

Figure 3-2 and Figure 3-3 provide PSDU (data payload) data rates considering 1 and 2 spatial streams.



	BPSK 1/2 MCS0	QPSK 1/2 MCS1	QPSK 3/4 MCS2	16-QAM 1/2 MCS3	16-QAM 3/4 MCS4	64-QAM 2/3 MCS5	64-QAM 3/4 MCS6	64-QAM 5/6 MCS7
[20 MHz] (Mbp/s)	6.5	13	19.5	26	39	52	58.5	65
[40 MHz] (Mbp/s)	13.5	27	40.5	54	81	108	121.5	135

Figure 3-2: IEEE802.11n HT PSDU data rate with Nss=1

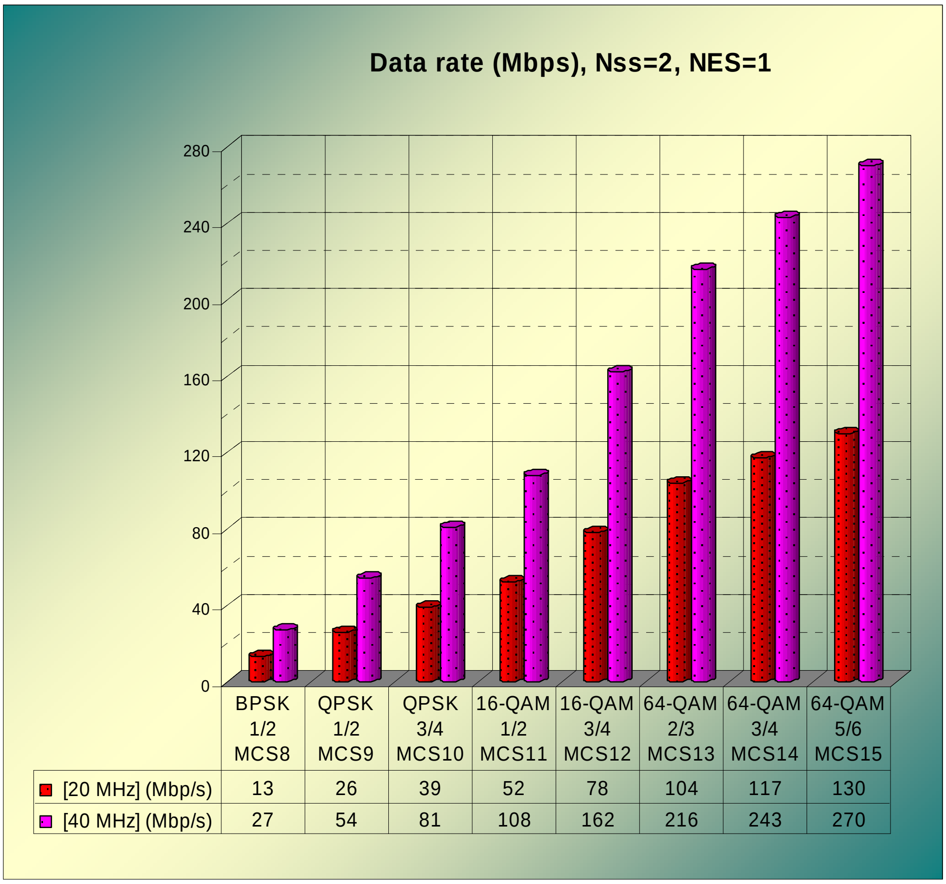


Figure 3-3: IEEE802.11n HT PSDU data rate with Nss=2

Four partial streams may be considered to increase the data rate. The highest PSDU data rate is achieved by using 64-QAM modulated sub-carriers with four spatial streams, 40 MHz bandwidth and a FEC code rate set to 5/6 (see Table 3-3). In some configurations, parallel FEC codes may be implemented to introduce diversity FEC schemes and facilitate decoding process.

Table 3-3: IEEE802.11n HT PSDU data rate with Nss=4.

MCS Index	Modu-lation	R	N_{BPSCS} (i_{SS})	N_{SD}	N_{SP}	N_{CBPS}	N_{DBPS}	N_{ES}	Data rate (Mbps)	
									800 ns GI	400 ns GI
24	BPSK	1/2	1	108	6	432	216	1	54.0	60.0
25	QPSK	1/2	2	108	6	864	432	1	108.0	120.0
26	QPSK	3/4	2	108	6	864	648	1	162.0	180.0
27	16-QAM	1/2	4	108	6	1728	864	1	216.0	240.0
28	16-QAM	3/4	4	108	6	1728	1296	2	324.0	360.0
29	64-QAM	2/3	6	108	6	2592	1728	2	432.0	480.0
30	64-QAM	3/4	6	108	6	2592	1944	2	486.0	540.0
31	64-QAM	5/6	6	108	6	2592	2160	2	540.0	600.0

3.2 System Throughput

3.2.1 System Scenario

The performance of a wireless network always depends on the given environment, which includes LOS and NLOS conditions, shadowing and, especially important in high-density scenarios, interference from other nodes. To evaluate the performance in an indoor scenario, an abstraction of a typical floor is used, as displayed in Figure 3-4. It can be seen from the figure that three different node types are assumed:

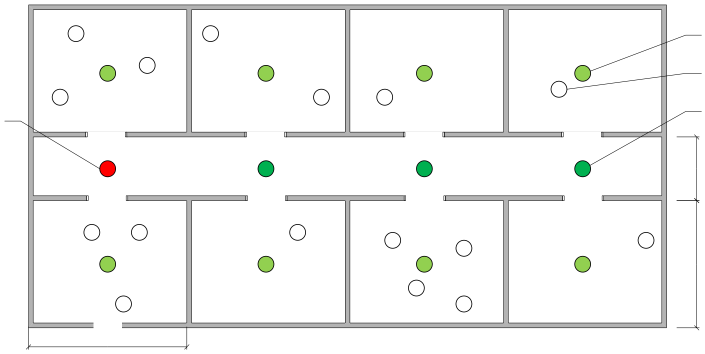


Figure 3-4: Typical floor plan

1. End-Devices, which are positioned randomly in the rooms. They can be either full-fledged mesh devices, i.e. They are able to forward other devices' data, or they are simple one-hop devices which have to connect either directly to the portal or use the service of a mesh point. Any device in the scenario represents a consumer and/or server of a traffic stream.
2. The portal, which connects the home network to a wired backbone and thus is the sink/source of all outgoing/incoming traffic streams.
3. Optionally, dedicated relays, mesh points, fixed either (at the ceiling) in the corridor between two rooms or at the centre of a room they are neither sinks nor sources, but only intermediate hops.

Depending on the capability of the devices and the existence of corridor/room mesh points, three different deployment concepts become possible: pure ad-hoc networking without any mesh points, mesh points in the corridor and mesh points in the corridor and the rooms.

Due to the geometry of the scenario, a variation of the number of rooms and thus the average route length becomes possible: starting from two rooms directly opposite to each other, the scenario can be enlarged by adding an even number of rooms. In the evaluation, scenarios with up to ten rooms are considered. Throughout the evaluation, the sources and sinks of each route are chosen randomly among the devices and the portal, such that

- the portal is the source of 50 % of all routes,
- no device connects multiple times to the portal and
- each route is bidirectional, divided into 90 % downlink for the data and 10 % uplink traffic for the control information.

<u>Pathloss and Physical Layer Model</u>

Of course, the system throughput depends on the pathloss and physical layer model. For the evaluation, we use the input from Figure 3-5 and Figure 3-6, which show

- the relation of the SINR and the achievable data rate, depending on the selected MCS,
- the maximum data rate of a transmission depending on the receiver location, taking into account the pathloss and the shadowing of walls.

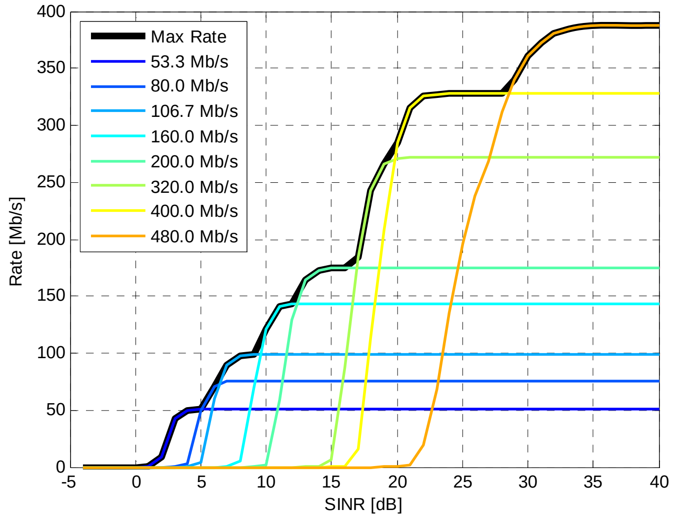


Figure 3-5: Achievable data rates based on SINR, for various MCS

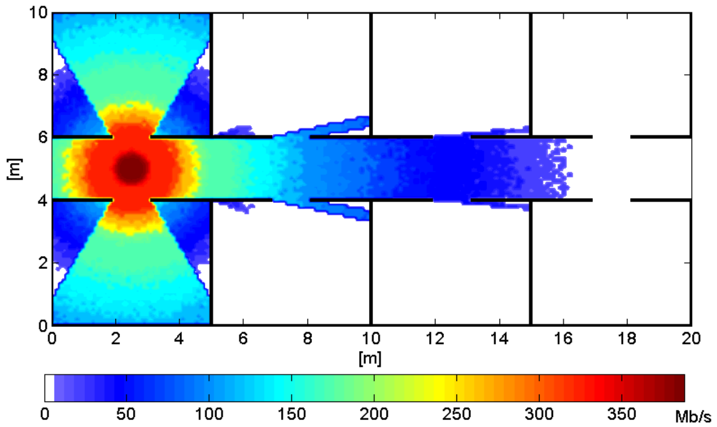


Figure 3-6: Data rates based on the receiver location, shadowing and path loss effects

Medium Access Control Model

While the PHY model abstracts the behaviour of a single link in the network (under which conditions the link is usable, what is its PER and resulting rate), the Medium Access Control (MAC) model is responsible for the behaviour of the multiple channel access. Due to the nature of the wireless channel, transmissions have to be scheduled without collisions.

To estimate the maximum achievable throughput capacity, the evaluation assumes an optimal coordinated DRP. This is modelled via an omniscient and omnipotent coordination entity, which

- has full knowledge about the PHY model for each link,
- controls the traffic load on each link, so that the end-to-end requirements are met,
- generates a DRP-schedule for the transmissions and
- disseminates this schedule to the nodes without costs.

All nodes operate under the guidance of this hypothetical controlling entity. This allows for an optimal schedule to be followed by the network, which maximizes the network throughput.

Evaluation

Pure Ad-hoc Networking

In the first deployment concept, all mesh points (green in Figure 3-4) are deactivated and the devices form an ad-hoc network between themselves and the portal. Hence, it is assumed that each device is capable of forwarding its peer's data frames, which requires a forwarding table and a routing protocol. Furthermore, it becomes much harder for each device to switch into power saving, as other devices might need its services as a forwarder. Of course, this concept provides the most flexible setup for the user, as no additional nodes other than the devices have to be installed.

Figure 3-7 shows the resulting system capacity. Immediately, several trends can be observed:

- For the smallest scenario size (blue graphs), the capacity is maximal (up to 230 Mbps) with few devices and converges to 90 Mbps/120 Mbps (without/with concurrent transmissions). This is rooted in the routing approach: with few devices, almost each user connects directly to the portal, which becomes the bottleneck of the network. Hence, almost no concurrent transmissions are used and the data rate is given by the average distance of 2.5 m. If the number of devices is increased, the average route length increases, as short, high-rate paths are preferred; this reduces the capacity as the small size reduces the benefit of concurrent transmissions.
- If the scenario size is increased, the capacity is reduced heavily for small network sizes, e. g. from 140 Mbps to below 50 Mbps for ten rooms and ten devices. This is a direct result of the increased path length and the routing overhead.
- In large scenarios with many devices, concurrent transmissions are able to absorb the burden of the longer routes; with 50 devices the difference between the smallest and the largest is halved to 50 Mbs in comparison to the network with only ten devices. Of course, this result assumes an optimal MAC scheduling, which is hard especially in large scenarios.

From the viewpoint of the user, an UWB network which is based on ad-hoc functionality, i.e. without specialized mesh points, is beneficial in dense networks only. As current users do not expect long transmission ranges from UWB devices, this acceptable for the common WPAN applications, but not for the connected home, which is enriched over time with more and more devices.

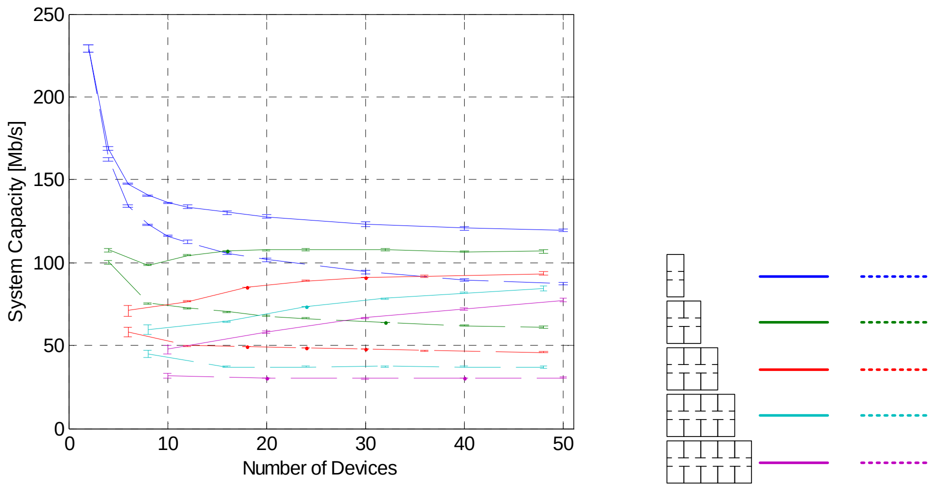


Figure 3-7: System capacity for ad-hoc network

Introduction of Mesh Points

Based on the findings in the previous section, dedicated mesh points are introduced; they form the mesh backbone which provides the service of data forwarding for the devices. In this deployment concept, the devices are limited to be either the source or the destination of a path, but not an intermediate relay.

The results in Figure 3-8 immediately show the advantage of the concept: In comparison with the ad-hoc network, the data rate is independent from the size of the network if a minimum threshold of around seven devices are present and optimal scheduling is assumed. In this case, a system capacity of 125 Mbps is obtained.

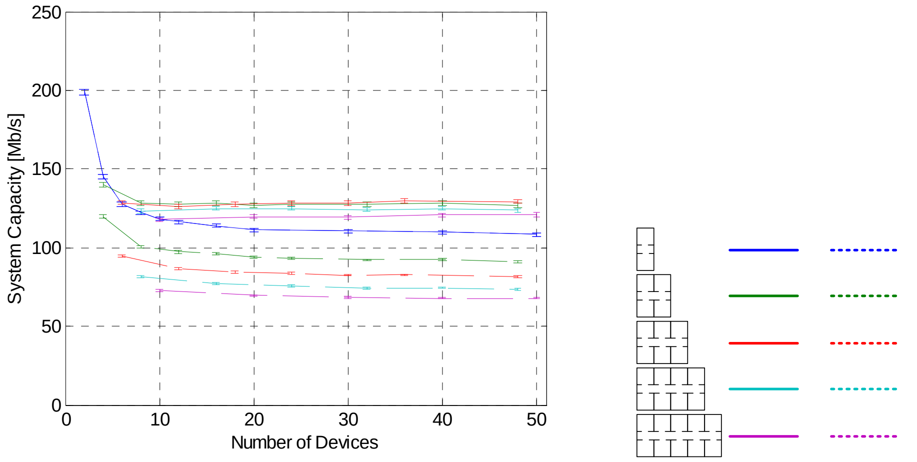


Figure 3-8: System capacity with introduction of dedicated mesh points

Full Mesh Point Concept

If the number of mesh points is increased by three times, it becomes possible to place one into each room next to the ones in the corridor. The resulting system capacity, shown in Figure 3-9, shows the same characteristics as in the deployment concept using few mesh points: again, the capacity is independent from the scenario size and the number of devices (assuming optimal MAC operation).

In comparison to the previous concept, the capacity can be increased by about 25 % to more than 150 Mbps.

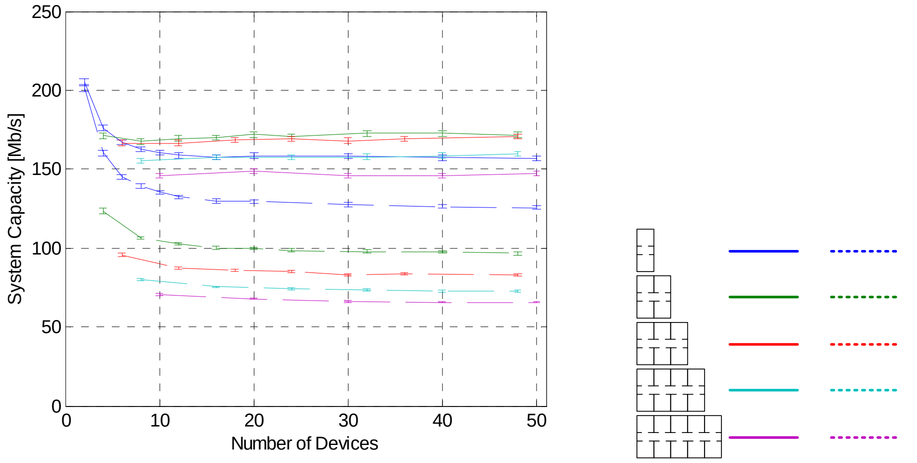


Figure 3-9: System capacity for full mesh points concept

Conclusions for OMEGA

The system throughput analysis in this section shows the limitation of current “high-speed” wireless transmission technologies in typical home scenarios: even with small number of concurrent users and an optimal MAC (i.e. without overhead and frame errors), the interference created by other transmissions decrease the maximum data rate significantly. While in this example the WiMedia UWB PHY supports data rates of up to 480 Mbps, a system capacity of only 150 Mbps can be reached. For five users that are active simultaneously, this results in 30 Mbps.

Therefore, it is a central task of WP2 to improve the system throughput to data rates which allow for the services expected in the future. This must involve

- Physical layer improvements to increase the data rates in multi-user environments under low SINR conditions
- MAC layer improvements to allow for optimized scheduling of concurrent transmissions in dense multi-hop networks; transmissions should be scheduled at the best time point, using the optimal wireless resource.
- Cross-layer improvements to allow for optimized link operation.

3.3 Error Rates/Packet Loss

The performance required for applications listed in Table 3-1 necessitates packet error rate (PER) less than 8 % (packets size being 2 Kbytes) or bit error rate (BER) less than 10^{-6}.

Each application or service requires a given maximum bit error rate or packet loss, in order to guarantee a given quality of service. Furthermore, the targeted bit error rate or packet error rate depends also on the use or not of an external code, as a Reed-Solomon code for example. The systems taken as references in OMEGA WP2 are IEEE 802.11n, IEEE 802.15.3a and IEEE.802.15.3c standards, respectively for WLAN, UWB and 60 GHz applications. Depending on the applications and on the related services, the constraints in terms of error rate can be defined as follows:

- IEEE 802.11n: PER = 10% with 4096 byte packet size
- WiMedia: BPER = 8%, with 1024 byte packet size
- IEEE 802.15.3c: BER $=10^{-6}$ for video streaming, PER = 8% with 2048 byte packet size for data transmission

In WP2, new PHY/MAC algorithms and mechanisms will be studied in order to fulfil these objectives taking as references the previous mentioned systems.

3.4 Link Budget

First link budget models defined in the OMEGA project are based on link level results and pathloss attenuation associated with a dedicated scenario and specific air interface. Link budget provides the minimum required received power, which we denote *multipath power sensitivity,* to successfully transmit data with a net bit rate D and a targeted QoS translated in BER/PER limits as defined in section 3.3. The *multipath power sensitivity* S_M is derived from link level simulations usually performed at the baseband level where RF front end degradations are modelled as equivalent selective filters. The *multipath power sensitivity* S_M is compared to the *available received power* which depends on the radiated power and propagation pathloss models associated with a WPAN/WLAN scenario. The *available received power* has to be superior to the *multipath power sensitivity* S_M , the equality between these two equations provides the largest radio coverage of the considered system delivering a given data rate D.

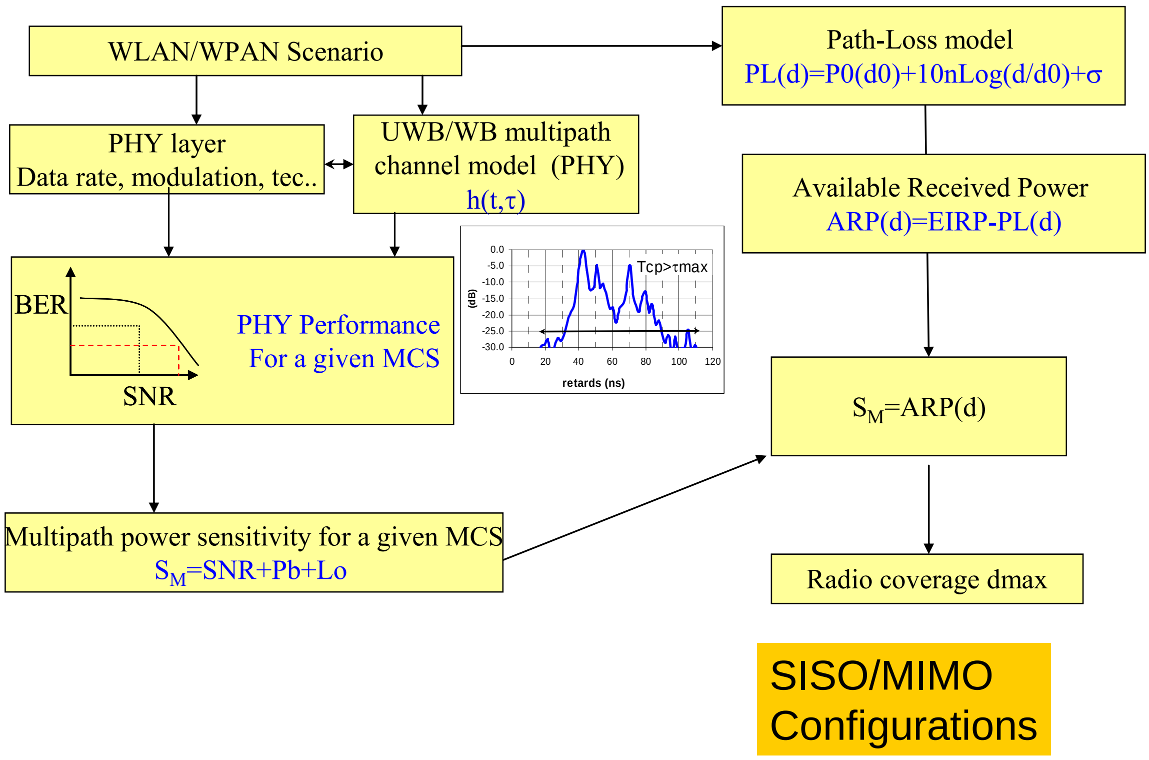


Figure 3-10: Budget link assessment overview

Several baseband equivalent models should be developed within the scope of OMEGA to refine RF degradations including non linear effects. Phase noise will be taken into account.

Several link budget models have been defined within the IST-MAGNET project, in order to differentiate multipath channel margin due to link level multipath degradations from path-loss impact on bit rate radio coverage [MAG, WP3.1, 06]. The *Multipath Channel Margin (MCM)* is defined as the additional relative power which is required to achieve the same data rate with the same QoS as in the case of perfect channel (no echo, AWGN) in presence of multipath. MCM is a quantitative parameter to assess the receiver ability to compensate multipath degradations upon BER measurements.

The power sensitivity S corresponds to the required received power to achieve a given data rate D when there is no echo on the propagation channel. It depends on the noise figure of the receiver (NF) due to thermal noise, the efficient bandwidth size Bw and the loss cable corresponding to connectivity loss.

By denoting SNR_c^{AWGN} the power to noise ratio under AWGN and SNRc the required power to noise ratio under multipath configuration associated with a BER set to 10^{-6}, the power sensitivity and the multipath power sensitivity are expressed as:

$$S = SNR_c^{AWGN} + 10 \cdot Log(kT_0) + NF + Lo + 10 \cdot Log(Bw)$$

$$S_M = SNR + 10 * Log(kTB) + Lo = S + MCM$$

$$ARP(d) = EIRP - PL(d)$$

$$S_M = ARP(d) \text{ ==> radio coverage dmax}$$

The thermal noise contribution *Pb* is split into two contributions, a reference thermal noise power level Pb_0 associated to a reference noise temperature set to T_0=290 K (17°C) and a noise figure *NF* corresponding to the ratio of the exact noise temperature T to the reference noise temperature T_o of the system.

$$Pb = 10 \cdot Log(kTB) = 10 \cdot Log(kT_0) + 10 \cdot Log(\frac{T}{T_0}) + 10Log(B_w)$$

$$Pb_0 = 10 \cdot Log(kT_0), \quad NF = 10 \cdot Log(\frac{T}{T_0})$$

The multipath power sensitivity may also be expressed with regards with data rate D and the average <EBu/No> as follow:

$$S_M = SNR + 10 \cdot Log(kTB_w) + L_0$$

$$S_M = <\frac{Ebu}{No}> + Pb_{[data]} + L_0$$

$$Pb_{[data]} = 10 \cdot Log(kTD) = 10 \cdot Log(kT_0) + 10 \cdot Log(\frac{T}{T_0}) + 10Log(D)$$

$$Pb_{[data]} = -114dBm + 10 * Log(D) + NF$$

3.4.1 WLAN link budget assessment

SISO and MIMO aspects and rules to carry out link budget.

MIMO link budget are expressed in considering the multipath power sensitivity per receiver antenna and a normalized radiated power at the receiver side.

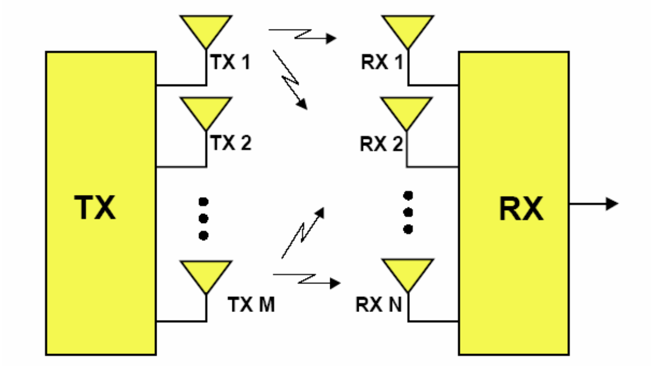


Figure 3-11: MIMO representation

On the j-th antenna, we have:

$$S_M^{(j)} = SNR^{(j)} + 10 \cdot Log(kTB_w) + L_0$$

$$SNR^{(j)} = \frac{P^{(j)}}{Pb}$$

$$S_M^{(j)} = SNR^{(j)} + NF + 10 \cdot \log(B_{w-MHz}) + Lo - 114$$

$$S_M = 10 \cdot Log(N_{RX}) + S_M^{(j)}$$

Typical link budget parameters have been defined within the framework of IEEE802.11n

Table 3-4: Typical link budget parameters issued from IEEE802.11n

Scenario	Transmitted power 1dB CP	Antenna Gain G_{TX}, G_{RX}	Noise Figure	Channel Margin and other Loss
Indoor applications	20 dBm	tbd	10 dB	5 dB

The power sensitivity S is calculated in the next tables for 20MHz and 40 MHz sub-channel sizes considering FTR&D link level performance. Power sensitivity is identical with standard power sensitivity specifications.

Table 3-5: RX power sensitivity, 20 MHz sub-channel size

	20 MHz						
MCS	**QPSK 1/2**	**QPSK 3/4**	**16-QAM 1/2**	**16-QAM 3/4**	**64-QAM 2/3**	**64-QAM 3/4**	**64-QAM 5/6**
Efficient bandwidth Bw (MHz)	17.81	17.81	17.81	17.81	17.81	17.81	17.81
Data rate D (Mbps)	13	19.5	26	39	52	58.5	65
Pb[data] (dBm)	-102.86	-101.10	-99.85	-98.09	-96.84	-96.33	-95.87
Pb (dBm)	-101.49	-101.49	-101.49	-101.49	-101.49	-101.49	-101.49
CMOS RX Noise Figure NF (dB)	10	10	10	10	10	10	10
Pb[data]+NF (dBm)	-92.86	-91.10	-89.85	-88.09	-86.84	-86.33	-85.87
Pb+NF (dBm)	-91.49	-91.49	-91.49	-91.49	-91.49	-91.49	-91.49
Eb/N0 (dB) **AWGN channel, BER=10^{-5}**	6.35	6.55	8.3	10.5	13.3	13.8	14.3
SNR (dB) **AWGN channel, PER=10%, 1000 bytes**	4.98	6.94	9.94	13.90	17.95	18.96	19.92
Loss (dB)	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Margin (dB)	5	5	5	5	5	5	5
Rx Power Sensitivity[2] (dBm)	-79.01	-77.05	-74.05	-70.09	-66.04	-65.03	-64.07

2 *Figures based on draft D2.0*

Table 3-6: RX power sensitivity, 40 MHz sub-channel size

	40 MHz						
MCS	**QPSK 1/2**	**QPSK 3/4**	**16-QAM 1/2**	**16-QAM 3/4**	**64-QAM 2/3**	**64-QAM 3/4**	**64-QAM 5/6**
Efficient bandwidth Bw (MHz)	35.9	35.9	35.9	35.9	35.9	35.9	35.9
Data rate D (Mbps)	27	40.5	54	81	108.	121.5	135
Pb[data] (dBm)	-99.69	-97.93	-96.68	-94.92	-93.67	-93.15	-92.70
Pb (dBm)	-98.44	-98.44	-98.44	-98.44	-98.44	-98.44	-98.44
CMOS RX Noise Figure NF (dB)	10	10	10	10	10	10	10
Pb[data]+NF (dBm)	-89.69	-87.93	-86.68	-84.92	-83.67	-83.15	-82.70
Pb+NF (dBm)	-88.44	-88.44	-88.44	-88.44	-88.44	-88.44	-88.44
Eb/N0 (dB) AWGN channel, BER=10^{-5}	6.35	6.55	8.3	10.5	13.3	13.8	14.3
SNR (dB) AWGN channel, PER=10%, 1000 bytes	5.11	7.07	10.07	14.03	18.08	19.09	20.05
Loss (dB)	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Margin (dB)	5	5	5	5	5	5	5
Rx Power Sensitivity[1] (dBm)	-75.84	-73.88	-70.88	-66.92	-62.87	-61.85	-60.90

3.4.2 WPAN link budget assessments

Within the framework of the IEEE802.15.3c TG groups, first link budget has been assessed in accordance with the novel CM channels defined for directive cases. A noise figure set to 8 dB is considered. Antenna gains are set to 15 dB with a transmitted power ranged from -3.1 to 1 dB at 1 dB point compression.

In case of OFDM a backoff of 6 dB should be considered. Free path-loss models are considered in simulations. Refined models issued from experimental measurements should be considered. In connection with recent WPAN scenarios, transmitted power, antenna gains and noise figure are specified to assess link budget and select appropriate RF front end modules.

Table 3-7: Typical link budget parameters issued from IEEE802.15.3c [TG3c07, 2]

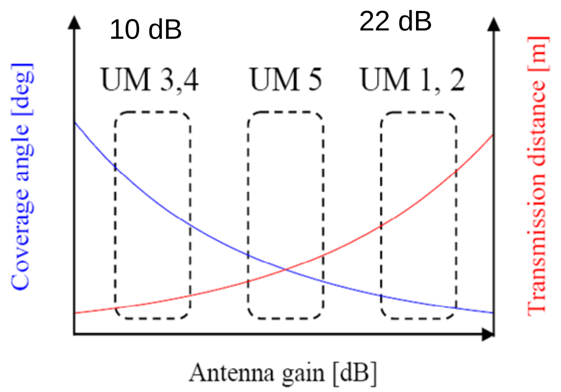
Scenario	Transmitted power 1 dB CP	Antenna Gain GTX, GRX	Noise Figure	Channel Margin and other Loss
Residential CM1.2 Portable application	-3.1 dBm	15 dB	8 dB	10 dB
Fixed application	10 dB	15 dB	8 dB	12.5 dB

Another IEE802.15.3c contribution [TG3c06, 2] oriented on usage models, suggest adaptive antenna gains for each usage models described in the section 1.2.

Table 3-8: flexible antenna gains for UMD

	Devices	Antenna beam-width factor (α)	Correspondent 3-dB beam-width [deg]	Maximum antenna gain [dBi]	Form factor [mm] *	Bandwidth [GHz]
UM1	TV	40	15	22	20 x 40	9 [57-66 GHz]
	STB	40	15	22	20 x 40	
UM2	TV	40	15	22	20 x 40	
	STB	40	15	22	20 x 40	
UM3	PC	2.5	60	10	4 x 1	
	Peripheral	2.5	60	10	4 x 1	
	TV	40	15	22	20 x 40	
UM4	PC	2.5	60	10	4 x 1	
	Wireless Bridge	2.5	60	10	4 x 1	
	TV	40	15	22	20 x 40	
UM5	Server (STB)	2.5	60	10	4 x 1	
	PDA	10	30	16	10 x 10	
*: Conocal Horn antenna: Diameter x Length						

The idea is to adapt and select antenna gain in accordance with typical UMD distance range, data rates and deployment considerations.



Usage Models (UMx)	Services
UM 3,4	PC, wireless bridge
UM5	Server (STB) PDA
UM1,2	TV, STB

Figure 3-12: Flexible antenna gains for UMD

Associated link budget models considering path-loss models detailed in [WWRF_1, 07] shall be developed considering IEEE802.15c like systems over AWGN channel models. These values result from first results from FTR&D.

Table 3-9: IEE802.15.3c like OFDM mode (FTR&D simulations)

Parameter	Value	Value	Value	Value
Efficient bandwidth	1.76 GHz	1.76 GHz	1.76 GHz	1.76 GHz
Sampling rate	2538 MHz	2538 MHz	2538 MHz	2538 MHz
MCS	QPSK-5/8	QPSK-3/4	16QAM-5/8	16QAM-3/4
PSDU Data Rate	1591 Mbps	1909 Mbps	3182 Mbps	3818 Mbps
NFFT	512	512	512	512

Nused/NSD	351/336	351/336	351/336	351/336
Symbol duration/samples	~252 ns/640	~252 ns/640	~252 ns/640	~252 ns/640
Average TX Power	15 dBm	15 dBm	15 dBm	15 dBm
Total Pathloss	86.075 dB	80.054 dB	74.034 dB	68.013 dB
Free pathloss	(@ 8 meters)	(@ 4 meters)	(@ 2 meters)	(@ 1 meter)
Available RX Power (Gr=4 dB)	-67.07 dBm	-61.05 dBm	-55.03 dBm	-49.01 dBm
Noise Power Per Bit	-81.98 dBm	-81.19 dBm	-78.97 dBm	-78.18 dBm
CMOS RX Noise Figure	8 dB	8 dB	8 dB	8 dB
Total Noise Power	-73.98 dBm	-73.19 dBm	-70.97 dBm	-70.18 dBm
Required Eb/N0	6.4 dB	6.6 dB	8.6 dB	10.5 dB
Implementation Loss	2.5 dB	3.0 dB	2.5 dB	3.0 dB
S (AWGN)	-65.08 dBm	-64.09 dBm	-59.87 dBm	-57.18 dBm

Within the framework of IEEE802.15.3a group, a noise figure NF=6.6 dB was considered with a loss set to 2.5 dB and a channel margin varying with the data rate (code rate) over QPSK modulated sub-carriers and AWGN case. MCM has to be added to link budget assessments over realistic channels. Antenna gains follow USB spectrum masks. No back-off was considered, a 6 dB back-off should be recommended.

An example of AWGN link budget is reported in Table 3-7 over AWGN channel considering system parameters summarized below.

Table 3-10: Typical link budget issued from IEEE802.15.3a TG

Parameter	Value	Value
Sampling rate	528 MHz	528 MHz
Information Data Rate	200 Mbps	480 Mbps
Coding rate (M=7)	5/8	3/4
Frequency domain spreading	No	No
Time Domain Spreading	Yes	No
Average TX Power	-10.3 dBm	-10.3 dBm
Total Pathloss	56.2 dB (@ 4 meters)	50.2 dB (@ 2 meters)
Average RX Power	-66.5 dBm	-60.5 dBm
Noise Power Per Bit	-91.0 dBm	-87.2 dBm
CMOS RX Noise Figure	6.6 dB	6.6 dB
Total Noise Power	-84.4 dBm	-80.6 dBm
Required Eb/N0	4.7 dB	4.9 dB
Implementation Loss	2.5 dB	3.0 dB
Link Margin	10.7 dB	12.2 dB
RX Sensitivity Level	-77.2 dBm	-72.7 dBm

MCM has been assessed within the framework of MAGNET project. MCM values are reported on the next table.

Table 3-11: BER performance, RX sensitivity and MCM

Information Data Rate	53 Mbps	106 Mbps	200 Mbps	320 Mbps	400 Mbps	480 Mbps
Modulation	QPSK 1/3	QPSK 1/2	QPSK 5/8	QPSK 1/2	QPSK 5/8	QPSK 3/4
Spreading operation	FS+TS	FS+TS	TS			
Eb/N0, AWGN (dB)	3.5	4	4.7	4.7	4.8	4.9
<Eb/N0>$_{min}$ CM1 (dB)	8	8	11	12	15	
<Eb/N0>$_{min}$ CM2 (dB)	8	7	10.5	11	13	16
<Eb/N0>min CM3 (dB)	8	7.5	11	11.5	13.5	17
<Eb/N0>min CM4 (dB)	8	8.5	12	12.2	14	18
Multipath Channel Margin (dB)						
CM1	4.5	4	6.3	7.3	10.2	
CM2	4.5	3	5.8	6.3	8.2	11.1
CM3	4.5	3.5	6.3	6.8	8.7	12.1
CM4	4.5	4.5	7.3	7.5	9.2	13.1
Power sensitivity-AWGN channel (dBm)						
RX Sensitivity Level	-84.16	-80.65	-77.19	-75.15	-74.08	-73.19

3.4.3 Radio coverage assessments

Coverage refers to the maximum distance at which a wireless device achieves a guaranteed performance, e.g. throughput. The evaluation of coverage can be done using large scale channel models, since performance depends on received signal energy, and the large scale channel model can be used to predict it. The large scale channel model includes path loss and shadow fading, thus it allows computing link budget, i.e. mean received power as a function of distance. Large scale parameter models depend on the operating band and therefore they are technology dependent. In OMEGA WP2, the reference models are taken from the IEEE 802.11n, IEEE 802.153a and IEEE 802.15.3c standards, respectively for WLAN, UWB and 60 GHz applications. The state of the art in terms of coverage can be summarized as follows:

- IEEE 802.11n – 100 Mbps at 100 m[WiM06],
- WiMedia – 110 Mbps at 10 m [WiM06],
- IEEE 802.15.3c – 1.5 Gbps at 5 m [TG3c06, 2]

The goal of WP2 is to design innovative PHY/MAC algorithms, hardware architectures, and cross-layer mechanisms that will allow improving system coverage both through improvements in the individual technologies and through collaborative systems, i.e., cooperation among heterogeneous wireless devices. The objective is to obtain full in-building coverage such that seamless, uninterrupted service will be provided to end users. This target can be achieved through multi-hop mesh network that are managed by an inter-MAC layer.

Comparison between WiMedia transposed at 60 GHz and FTR&D system (EIRP: 20 dBm, Gr=4 dBi) is illustrated on the next figure. The Obstructed LOS (OLOS) corresponds to the case where a direct link exists and multipaths interfere upon the radio link. The NLOS in the case s of 60 GHz corresponds to the case where the transmission is performed thanks to reflections. It is the case when transmitter and receiver are in separate rooms with opened doors.

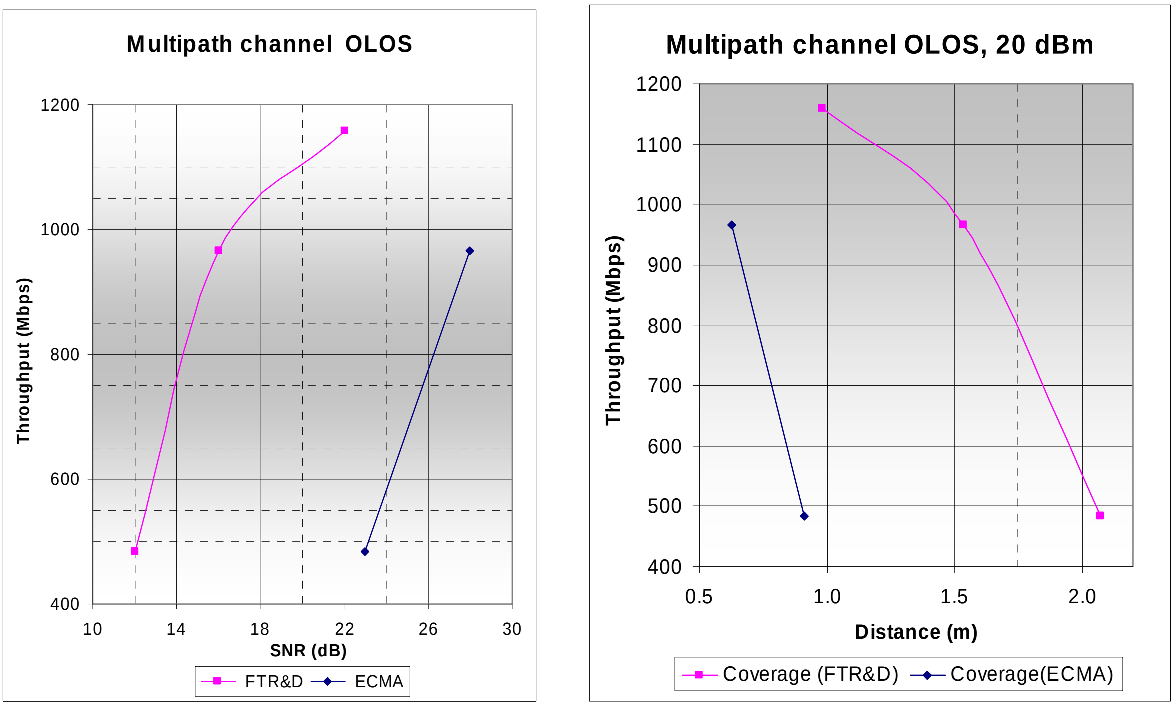


Figure 3-13: 60 GHz bit rate radio coverage issued from FTR&D results

Some typical Wi-Media radio coverage extracted from MAGNET Beyond results are reported here, following UWB spectrum masks given in the section 2.2.1.

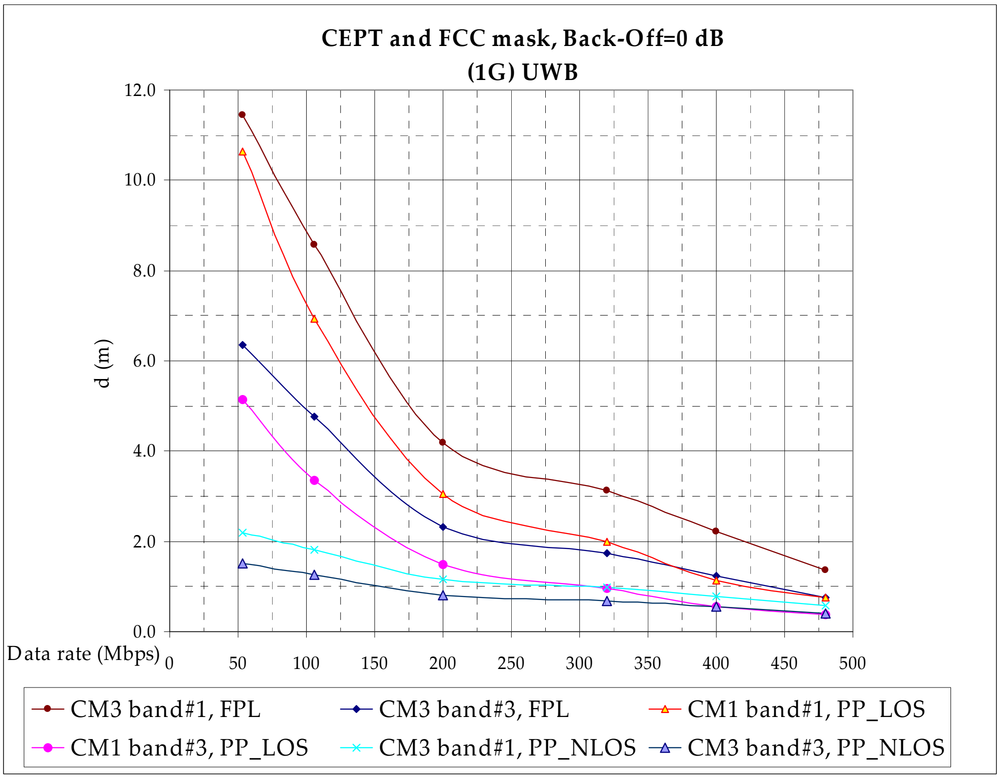


Figure 3-14: Extrapolated radio coverage for the extended UWB-OFDM system

3.5 Hardware Requirements

In the following parameters and requirements for the UWB implementation is given. The parameters according to the WiMedia Standards are listed below.

WiMedia/MBOA Standard

- OFDM-Parameters and Frequency Plan

  - Bandwidth 528 MHz
  - Subcarrier spacing 4.125 MHz
  - 128 subcarriers (100 data-, 12 pilot-, 10 guard-tones, 6 tones are set to zero)
- Data rates:
  - 33.3/106.7 and 200 Mbps mandatory
  - 80/160/320/400/480 Mbps optional

The specification challenges for UWB are listed below. Additional to the requirements for the transmission protocols and implementations, the different transmission standards and regulations are given. The implementation with using the CMOS technology ensures high integration and low system costs.

CMOS Design Challenges for UWB

- Wide RF bandwidth: 3 to 10.6GHz
- Wide BB bandwidth: DC to ± 264 MHz
- EVM: -28 dB in TX for highest performance
- Max TX power with integrated PA
- Time Frequency Interleaved (TFI) Modes
  - Band-hopping < 9.5 ns
- Coexistence and regulation
  - Crowded spectrum: GSM, WCDMA, WLAN, BT,...
  - Requirements like DAA (Detect And Avoid) might be expensive
- High integration (no ext. PA, LNA)

Mayor building blocks for the PHY are the I,Q ADC and DAC.

The following table shows the parameters for th0e I,Q ADC.

Table 3-12: Parameters for I,Q ADC

No.	Parameter	Value	Comment
1.	ADC Channels	I,Q	Pair comprising I and Q
2.	ADC ENOB	> 9.0	Signal in 20 MHz BW at 80 Msps
3.	Resolution	10 bits	
4.	ADC Sampling rate	20 MHz to 80 MHz	
5.	ADC Latency	6 Ts	Ts = sampling clock periods
6.	ADC Wake up (from shutdown)	< 2 µs	
7.	ADC Wake up (from standby)	< 1 µs	
8.	Common Mode Voltage	0.5 V to 0.7 V	RF dependent
9.	Voltage Range (peak-to-peak,for full-scale output)	1 V	Differential peak-peak. RFdependent.
10.	IQ Input Impedance	>10k Ohms, < 1.5 pF	RF Dependent
11.	Gain mismatch between I and Q in a pair	< 0.1 dB	
12	Power Consumption	< 42 mW at 40 Msps < 79 mW at 80 Msps	

The following table shows the parameters for the I,Q DAC.

Table 3-13: Parameters for I,Q DAC

No.	Parameter	Value	Comment
1.	DAC channels	I,Q	Pair comprising I and Q
2.	Resolution	10 bits	
3.	DAC SINAD	> 57	At 20 MHz
4.	DAC Sampling rate	20 - 80 Msps	
5.	Output common mode voltage	0.6 V	RF Dependent
6.	Output voltage range	1 V pk-pk	RF Dependent
7.	DAC Settling time	40 ns	
8.	Gain Mismatch	< 0.1 dB	
9.	DAC Wake up from shutdown	< 2 µs	
10.	DAC Wake-up from Standby	< 1 µs	
11.	Power	< 3 mW	

3.6 Latency

Figures provided in Table 1-1 and Table 1-2 for latency could be considered as references for latency requirements. However, these figures are rather conservative, and it is foreseen that latencies obtained with OMEGA radio systems should be lower than these figures. The OMEGA consortium will work on improving these figures for transmission delays

3.7 Type of traffic

As discussed in Section 3.2, the system throughput is limited severely in dense multi-user environments. Rates of more than 30 Mbps per user cannot be expected using current high-speed technology (e.g. UWB with 480 Mbps peak PHY rate). Hence, state-of-art technology cannot fulfil the requirements of downloading and cable replacement. Furthermore, the combination of several flows with different traffic requirements (rate and delay), including different directions, cannot be handled appropriately using current technology.

Table 3-14: Different types of traffic

Profile Type	Bit rate	Delay	Jitter	Packet loss	ARQ	TCP
Web navigation	Variable from some kbps to 1.5 Mbps					Variable backward flow < 4% of data
VoIP	2 CBR flows, some 10 kbps	Real time constraint < 10…100ms	< 20 ms	$< 10^{-3}$	No	UDP
Downloading	VBR flow up to the Gbps				Yes	Variable flow for TCP ACK < 4% of data
Audio and video diffusion	CBR flow with peaks for admission control, some kbps in audio, 2 to 50 Mbps for video	Video-audio sync constraints < 400ms		$< 10^{-5}$	Yes	Low bit rate CBR or VBR
Video conference	2 flows from 128 kbps to 4 Mbps	10…100 ms	< 10 ms	$< 10^{-5}$	No	

Gaming	Flow < 100 kbps	< 50ms	< 1 ms	$< 10^{-3}$		UDP
Cable replacement	Mono-directional flow, 1 Gbps or more	< 400ms	< 1 ms		No	

3.8 Coexistence

The number of wireless devices in a house is increasing and should continue even faster. The success of Wi-Fi leads to its integration into a wide variety of devices, and this trend should be confirmed with the new generation IEEE 802.11n.

A single-point switch of legacy against OMEGA devices from a home user cannot be expected; even under this assumption, neighboring networks would still be operating using legacy technology. Therefore, two levels of compatibility must be ensured:

1. Coexistence: In most usage scenarios, it can be expected that multiple overlapping home networks based on radio technology are used and owned by different entities exist. These networks use the same license-exempt spectrum; therefore, their capacity is interference-limited. Due to the increased resource demands enabled by the OMEGA technology, it can be expected that the mutual effect of these networks will increase.

   Therefore, it must be ensured that any OMEGA-based network follows a noninvasive strategy when occupying wireless resources. At a minimum, this means that its effect on any already existing, neighboring network is at most as high as the effect of a legacy network which would be installed instead. As an example, OMEGA networks must not deviate from the general listen-before-talk scheme of IEEE 802.11 if used in an environment (frequency and spatial) where other IEEE 802.11 networks are operating.

2. Cooperation: In contrast to coexistence, cooperation is necessary only in networks where all devices are used and owned by the same person. This person expects to a certain degree that all devices, bought at different times and most likely following different versions from the same standard, are able to work with each other. To fulfil this requirement, OMEGA devices need to conform to the radio standard they are based on; furthermore, they have to be able to recognize non-OMEGA devices so that they can be included into the network. Of course, these legacy devices will provide a lower set of capabilities in comparison to OMEGA devices.

Spectrum occupancy will represent a key issue for coexistence or radio systems. The coexistence issue that appeared with the first 802.11n devices showed that spectrum availability is becoming crucial for WLAN systems. As more devices operate in the already crowded 2.4 GHz band and new generations call for larger bandwidth (from 20 MHz to 40 MHz with 802.11n, maybe even more with 802.11vht), specific mechanisms will be necessary to enable reliable operations of different kinds of devices and avoid issues such as overlap of transmission and their consequences on QoS. For example, if larger bandwidths are required for higher throughput WLAN systems, other parts of the spectrum should be identified, and this is probably the path that will follow IEEE 802.11vht, seriously looking at the 60 GHz frequency band.

In parallel, new wireless devices are arriving on the market: UWB terminals are starting to be available under the label Wireless USB, and 60 GHz products should be commercialized soon. UWB devices use the same frequency bands as other systems, and coexistence is a crucial aspect. Regulation has been defined accordingly, and Detect And Avoid mechanism are currently being defined to guarantee protection of these systems. These mechanisms will set constraints on UWB systems, which will have to listen to other system, identify them, and adjust their emission levels accordingly.

OMEGA radio systems will therefore have to implement and be compliant to the regulatory mechanisms. Design of these systems will have to respect the spectrum occupancy of neighboring systems, avoid mutual interference and guarantee reliable operation from both sides.

3.9 Target Cost

Defining target costs is a difficult task, especially for WPAN systems as High Data Rates WPAN systems are just starting to hit the market. There are fewer uncertainties with WLAN market, and two phases can be foreseen in the coming years regarding commercialization of WLAN systems:

- Short- to Medium-Term Evolution--Pervasive Adoption of Wireless LANs: 2008-2010:

  The enterprise market continues to swell, with a cycle of upgrading driven by 802.11n; WLAN is firmly established as a mainstream technology in the enterprise market, and as a public Wi-Fi network; VoIP over WLAN drives both segments; the availability of mobile WiMAX and cellular broadband services inhibit growth of public Wi-Fi adoption and become viable alternatives to WLAN for enterprise wireless data connectivity.

- Long-Term Evolution to Converged Wireless LAN/WAN Networks: 2011 and beyond:

  There will be a convergence of local and wide area wireless networks, with enterprise WLAN and service provider mesh (and possibly WiMAX) networks converging to deliver more personalized wireless services beyond high speed access; Wi-Fi is ubiquitous in enterprise and public venues in developed markets; growth continues in developing markets.

Some market figures can be pointed out: worldwide WLAN equipment revenue hit $1.9B in CY07, up 20% from CY06; revenue will grow 28% to $2.2M in CY08. Worldwide revenue in CY11 is forecasted to hit $3.4B; WLAN continues to penetrate further into the enterprise and service provider markets, with enhanced product features, new wireless applications (including VoIP/video) and higher speed infrastructure (802.11n) driving growth in all product categories and all regions during our forecast period. (Source: Infonetics)

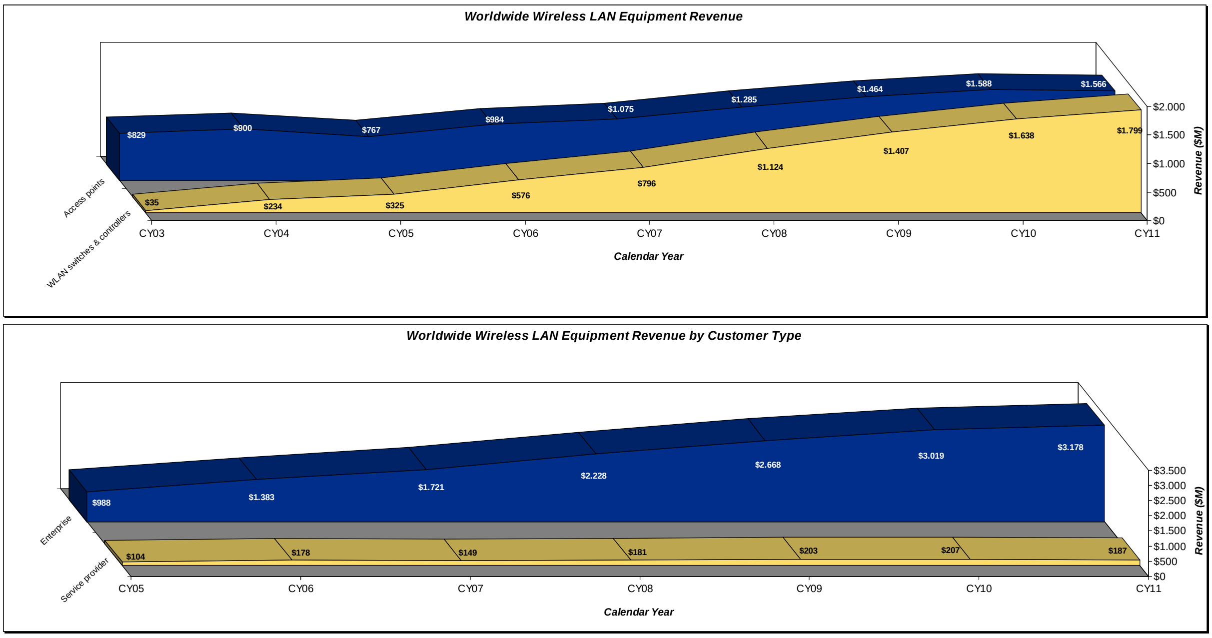


Figure 3-15: Predictions for WLAN equipment revenues

4 Conclusion

This document provides an overview of the radio technologies that could be used for OMEGA home networks, and that will be investigated in the framework of the project. The status of these technologies regarding regulation, standardization and perspectives of evolution has been described. The application scenarios and use cases from WP1 have also been analyzed, in order to derive guidelines and requirements to focus the investigations on the project's main objectives. This will serve as a basis for the studies, as these three types of technologies will be compared and assessed regarding their suitability to fulfil OMEGA needs.

5 References

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6 **Annex:** IEEE 802.15.3c MCS parameters

The SC mode, HSI OFDM mode and AV OFDM mode data rate dependent parameters are listed in Table 6-1 and Table 6-2. Highlighted cells correspond to mandatory modes:

- SC mode: Low Rate 1: Common Rate (CR) and Mandatory Low Rate (MLR)
- HSI OFDM mode: index 0,
- AV OFDM mode: HRP indexes 0 and 1.

Table 6-1: IEEE 802.15.3c SC MCS parameters

MCS class	MCS ID	Data Rate (Mbps)	Modulation Scheme	FEC Type	FEC rate
SC1	LR1	50.6	π/2-BPSK / (G)MSK	RS(255,239)	0.937
		379.6			
		759.2			
		1518.4			
	LR2	607.5	π/2-BPSK / (G)MSK	LDPC(576,432)	0.75
		1215			
	LR3	810	π/2-BPSK / (G)MSK	LDPC(576,288)	0.5
SC2	MR1	1620	π/2-QPSK	LDPC(576,288)	0.5
	MR2	2430	π/2-QPSK	LDPC(576,432)	0.75
	MR3	2835	π/2-QPSK	LDPC(576,504)	0.875
	MR4	3024	π/2-QPSK	LDPC(1440,1344)	0.933
	MR5	3036.7	π/2-QPSK	RS(255,239)	0.937
SC3	HR1	4555.1	π/2-star 8 QAM	RS(255,239)	0.937
	HR2	6073.4	π/2-16QAM	RS(255,239)	0.937
SC4	OOK1	759.2	OOK	RS(255,239)	0.937
		1518.4			
	OOK2	3036	Dual Rail Bipolar	RS(255,239)	0.937

Table 6-2: IEEE 802.15.3c OFDM MCS parameters

MCS Class	MCS ID	Data Rate (Mbps)	Modulation Scheme	Coding mode	Inner FEC rate MSB 8b	Inner FEC rate LSB 8b	Outer FEC rate
HSI	0	59	QPSK	EEP	1/2		0.94
	1	708	QPSK		1/2		0.94
	2	1416	QPSK		1/2		0.94
	3	2124	QPSK		3/4		0.94
	4	2478	QPSK		7/8		0.94
	5	2832	16-QAM		1/2		0.94
	6	4248	16-QAM		3/4		0.94
	7	4956	16-QAM		7/8		0.94
	8	6372	64-QAM		3/4		0.94

	9	1512	QPSK	EEP	1/2		1
	10	2664	QPSK		7/8		1
	11	4536	16-QAM		3/4		1
	12	1770	QPSK	UEP	1/2	3/4	0.94
	13	2301	QPSK		3/4	1/2	0.94
	14	3540	16-QAM		1/2	3/4	0.94
	15	4602	16-QAM		3/4	7/8	0.94
AV	HRP 0	950	QPSK	EEP	1/3		0.96
	HRP 1	1900	QPSK		2/3		0.96
	HRP 2	3810	16-QAM		2/3		0.96
	HRP 3	1900	QPSK	UEP	4/7	4/5	0.96
	HRP 4	3810	16-QAM		4/7	4/5	0.96
	HRP 5	950	QPSK	MSB only retransmission	1/3	-	0.96
	HRP 6	1900	QPSK		1/3	-	0.96
	LRP 0	2.5*8	BPSK	-	1/3		-
	LRP 1	3.8*8			1/2		-
	LRP 2	5.1*8			2/3		-
	LRP 3	10.2*4			2/3		-