



Integrated Project - EUWB

Contract No 215669

Deliverable

D7.1.3

Combined LDR-LT/HDR platform requirements, feasibility analysis and specification

Contractual date:	M18
Actual date:	M19
Authors:	Lorena de Celis (ACO), Dirk Burggraf (GWT), Shangbo Wang (UDE), Christian Kocks (UDE), Alexander Viessmann (UDE), Mohammed Al-Olofi (UDE), Amir Krause(WIS)
Participants:	ACO, GWT, UDE, WIS
Work package:	WP7
Security:	PU
Nature:	Report
Version:	1.0
Total number of pages:	48

Abstract

This document proposes a combined LDR-LT/HDR structure and the cooperation possibilities between the two systems. A possible structure that utilizes the LDR physical layer to transmit and receive the HDR signaling information for an improved system performance and less power consumption is investigated.

Keywords

HDR/LDR combination, Adaption Layer, power consumption, UWB

Table of Contents

1 Executive summary	10
2 Introduction	11
3 Description of LDR-LT Platform	13
3.1 Application Areas	13
3.2 Analysis of Energy Efficiency	15
4 Description of HDR Platform	19
4.1 General Description	19
4.1.1 Introduction	19
4.1.2 HDR Design considerations for a combined platform	20
4.1.2.1 Frequency Band: Supported frequencies, Time frequency Codes (TFC) and Mask ..	20
4.1.2.2 Impact	22
4.1.2.3 MAC supported timing	22
4.1.3 IOGear	25
4.2 Application Areas	25
4.2.1 IOGear	25
4.3 Analysis of Energy Efficiency	27
4.3.1 General Considerations	27
4.3.2 IOGear	28
5 Combined LDR-LT and HDR Platform	29
5.1 Introduction	29
5.2 Application Areas and Requirements	29
5.3 Feasibility Analysis	30
5.3.1 Introduction	30
5.3.2 HDR/LDR Adaption Layer	31
5.4 Adaption layer internal protocol	31
5.4.1 Introduction	31
5.4.2 Adaption layer state machine	33
5.4.3 Performance Analysis	33
5.5 Power saving by combining HDR/LDR TRX	45
6 Conclusions	46
7 References	47
8 Acknowledgement	48

Page intentionally left blank

List of Figures

Figure 2.1: The Possible HDR/LDR combinations	11
Figure 3.1: Location and tracking scenario	14
Figure 3.2: Die photo and performance summary of digital baseband processor [4].....	17
Figure 3.3: Breakdown of energy per bit consumed by the digital baseband processor [4].....	17
Figure 3.4: Receiver energy/bit values versus data rate for UWB and narrow-band receivers [4]......	18
Figure 4.1: The HDR TRX structure.....	19
Figure 4.2: WiMedia Frequency bands plan	20
Figure 4.3: UWB Transmitted signal shape	22
Figure 4.4: WiMedia MAC reservations.....	24
Figure 4.5: Dongle from IOGear using USB as host controller interface	25
Figure 4.6: Layer model of IOGear platform (green indicates support by platform).....	26
Figure 4.7: Comparison of PAL multiplex architectures	26
Figure 4.8: Average Power vs. Data Rates.....	27
Figure 5.1: Concept of HDR/LDR Combined TRX.....	29
Figure 5.2: Application scenario for a combined HDR/LDR device	30
Figure 5.3: Home intranet scenario using a combined HDR/LDR device	30
Figure 5.4: Combined HDR/LDR with adaptation layer.....	31
Figure 5.5: Adaption layer protocol	32
Figure 5.6: P_{block} as a function of distance and data rata in AWGN environment.....	35
Figure 5.7: P_{block} as a function of distance and data rata in CM1 environment.....	35
Figure 5.8: P_{block} as a function of distance and data rata in CM2 environment.....	36
Figure 5.9: P_{block} as a function of distance and data rata in CM3 environment.....	36
Figure 5.10: P_{block} as a function of distance and data rata in CM4 environment.....	37
Figure 5.11: Throughput as a function of distance and data rata in AWGN environment.....	38
Figure 5.12: Throughput as a function of distance and data rata in CM1 environment.....	38
Figure 5.13: Throughput as a function of distance and data rata in CM2 environment.....	39
Figure 5.14: Throughput as a function of distance and data rata in CM3 environment.....	39
Figure 5.15: Throughput as a function of distance and data rata in CM4 environment.....	40
Figure 5.16: Block error rate vs E_s/N_0 in AWGN Channel.....	40
Figure 5.17: LDR Block error rate as a function of distance in AWGN channel with Tx power of -30 dBm	41

Figure 5.18: LDR Throughput as a function of distance in AWGN channel with Tx power of -30 dBm	42
Figure 5.19: LDR Block error rate as a function of distance in AWGN channel with Tx power of -42 dBm	43
Figure 5.20: LDR Throughput as a function of distance in AWGN channel with Tx power of -42 dBm	43
Figure 5.21: LDR block error rate in IEEE UWB channel	44
Figure 5.22: LDR block error rate in IEEE channel with Tx power -42 dBm	44
Figure 5.23: LDR throughput as function of distance in IEEE channel with Tx power -42 dBm	45

List of Tables

Table 3.1: LDR platform sensing capabilities.....	13
Table 3.2: Essential functionalities of the LDR platform.....	15
Table 3.3: Measured power consumption figures for the different parts of the TCR chip integrated on V1 validation platforms.	16
Table 3.4: Power consumption in the different parts of the MAC	16
Table 4.1: WiMedia Band Plan	20
Table 4.2: WiMedia TFC	21
Table 4.3: Power consumption numbers for a multiband OFDM system	27
Table 5.1: Combination HDR/LDR operation states	33
Table 5.2 Transceiver distance at which block error rate equals 10^{-1} in AWGN scenarios.	34

Abbreviations

AWGN	Additive White Gaussian Noise
DBPSK	Differential Binary Phase Shift Keying
BP	Beacon Period
BPST	Beacon Period Start
BT	Bluetooth
BW	Bandwidth
CMOS	Complementary Metal Oxide Semiconductor
CTI	Chekmate2 Test Interface
DAA	Detect And Avoid
DCM	Dual Carrier Modulation
DEMUX	Demultiplexer
EUWB	Coexisting Short Range Radio by Advanced Ultra-WideBand Radio Technology
FFC	Fixed Frequency Code
FFI	Fixed Frequency Interleaving
FFT	Fast Fourier Transform
FPGA	Field Programmable Gate Array
GPS	Global Positioning System
HDR	High Data Rate (50Mbps to 480Mbps PHY bit rate)
HW	Hardware
IO	Input/Output
IP	Internet Protocol
LDR	Low Data Rate
LED	Light Emitting Diode
LT	Location/Tracking
LOS	Line Of Sight
MAC	Medium Access Controller
MAS	Medium Access Slot
MBOFDM	Multi-Band OFDM
OFDM	Orthogonal frequency division multiplexing
PAL	Protocol Abstraction Layer
PHY	Physical layer

PIR	Passive Infra-Red
PLB	Processor Local Bus
PLCP	Physical Layer Convergence Protocol
PPC	Power PC
PPM	Pulse Position Modulation
QOS	Quality Of Service
QPSK	Quadrature phase shift keying
RF	Radio Frequency
SNR	Signal To Noise Ratio
TFC	Time Frequency Codes
TFI	Time Frequency Interleaving
TPC	Transmit Power Control
TRX	Transmitter/Receiver
TX	Transmitter
UMAC	Upper MAC Software component
USB	Universal Serial Bus
UWB	Ultra-Wideband
WSN	Wireless Sensor Network
WUSB	Wireless USB

1 Executive summary

In this document, an architecture of a combined HDR/LDR device is proposed and a feasibility analysis is carried out. After a brief introduction of the HDR and LDR UWB systems, potential applications of a combined platform are indentified and requirements on the platform are defined. The document is organized as follows.

Chapter 2 introduces in possible LDR/HDR combination strategies and identifies important scenarios.

Chapters 3 and 4 give a brief introduction on the LDR-LT and HDR platforms, which is needed for the combination feasibility studies carried out in what follows. In this context, the energy which is consumed during the modulation process per bit is emphasized.

Chapter 5 presents the concept for a combined HDR/LDR transceiver architecture. For feasibility reasons, the coverage of both systems are simulated and compared. The quality of service constraints used for this simulation are block error ratios and throughput. The adaption layer, which is necessary for the combination, is introduced and its protocols are described.

Chapter 6 concludes this deliverable.

2 Introduction

The HDR and LDR ultra wideband systems operation principles have offered a wide range of applications. For HDR systems, a stable high data throughput is an essential prerequisite to support applications like multimedia and web services. In fact, HDR-UWB systems suffer from the fact that they show high power consumption, especially when compared to LDR-UWB systems. However in LDR the power consumption and size are important issues in the system performance, since LDR applications such as sensors and home, office and medical automation do not mainly depend on high data rate. While in pulse based data transmission the power consumption scales with the throughput which is needed, the power consumption of an HDR-UWB system cannot be significantly reduced by reducing that data payload. A combined HDR/LDR system can combine advantages of both systems.

To take advantage of LDR power consumption in combined HDR/LDR, the traffic can be separated into data and signalling traffic.

It is suggested to transmit the data traffic via HDR Physical layer and signalling information over the LDR system. However, the combined HDR/LDR in Figure 2.1 can also be used as cooperative system or as either HDR or LDR system. The four system operation states showed in Figure 2.1 are:

1. LDR-UWB system
2. HDR-UWB system
3. HDR/LDR system (the two interface not working simultaneously)
4. HDR/LDR system (the two interface working simultaneously)

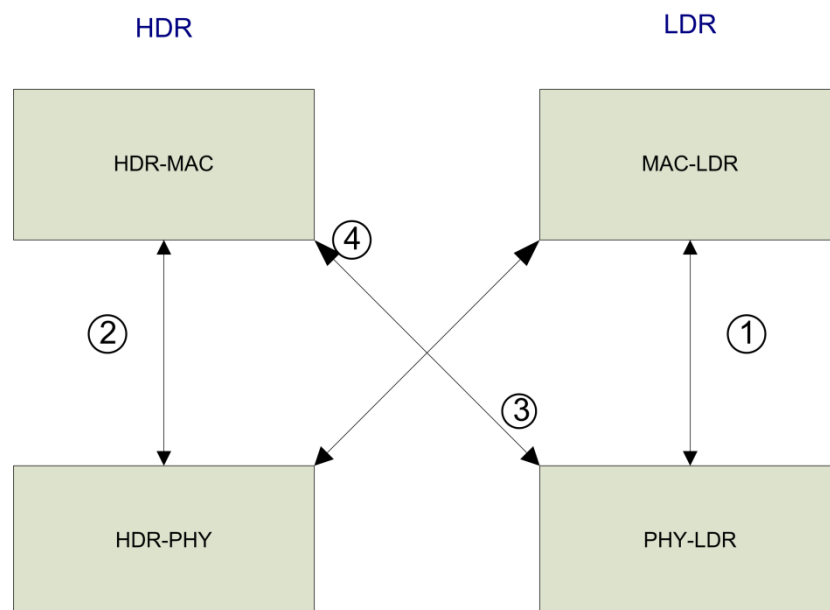


Figure 2.1: The Possible HDR/LDR combinations

This manuscript gives an overview on HDR and LDR transceivers (TRXs) and their MAC layer frame structures, which are needed for the clear presentation of the combination protocol. The power consumption for HDR and LDR systems is investigated. In addition, an adaption layer is proposed, which organizes the cooperation between the two systems by following newly developed protocols. Finally, the system performance of the combined system is discussed.

3 Description of LDR-LT Platform

3.1 Application Areas

LDR platform is formed by nodes with different radio, location, and sensing capabilities. The major application area of LDR platform is location and tracking, but also depending on the different sensing capabilities, this platform can be used in different areas.

Concerning Wireless Sensor Networks (WSN) capabilities, it can be distinguished different functionalities taking account the sensors and actuators embedded:

- Sensors
 - Can measure one or several environmental parameters. Can relay environmental measurements to a collecting point in the network. The sensors included in every board, are
 - 3D accelerometer
 - 3D magnetometer
 - thermometer
 - Passive Infra-Red (PIR) movement detector
- Actuators
 - Can react to an injunction delivered by a central or neighbouring entity by modifying its own status or setting off a particular action. Two types of actuators have been included in every board:
 - four high-power LED
 - buzzer

Following table summarizes the main sensing capabilities that can offer the LDR platform:

Table 3.1: LDR platform sensing capabilities

LDR platform sensing capabilities	
SENSORS	
3D accelerometer	To measure the acceleration. Multi-axis models are available to detect magnitude and direction of the acceleration as a vector.
3D magnetometer	To measure the strength and/or direction of the magnetic field in the vicinity of the sensors. They are most often paired up with accelerometers in drilling tools so that both the inclination and azimuth of the drill bit can be found.
Thermometer	Measure the temperature
Passive Infra-Red (PIR)	To measure infrared (IR) light radiating from objects in

movement detector	its field of view. Apparent motion is detected when an infrared source with one temperature, such as a human, passes in front of an infrared source with another temperature, such as a wall.
ACTUATORS	
High Power LEDs	Electronic light source. Can be used as a light alarm
Buzzers	Audio actuator (piezoelectric buzzer); the sound frequency and duration are fully software defined.

As it has been commented previously, the major area of application of this platform is based on its radio functionalities and their ranging capabilities. From the LT, location and tracking perspective, the basic scenario is depicting in Figure 3.1:

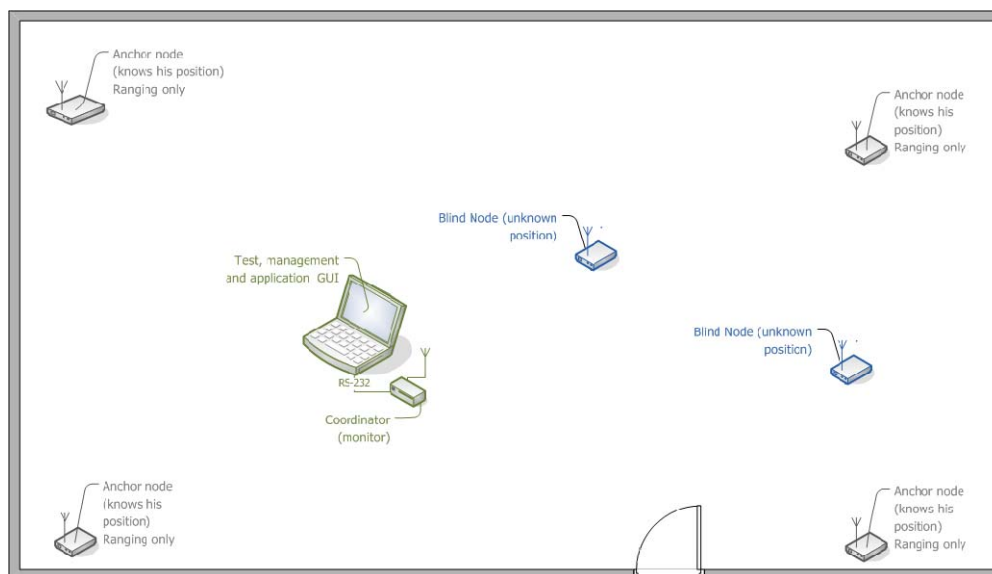


Figure 3.1: Location and tracking scenario

As it is shown in Figure 3.1, it can be made the distinction between the different location devices, the anchor nodes and blind/mobile nodes:

- Anchor node
 - Has fixed known position set by hand (No Global Positioning System (GPS), no synchronization backbone)
 - Can request or reply to ranging frames (implements proper ranging primitives)
 - Can calculate the range with respect to a blind node
 - Can send its own range measurements to a central point for further processing (i.e. positioning/tracking)
- Blind/Mobile node
 - Has unknown position to be estimated and/or tracked
 - Can request or reply to ranging frames (implements proper ranging primitives)
 - Can calculate the range with respect to a blind node or an anchor node

- Can send its own range measurements to a central point for further processing or update its own position estimate based on range measurements in the distributed positioning approach (with proper application capabilities for positioning)

The main aim of the applications addressed for this scenario is the location of people or equipment (low mobility: < 2 m/s), with the possibility of sending and receiving data (<100 kbps). This kind of scenario is featured by a reduced number of nodes, located in an indoor environment with some rooms/halls/desks and so with medium range requirements (<20 m). A trade-off between the location accuracy (~0.5 m) and the data rate is required.

The essential functionalities which are offered by the LDR platform are summarized in Table 3.2:

Table 3.2: Essential functionalities of the LDR platform

Location and Tracking applications	Radio and network management	Sensor/actuator-oriented applications
Peer-to-peer or broadcasted ranging (including Blind-to-Anchor ranging and Blind-to-Blind ranging)	Peer-to-peer communications	Relay of heterogeneous data flows
Distributed positioning	Association and disassociation	Relay of critical alarms or instructions
Centralized positioning	PicoNet (PN) synchronization	Environment monitoring and context awareness
	Beacon relaying	
	Mesh networking	
	Network discovery	
	Optimal routing	
	Topology control	

3.2 Analysis of Energy Efficiency

The LDR-UWB system is very suitable for low data rate applications like sensors networks due to its low power consumption. This fact is referred to the nature of device operation where the devices have less data to exchange and need to transmit more than they receive.

Also for the RF part, the employment of modulation schemes such as DBPSK and PPM leads to a power efficient data transmission. In this section, an investigation on the power consumption of LDR-UWB transceivers is presented.

The LDR-UWB PHY implemented on TCR chip has two operating mode Stand-Alone and Baseband active. Table 3.3 summarises the power consumption in the different parts of the PHY.

Table 3.3: Measured power consumption figures for the different parts of the TCR chip integrated on V1 validation platforms.

Operating Mode	Digital	Tx	Rx	I/O
Stand-Alone	10 mW	400 μ W	8 mW	11 mW
Baseband active	35 mW	400 μ W	8 mW	2 mW

In stand-alone mode, the chip provides the sampled signal to an external FPGA for example. Since the data flow is quite high (1 Gsample per second), the resulting digital and I/Os power consumption is high as well. In baseband mode, I/Os activity is significantly lowered, and the resulting power consumption is reduced accordingly. It can be observed that for the chosen modulation parameters, the active power consumption is 20 times lower than the Rx one.

For MAC part, Table 3.4 summarises the figures available so far as regards to power consumption in the different parts of the MAC.

Table 3.4: Power consumption in the different parts of the MAC

	PPC @ 100 MHz PLB @ 100 MHz HMAC @ 50 MHz	PPC @ 50 MHz PLB @ 50MHz HMAC @ 25 MHz
Static (FPGA empty)	42 mW	42 mW
Static (FPGA design loaded)	152 mW	164 mW
Dynamic (PPC + peripherals)	127 mW	60 mW
Dynamic (HMAC)	33 mW	15 mW

The MAC is implemented inside an FPGA and the power results are measured from platform power consumption dedicated to the MAC. As it can be observed, figures for the MAC coprocessor are quite in line with the ones for the digital part of the PHY. If ASIC integration is envisioned, it can be expected that the resulting figures are even lower. Also as a result of using an FPGA, the static power consumption is high. In order to reduce the overall power consumption of the platform, it is envisioned to switch to an external processor

Another investigation for power consumption which is relevant for the work presented in this chapter is presented in [4]. The baseband processor is implemented in a standard-VT 90-nm CMOS process and demonstrates 100-Mb/s operation at 0.4 V with an operating frequency of 25 MHz. A die photo and the performance metrics summary are shown in Figure 3.2. Note that only 23% of the die area is active as the design was pad-limited [4].

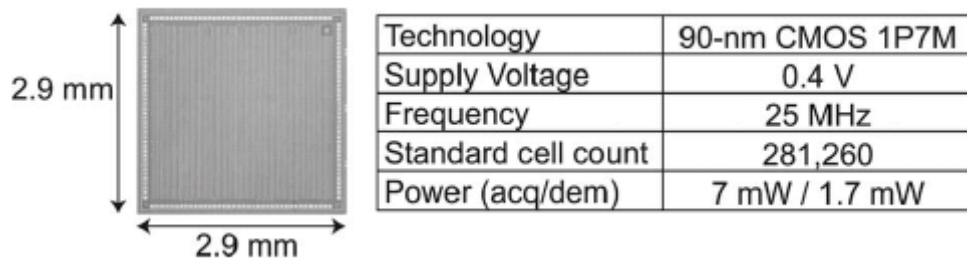


Figure 3.2: Die photo and performance summary of digital baseband processor [4].

The breakdown of the energy per bit consumed by the digital baseband processor is shown in Figure 3.3. The average energy overhead consumed during acquisition is fixed for a packet [4]. Thus, the shorter the payload, the greater the overhead energy per bit as the overhead energy is amortized over fewer bits [4]. For a 4-kbit packet, using the measured power for acquisition and demodulation provided in Figure 3.3, the average energy per bit consumed by the digital baseband processor is 20 pJ, with 3 pJ for acquisition and 17 pJ for demodulation [4].

Figure 3.4 shows receiver energy/bit as well as the energy/bit of the receiver presented in [4]. The energy per bit for this paper was calculated as the sum of the receiver energy/bit plus the leakage power component, which causes the energy/bit to rise at lower data rates. For data rates below 100 kb/s, our work on low-rate UWB systems targets energy efficiency that is orders of magnitude better than historical low-rate narrow-band systems.

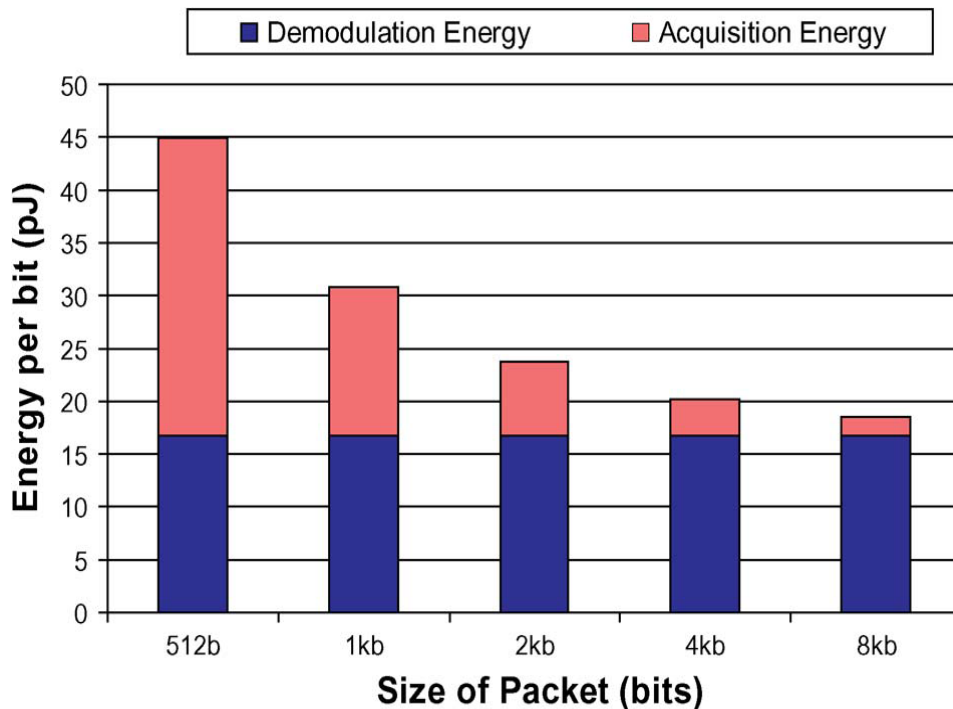


Figure 3.3: Breakdown of energy per bit consumed by the digital baseband processor [4].

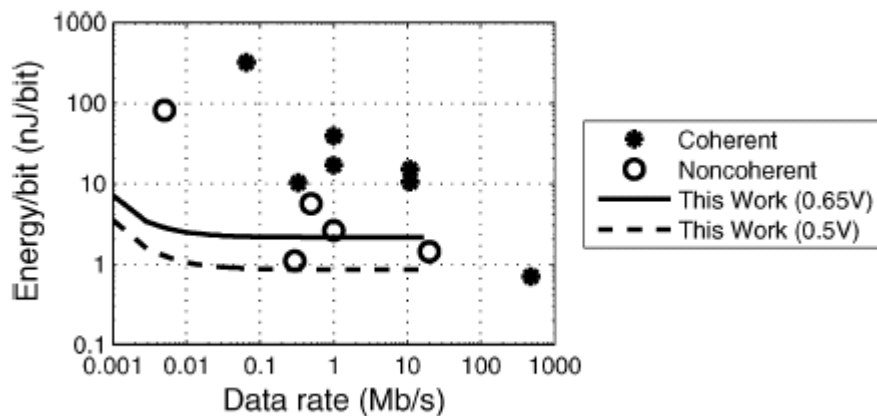


Figure 3.4: Receiver energy/bit values versus data rate for UWB and narrow-band receivers [4].

4 Description of HDR Platform

4.1 General Description

4.1.1 Introduction

The HDR-UWB TRX in Figure 2.1 consists of an HDR-MAC and HDR-PHY connected to the receiver side over an antenna interface. The system uses the 3100 – 10600 MHz frequency band to transmit and receive UWB signals, supporting data rates of 53.3 Mb/s, 80 Mb/s, 106.7 Mb/s, 160 Mb/s, 200 Mb/s, 320 Mb/s, 400 Mb/s and 480 Mb/s.

The UWB spectrum is divided into 14 bands with a bandwidth of 528 MHz each. The HDR-UWB utilizes a Multi-Band Orthogonal Frequency Division Modulation (MBOFDM) scheme to transmit information. A total of 110 sub-carriers (100 data carriers and 10 guard carriers) are used per band to transmit the information. In addition, 12 pilot subcarriers can be used for various estimation schemes. Frequency-domain spreading, time-domain spreading, and forward error correction (FEC) coding are used to vary the data rates. The FEC used is a convolutional code with coding rates of 1/3, 1/2, 5/8 and 3/4 and then coded data is spread using a time-frequency code (TFC). A PHY packet contains a PLCP preamble, PLCP Header (PHY header, MAC header and its channel encoding components), and PSDU, i.e. the payload plus its channel encoding and pad bits [1].

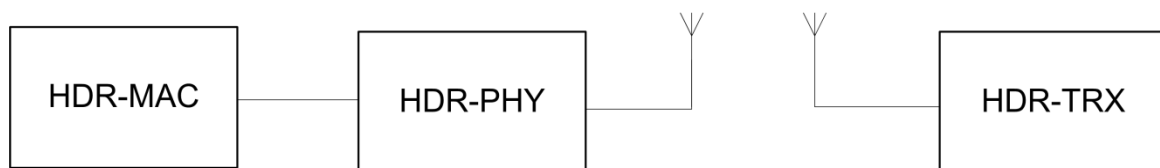


Figure 4.1: The HDR TRX structure

On the other hand, the HDR-MAC provides medium resource control which upper layers can efficiently and effectively communicate with their counterparts in other devices. It makes sure the users of the medium do not interfere with each other even if they are using different applications. It also allows dynamic control of the communications parameters in order to address the varying wireless channel conditioning that can cause data packet corruption or loss [2].

4.1.2 HDR Design considerations for a combined platform

This section is intended as a short summary of the main features of an HDR platform, relevant to a combined platform and does not replace the HDR standards and system specification. The selection criterion for the features in this section is the impact on the combined platform which is described in each section. Thus, features related to Frequency Planning and Timing are described, while other features are not.

4.1.2.1 Frequency Band: Supported frequencies, Time frequency Codes (TFC) and Mask

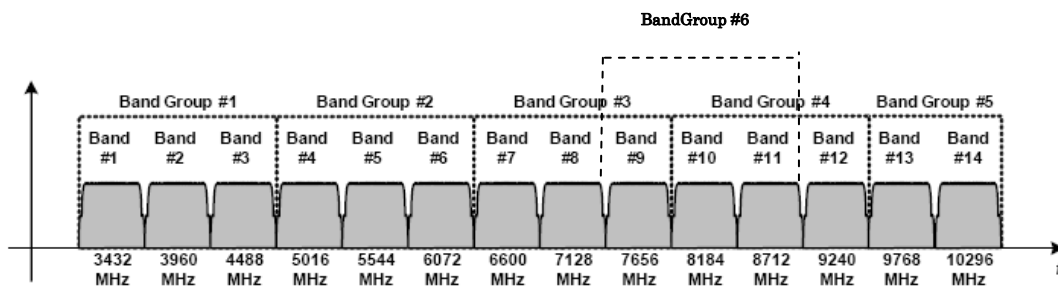


Figure 4.2: WiMedia Frequency bands plan

The WiMedia frequency plan is constructed of five (5) orthogonal Band-Group (BG) definitions and one additional overlapping band group (#6). Most Band-Groups are composed of three (3) separate bands except for BG #5 which has only two (2) bands. Figure 4.2 and Table 4.3 give explicit description of the WiMedia Frequency plan including Band-Width and center frequencies.

Not all bands are allowed for usage by the World Wide regulatory bodies. Particular attention has been given to BG #1 which may only be utilized in Europe for a limited time, except for utilizing Band #3 with Detect and Avoid (DAA). Further, most manufacturers and regulators seem to agree not to utilize BG #2 due to high density of wireless services in that spectral band.

Table 4.1: WiMedia Band Plan

Band Group	BAND_ID	Lower Frequency (MHz)	Center Frequency (MHz)	Upper Frequency (MHz)
1	1	3168	3432	3696
	2	3696	3960	4224
	3	4224	4488	4752
2	4	4752	5016	5280
	5	5280	5544	5808
	6	5808	6072	6336

3	7	6336	6600	6864
	8	6864	7128	7392
	9	7392	7656	7920
4	10	7920	8184	8448
	11	8448	8712	8976
	12	8976	9240	9504
5	13	9504	9768	10032
	14	10032	10296	10560
6	9	7392	7656	7920
	10	7920	8184	8448
	11	8448	8712	8976

Several TFCs are defined by the WiMedia standard, as described in Table 4.2.

Table 4.2: WiMedia TFC

TFC	Num of Bands used	Max relative Power	Orthogonal in group	Comments
1,2	3	+5dB	No	
3,4	3	+5dB	No	Not recommended for usage
5,6,7	1	0dB	Yes	Also called FFC (Fixed Frequency Code)
8,9,10	2	+3dB	No	Each is orthogonal to one FFC.

Actual UWB receivers attenuate the signal at the edge of each band, to reduce the interference from neighboring bands and improve the SNR. The ECMA 368 standard defines 2.5 Null tones $\approx 10.3\text{MHz}$ at the edge of each band. Then 5 Guard tones $\approx 20.6\text{MHz}$, with repeated information, are defined near the edge, a designer may decide to receive these latter tones attenuated or not decode them at all, to reduce the RF filters quality requirements (filter slope), since utilizing only the NULL tones yields a very difficult high order filter. Figure 4.3 provides some clarification, showing the transmit power mask of such a signal, note the filtering may start at lower frequencies than 285MHz. While the ECMA 368 UWB devices are extremely frequency agile, this agility is limited to operation in the central frequencies of the specified bands. These central frequencies are related to the BW (multiples by integer plus half) and may be derived from the same clock. Therefore the frequency agility can not solve the problem of sensing a signal in the attenuated band edges. Thus, a UWB receiver is likely to only partially cover the $\sim 31\text{MHz}$ at the edge of each band; the coverage level would depend on the exact implementation.

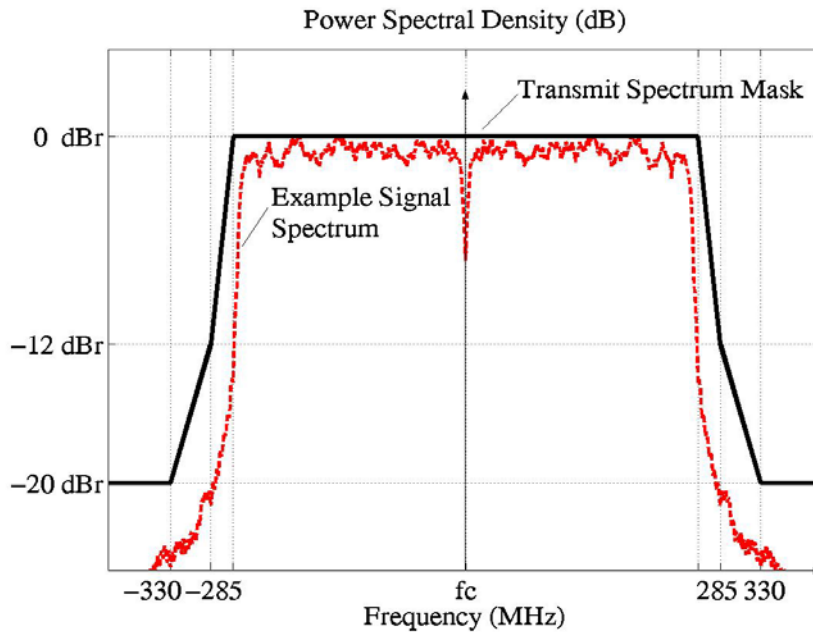


Figure 4.3: UWB Transmitted signal shape

The ECMA 368 standard required the devices to be change bands at approximately 3MHz, such changes when performed in the same TFI channel, are even required to maintain frequency tracking within each band. But, this frequency agility, is limited to operation in the same Band-group, changing a Band-Group may take unspecified duration which may be significantly longer even to the point at which it affects the TDMA scheduling (see below). Note these features define the RF circuitry of the UWB devices. An area which is relatively complex and demanding based on the current ECMA 368 requirements.

4.1.2.2 *Impact*

The combined platform should either attempt to select frequencies in a manner avoiding in-band interference to either LDR or HDR or use some time domain separation.

The planning of the combined platform, should take into account both the mask described above, and all the other non-desirable radiation created by the devices should be considered, including spurs and wide-band phase noise. Since most HDR systems only support the lowest Band-group, and the non-desirable radiation normally requires specific expensive means to prevent interference – the time domain solution appears preferable.

4.1.2.3 *MAC supported timing*

The ECMA standard defines a fixed periodic duration, caller superframe, of approximately 65.5mSec (256 MASs), for its operation. At the start of each superframe, devices in the relevant channel must transmit a beacon notifying other devices of their existence and reservations. Within each superframe, the ECMA protocol defines a means for time reservations. Time is allotted in quanta of 256 μ Sec, called MAS (Medium Access Slot). The standard allows each device to reserve MASs for itself to

communicate on. The reservation is only allowed if those MASs are not occupied by neighboring devices. If multiple devices wish to reserve MASs, the reservations must follow a set of complex set of restrictions, the whole of which is out of scope, but one point should be mentioned – a device may not reserve more than 122MASs if other devices wish to communicate too.

A devices group, such as a WUSB cluster or a link (two devices), is expected to have only one MAS reservation set, done by the host/initiating UWB device. During that reservation, the devices belonging to that group may communicate in any manner the internal group protocol allows (Current existing protocols are the ECMA itself and the WUSB, BT is expected to announce another protocol soon). Some specific protocols also allows devices to transmit in non-reserved times thus the network can not promise silent periods for sensing.

MASs are reserved in either lines or columns. The Figure 4.4 shows a typical MAS allocation table in a superframe. The numbering of the MASs is sequential, the MAS at the top left is the first MAS in a superframe, the MASs then progress down, and at the end of each column (~4mSec), continue at the top of the column to its right. Line reservations should start from the bottom line, and continue up (see MASs 12-15,28-31,...252-255 in Figure 4.4). A L lines reservation provides L MASs out of every 16 MASs in a column and is suited for services wishing to limit the delay spread while operating in a short periodic manner. Column reservations start from the top. A column reservation of C columns would provide C columns either once or several times but not in each column(see MASs 16-20,144--148 in Figure 4.4) . Column reservations are best suited for applications requiring few long reservation, well separated.

The Beacons (see MASs 0-3 in Figure 4.4)have priority over the reservations. The beacons location starts at the first MAS and continues until all the beacons have sufficient time (including time for new additional devices). The beacon period may overlap over a line reservation.

0	16	32	48	64	80	96	112	128	144	160	176	192	208	224	240
1	17	33	49	65	81	97	113	129	145	161	177	193	209	225	241
2	18	34	50	66	82	98	114	130	146	162	178	194	210	226	242
3	19	35	51	67	83	99	115	131	147	163	179	195	211	227	243
4	20	36	52	68	84	100	116	132	148	164	180	196	212	228	244
5	21	37	53	69	85	101	117	133	149	165	181	197	213	229	245
6	22	38	54	70	86	102	118	134	150	166	182	198	214	230	246
7	23	39	55	71	87	103	119	135	151	167	183	199	215	231	247
8	24	40	56	72	88	104	120	136	152	168	184	200	216	232	248
9	25	41	57	73	89	105	121	137	153	169	185	201	217	233	249
10	26	42	58	74	90	106	122	138	154	170	186	202	218	234	250
11	27	43	59	75	91	107	123	139	155	171	187	203	219	235	251
12	28	44	60	76	92	108	124	140	156	172	188	204	220	236	252

13	29	45	61	77	93	109	125	141	157	173	189	205	221	237	253
14	30	46	62	78	94	110	126	142	158	174	190	206	222	238	254
15	31	47	63	79	95	111	127	143	159	175	191	207	223	239	255

Figure 4.4: WiMedia MAC reservations

A super frame may drift in time. Since multiple devices co-operate in a super frame, and their clocks are allowed to drift up to ± 20 ppm. The standard has provided a stepped mechanism for the devices to adjust their clocks and synchronize the super frame accordance to the clock of the slowest device participating in the super frame. As a result, from the perspective of most of the devices, a super frame is expected to drift.

Devices are required not to interrupt with the beacon period, even if two piconets are merging, each device group is expected to reserve the time of the other groups beacons until the merger is completed. However, since this is a wireless MAC. A device is required to operate correctly and respect the reservation of another device, even if it only correctly receives one of every four(4) beacons of that device.

Note that trying to co-exist in a combined platform on a scale smaller than a MAS is extremely problematic. The standard allows for multiple ACK policies, each best suited to a different service type. The quick turn-over from transmit to receive for these ACKs would make it impractical to coordinate LDR and HDR devices transmission and reception.

Impacts –

1. Period – ECMA368 UWB would be best combined to coexist with LDR, if the LDR could be allocated a time period in a manner consistent with the above MAC definitions, and in the same period.
2. Beacons – The Beacon period of the ECMA368 (HDR UWB) should be protected for it to co-exist in a combined platform with other services. At worst, at least one out of every four (4) beacons packets must be received for devices in a piconet to continue operation normally.

4.1.3 IOGear

The IOGear-platform is an assembly of the IOGear dongle (see Figure 4.5), which includes the MAC/PHY layers according to ECMA 368, and common personal computer working as the host. The connection between them is done by USB.



Figure 4.5: Dongle from IOGear using USB as host controller interface

The dongle consists of the following main hardware components:

MAC-Chip (Intel SL9N3): It is an Intel Wireless UWB Link 1480. The circuit supports the standard ECMA 368 with the specific MAC-PHY interface.

Baseband-Chip (Alereon AL4200): This chip from the manufacturer Alereon includes the base band processing.

RF-Transceiver (Alereon AL4100): It is the analog PHY frontend chip, also from Alereon, for the radio frequency parts like filters and mixers.

Antenna (TDK Ant1085): UWB antenna from manufacturer TDK, which supports 3.1 to 5.2 GHz

The overall support of the dongle's frequency range is limited to Band Group 1.

4.2 Application Areas

4.2.1 IOGear

The analysis of the IOGEAR dongle solution had shown the ability to transfer 120 MBit/s in a 3 device network scenario. The supported range of this platform is up to 10 m within an LOS channel. The host interface between MAC and PAL/network layer respectively is built via a USB connection. Figure 4.6 gives a coarse overview about the supported layer model.

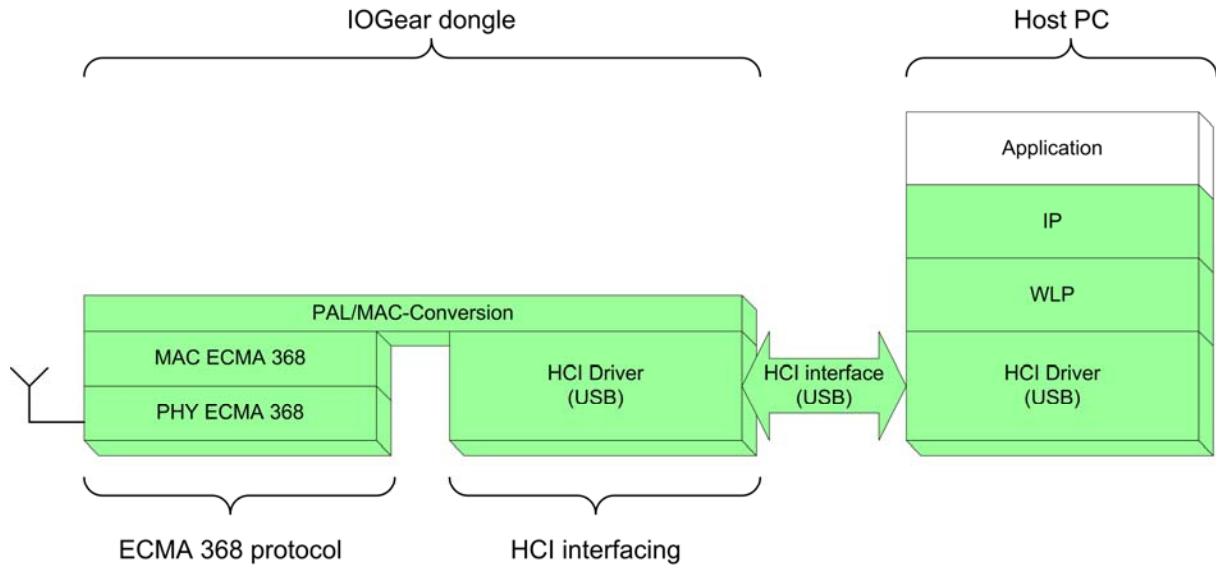


Figure 4.6: Layer model of IOGear platform (green indicates support by platform)

In the investigated assembly a proprietary implementation of WLP is used as the PAL layer, which links the MAC to the common IP network layer via the host controller interface. The implementation bases on the draft specification WLP 0.99. Note, that there is currently no multiplex support, hence the ECMA 368 MAC resource can only be used by one network layer instance and so consequently the network interface can only use the dedicated host controller interface. A comparison to a conceivable multiplex support is illustrated in Figure 4.7.

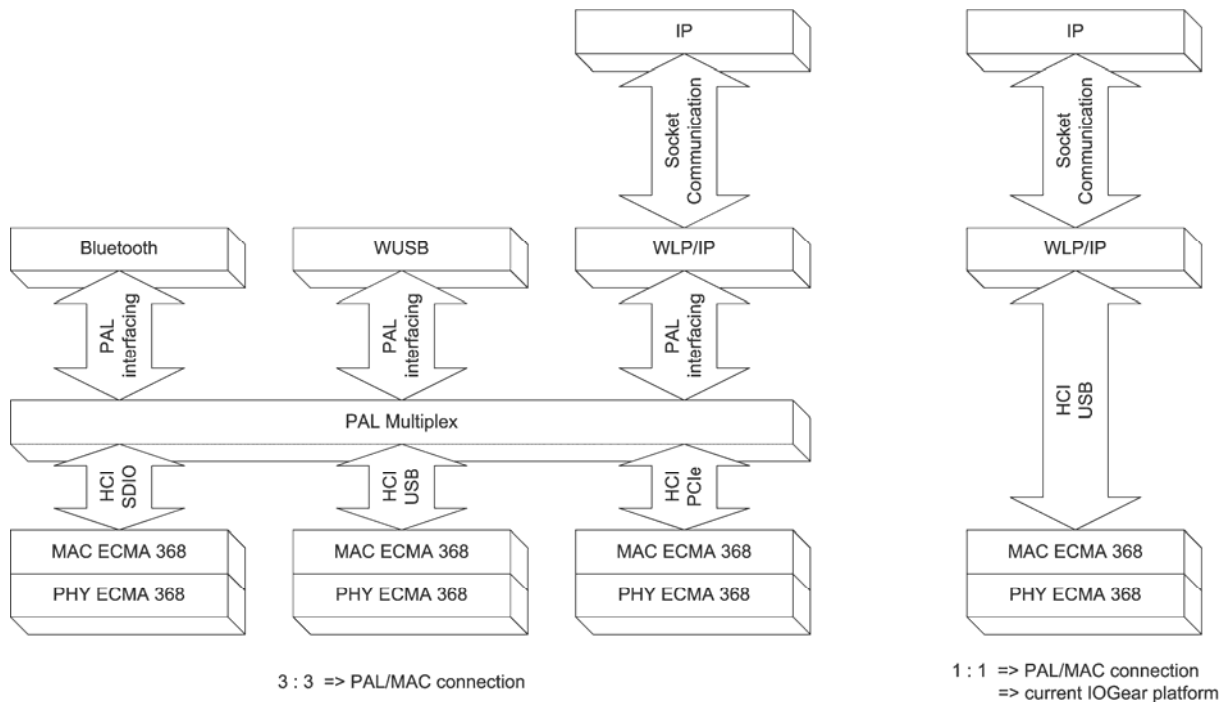


Figure 4.7: Comparison of PAL multiplex architectures

Other strict limitations of the assembly are the support of only one data transfer link per device and that there is a heavy dependency on the usable operation systems on the host system, which has to be a newer Linux distribution (e.g. kernel version 2.6.24-24) to support the current WLP implementation.

The great advantage of the WLP layer is the direct support of the IP network link. So the IOGear-resolution can be accessed by an application in the common way to use socket communication by the help of the IP layer. This allows a broad scheme of applications (e.g. video streaming with UDP, data transfer with TCP and so on) and also allows the reuse of already built applications.

4.3 Analysis of Energy Efficiency

4.3.1 General Considerations

In HDR-UWB high power consumption often imposes a limitation on the use of UWB for applications where low power is desired, or sometimes required. Although the MAC and higher layers significantly affect the overall power consumption of the system, they generally have little impact on the design of the hardware system. The physical layer specification, however, is directly related to the operation of the hardware and needs to be fully comprehended in order to achieve a hardware design with optimal power consumption [4]. Figure 4.7 shows the average transmit power as a function of the data rate for standard multiband schemes.

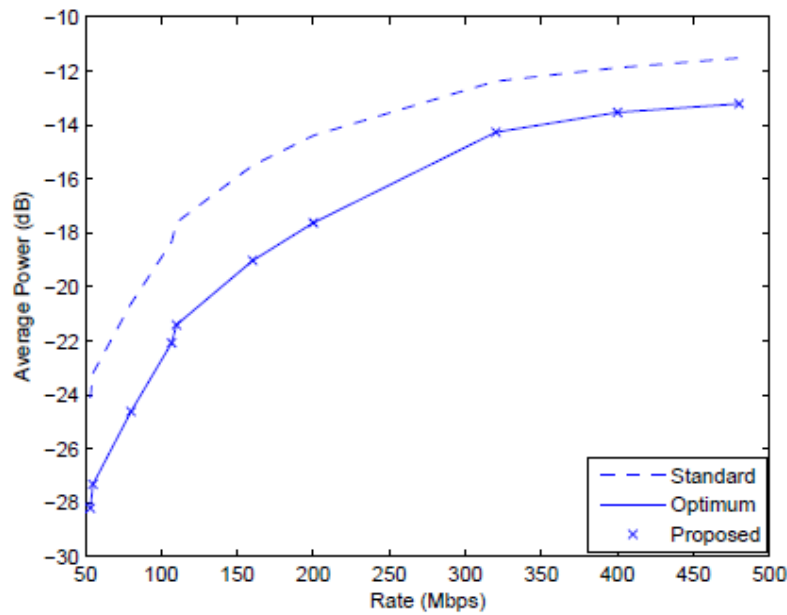


Figure 4.8: Average Power vs. Data Rates

The transmit power in 90 nm and 130 nm OFDM UWB chips for data rate of 110, 200, and 480 Mb/s is illustrated in Table 4.3 [5].

Table 4.3: Power consumption numbers for a multiband OFDM system

Process Node	Rate (Mb/s)	Active Transmit Power	Active Receive Power	Clear Channel Assessment	Power Save (Deep Sleep Mode)
90 nm	110	93 mW	155 mW	94 mW	15 μ W

	200	93 mW	169 mW	94 mW	15 μ W
	480	145 mW	236mW	94 mW	15 μ W
130 nm	110	117 mW	205 mW	117 mW	18 μ W
	200	117 mW	227 mW	117 mW	18 μ W
	480	180 mW	323 mW	117 mW	18 μ W

4.3.2 IOGear

Because the IOGear-platform is not an integrated one, it makes sense to split the efficiency remarks into the host part and the dongle part.

- Host: For development purposes the host is still built by a common personal computer platform, hence the energy consumption is not optimised. Further platform integration can target to a more dedicated solution with a support of embedded Linux on power saving processor cores.
- Dongle: The power consumption is noted with max. 2.1 Watt (full TX-power) powered by the USB connection. Because that is fixed by the manufacturer IOGear no optimisation is possible.

5 Combined LDR-LT and HDR Platform

5.1 Introduction

The combination of HDR and LDR UWB system can be separated into two categories. Full combined and half combined. The full combined system can operate as HDR system and LDR system in the same time. The half combined system is operating as HDR system and utilizing LDR-UWB TRX to enhance system performance. In this section we introduce a half combined system, which is composed of HDR system and MAC-PHY LDR to reduce power consumption in HDR-UWB TRX.

In the HDR system the power consumption is high and generally related to the OFDM modulation scheme. Also power consumption does not change significantly with throughput. Moreover, the high throughput in the HDR system comes from the size of data frames and is not affected by signalling frames. The power used for sending signalling information is in the same level of that used to send data information.

From this point of view we can send HDR signalling information using LDR physical layer since its power consumption is low and does not need high data rate transmission. As shown in Figure 5.1 the MAC frames can be split into data and signalling frames where data sent via HDR-PHY to maintain data rate requirements. The signalling is sent over LDR-PHY layer for saving power.

In order to coordinate operation of the two physical layers, an adaption layer is required and shall be designed. This layer deals with routing, synchronization, and power control issues. In the next section we will illustrated an elaboration for the adaption layer and its functionalities.

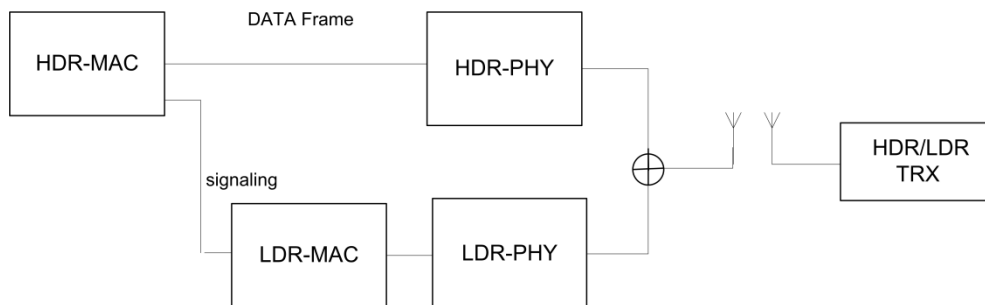


Figure 5.1: Concept of HDR/LDR Combined TRX.

5.2 Application Areas and Requirements

A common scenario for the HDR devices is the deployment in the field of home entertainment, mainly for video transmission. In this scenario, one possibility is the usage of the HDR Platform for the transmission of a HD video source to a viewer device like shown in Figure 5.4. The system can use the LDR platform for the remote control in substitution of the widely used infrared communication with both imaging devices. The power consumption of the remote control will be reduced and the localization could be used for knowing the position of the remote control and the user. Another application are of the LDR-HDR platform could be to implement two independent channels for the

same system. In this case, the HDR platform works as a pure data channel and the LDR platform defines a channel for the flow control of data communication.



Figure 5.2: Application scenario for a combined HDR/LDR device

In another application scenario of a combined LDR/HDR platform in home environment is the development of an in-house network. For example, in every smart device like a PDA or other handheld device, the LDR platform can be used as a way to synchronize the device. The HDR mode can be used for the raw data transmission like used for internet or file transmission. Besides that, all the devices can be located and show its position to the user (LDR features) while offering low power modes using the LDR.

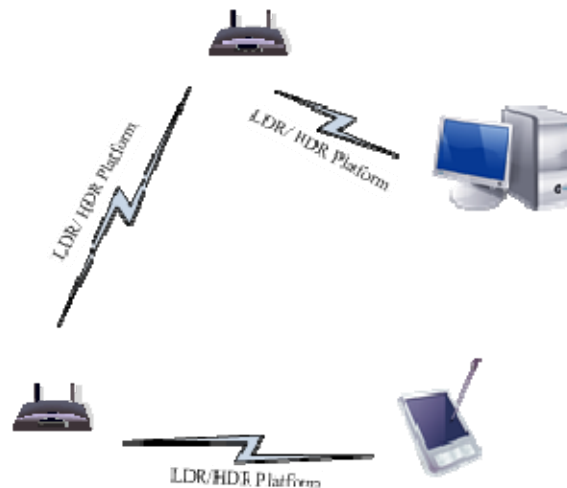


Figure 5.3: Home intranet scenario using a combined HDR/LDR device

5.3 Feasibility Analysis

5.3.1 Introduction

Although the comparison which was presented in chapters 3 and 4 leads to the conclusion, that a variety of differences exist between HDR and LDR systems, a combination is desirable. For the

feasibility of the suggested combination, an adaption layer is suggested, which implements functionality which is needed for the combination.

5.3.2 HDR/LDR Adaption Layer

The adaption layer connects the HDR-MAC with both of systems physical layers. Figure 5.4 show a simple HDR/LDR TRX with an adaption layer that splits traffic at MAC/PHY interface to data and signalling frames. This layer operates as demultiplexer (DEMUX) in the transmission mode and as multiplexer (MUX) in the receiving mode. Its functions include recognition of the frame type, interpolation the signalling frames to be appropriate for LDR side, remapping of the LDR-MAC frame, exclusion of the HDR-MAC signalling from LDR-MAC frames, power control, and synchronization. An adaption layer protocol should be a translator for protocols used in LDR and HDR systems.

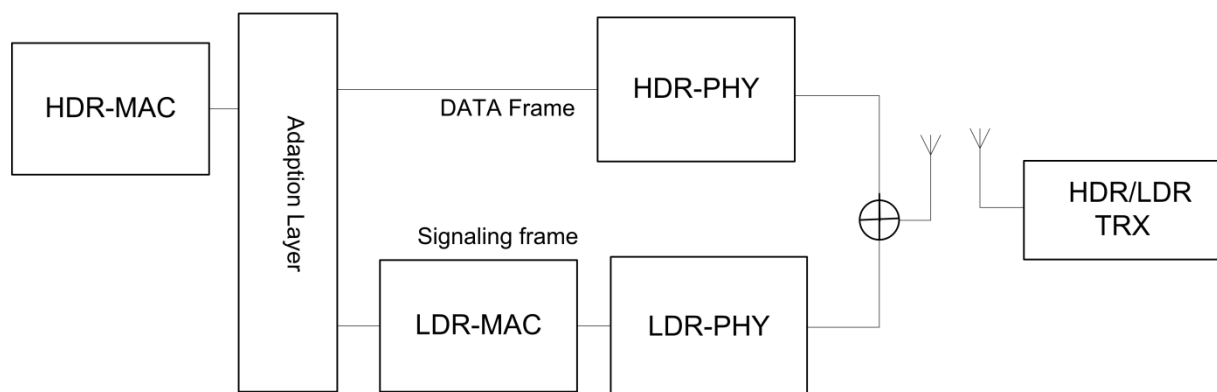


Figure 5.4: Combined HDR/LDR with adaptation layer

5.4 Adaption layer internal protocol

5.4.1 Introduction

The adaption layer protocol coordinates the operation of two different devices using different protocols. It allows having both system functionalities on the same device. Figure 5.5 shows the model representation of the adaption layer protocol. The adaption layer protocol starts with a data-analysis, where the received MAC frames are separated in data- and signalling frames defined in according to the classification given in Chapter 2.

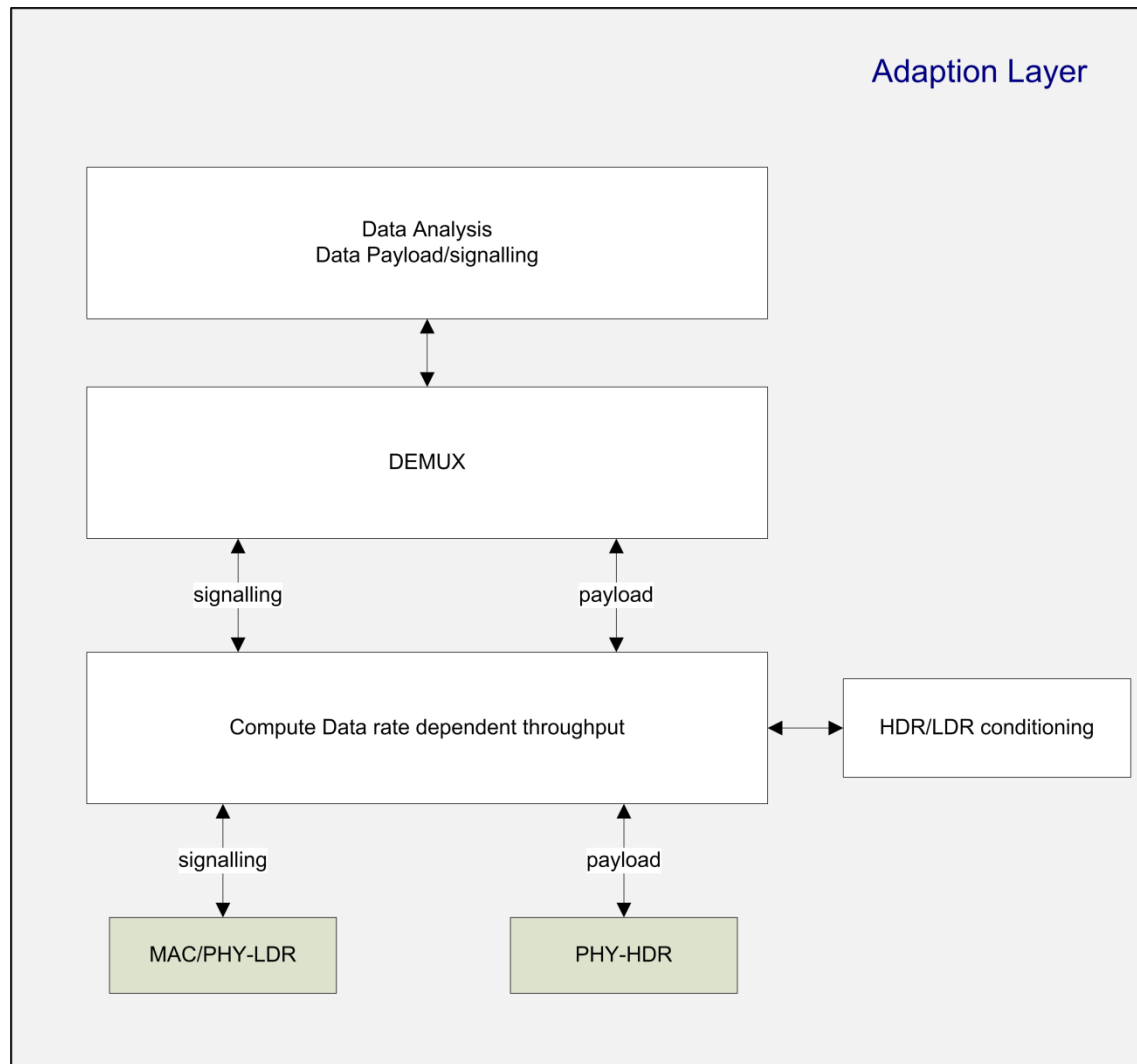


Figure 5.5: Adaption layer protocol

Based on the frame type the DEMUX switches its output to the next stage. The coverage for both systems should be identical to decrease the multipath and interference effects especially for the LDR TRX part. Since the LDR coverage is higher than HDR system the transmission power should be minimized to not fall behind the receiver. At this point, the adaption protocol computes the required power to transmit the LDR frames using power-distance relation in HDR and LDR TRXs. The computation starts with observation of the throughput, distance and power relation in the HDR system that will be stored in HDR/LDR conditioning stage. Then from the HDR power consumption value it will choose the LDR data rate and power needed to transmit the signalling frame to the same distance used for HDR TRX. At the final stage the protocol will route the signalling frame to be inserted as payload for LDR MAC frames and send it over the interface. In the data frame case, the adaption protocol forwards the frames to the HDR physical layer with the data rate and power defined through HDR-MAC layer.

The transmission and receiving over the LDR part should be invisible for the HDR system. This implies that all the switching and transmission process should be done in the reserved HDR medium access slot (MAS) to maintain the timing for the main system which is HDR system.

5.4.2 Adaption layer state machine

In the proposed HDR/LDR transceiver concept exist to physical layer implementations. The operation states for both parts are controlled by the adaption layer in the proposed concept. In the data traffic mode, the HDR forwards HDR-MAC layer frames and changes the HDR-PHY layer state from sleep to ready and then to transmit or receive state and turn LDR-PHY to sleep state. Also in signalling traffic mode the adaption layer inform LDR to switch the LDR-PHY to ready state to prepared for transmit or receive state. Table 5.1 shows the states of two layers.

Table 5.1: Combination HDR/LDR operation states

Traffic	LDR-PHY	HDR-PHY
Data	SLEEP	READY
Signalling	READY	SLEEP

One of the two systems is allowed to be in active state and this is a direct result of using HDR-MAC frames contents as controller for switching process.

5.4.3 Performance Analysis

In this section, results specifying the HDR and LDR transceivers performance and coverage, are presented. The HDR system is based on WiMedia ECM-368 standard. This system utilizing MB-OFDM with 128 sub-carriers modulated using QPSK. Only 122 sub-carriers are carrying power and divided as 100 sub-carriers for data, 12 for pilot tones and the remaining as guard tones. The detailed HDR transceiver architecture and system parameters are reported in [6]. The performance is evaluated in both AWGN and multipath channel environments CM1-CM4. Channel model 1 is used to represent indoor configurations for which the transmitted signal has limited interaction with the propagation environment. CM1 channels are defined as Line Of Sight (LOS), with a limited transmission range (0-4 m) whereas CM2 and CM3 describe the Non Line Of Sight (NLOS) channels measurements with ranges of (0-4m) and (4-10m) respectively. Channel model 4 is a good representative of indoor transmission channels for which the transmitted signal is blocked and spread by the environment.

The link budget analysis for a multiband OFDM system in AWGN environment is reported in [6]. This analysis is employed to obtain the block error rate and throughput performance as a function of distance.

$$\frac{E_s}{N_0} = \frac{P_r T_s}{P_N / B} = \frac{P_r / R_s}{P_N / B} \quad (4.1)$$

Thus,

$$\begin{aligned} 10 \log \frac{E_s}{N_0} &= 10 \log \frac{P_r}{P_N} + 10 \log \frac{B}{R_s} \\ &= 10 \log P_r - 10 \log P_N + 10 \log B - 10 \log R_s \end{aligned} \quad (4.2)$$

With

$$P_N = k_b \cdot T_0 \cdot B \quad (4.3)$$

It can be easily seen that

$$10 \log P_L = 10 \log P_T - 10 \log \frac{E_s}{N_0} - 10 \log R_s + 10 \log (k_b T_0 B) - N_F \quad (4.4)$$

In the model, which is assumed, P_L is defined by

$$P_L = \left(\frac{4\pi d \cdot f_c}{c} \right)^\eta \quad (4.5)$$

Where η is the path loss decay exponent which equals 2 in a free-space environment. With the definition of

$$p_L = 10 \log_{10} \left(\frac{4\pi d \cdot f_c}{c} \right)^\eta \quad (4.6)$$

the relationship between path-loss and distance can be shown to be

$$d = \frac{c}{4\pi f_c} \cdot 10^{\left(\frac{p_L}{10\eta}\right)} \quad (4.7)$$

with

$$f_c = \sqrt{f_{\min} \cdot f_{\max}} \quad (4.8)$$

In the presentation what follows, the relation between the distance and $\frac{E_s}{N_0}$ is calculated with the help of formulas (4.4) and (4.7) at a given transmit power.

The Block error rate (BLER) performance in an additive white Gaussian noise (AWGN) channel as a function of distance and the data rate is shown in Figure 5.6. The data rates used in this simulation are 110 Mb/s, 200 Mb/s, and 480 Mb/s with DCM and QPSK modulation scheme. In addition, BLER performance for the channel models CM1 through CM4 is shown in Figure 5.7 to Figure 5.10. For a BLER performance equal to 10^{-1} the coverage of this quality of service (QoS) is illustrated in Table 5.2. The employment of DCM in 480 Mbps data rate modes extends the range in NLOS channels (CM2-CM4) as a result of the diversity exploitation in these channels.

Table 5.2 Transceiver distance at which block error rate equals 10^{-1} in AWGN scenarios.

Data Rate	AWGN	CM1	CM2	CM3	CM4
110 Mbps	21.4	18.05	19.6	19.9	17.7
200 Mbps	14.5	10.9	12.8	12.3	10.4
480 Mbps (DCM)	8.9	5.2	6.9	6.3	4.8

480	Mbps	8.9	4.8	5.9	5.5	3.9
-----	------	-----	-----	-----	-----	-----

(QPSK)

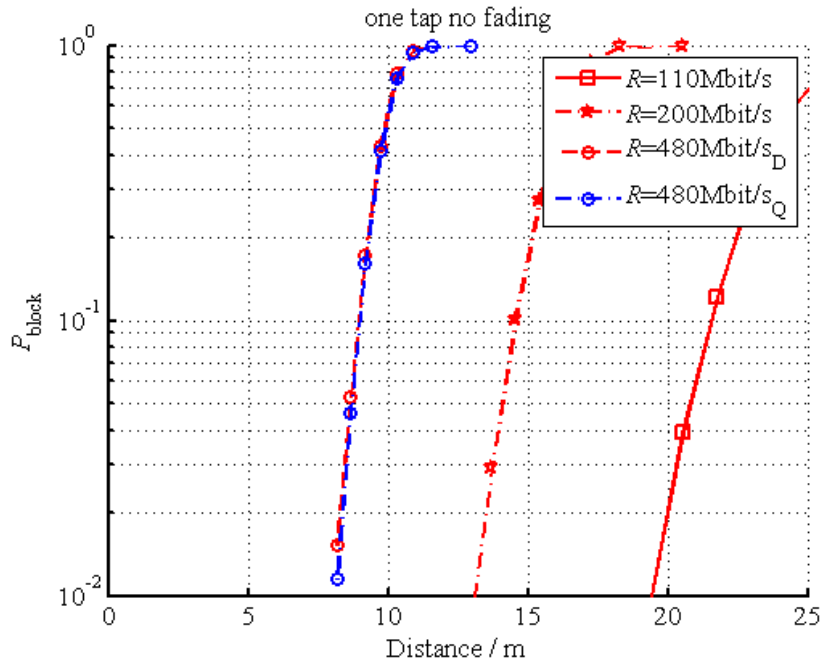


Figure 5.6: P_{block} as a function of distance and data rate in AWGN environment.

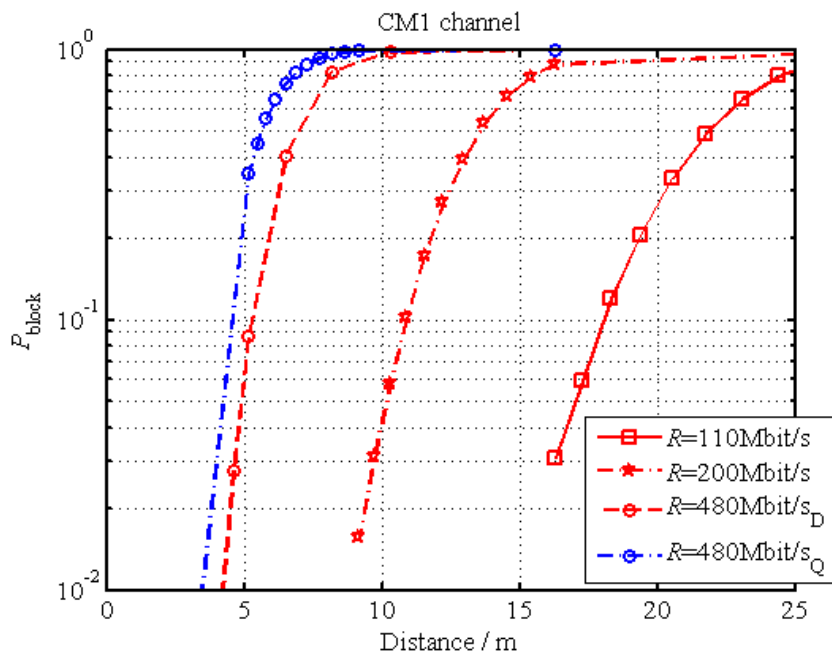


Figure 5.7: P_{block} as a function of distance and data rate in CM1 environment.

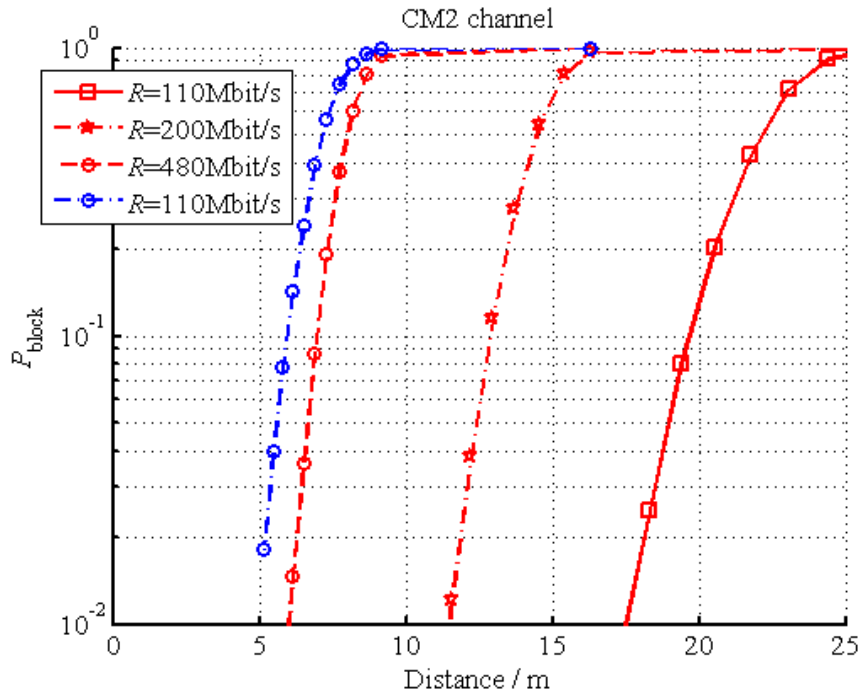


Figure 5.8: P_{block} as a function of distance and data rate in CM2 environment.

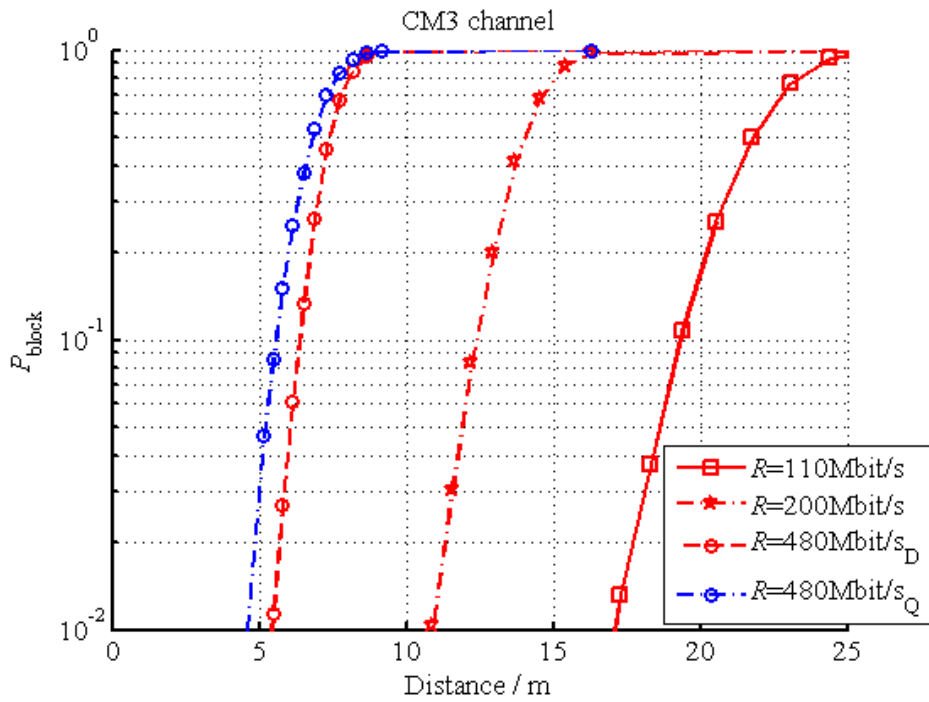


Figure 5.9: P_{block} as a function of distance and data rate in CM3 environment.

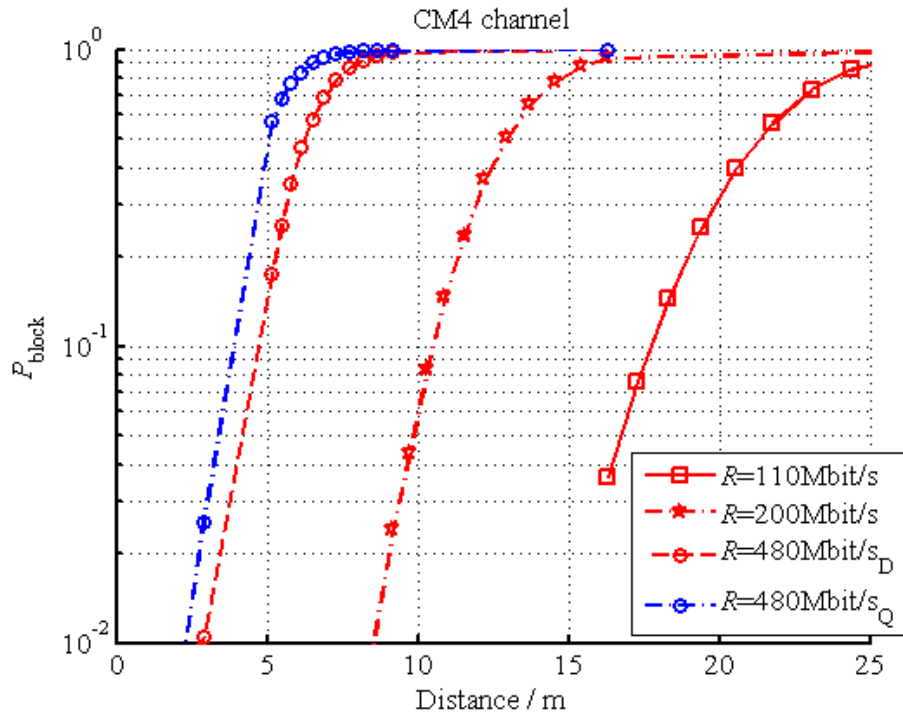


Figure 5.10: P_{block} as a function of distance and data rate in CM4 environment.

In addition, the throughput can be estimated from the BLER and peak data rate. The data rate depends on several parameters as FFT size, modulation scheme, and symbol rate, bandwidth and OFDM symbol structure and spreading parameters. As an example, in the 200 Mb/s mode the deployed modulation scheme is QPSK with two bits in each symbol and coding rate $=5/8$. The number of data carriers per OFDM symbol of length 128 is 100. The peak data rate R_b can be calculated with the knowledge of the number of data subcarriers, the OFDM symbol rate, the coding rate, the number of bits per subcarrier and a spreading factor according to

$$R_b = \frac{N_D F_{sym} R N_{bit}}{N_{div}} \quad (4.9)$$

As an example, the calculation for the 200 MBit/s mode is given

$$\begin{aligned} R_b &= \frac{100 * 3.2 \times 10^6 * (5/8) * 2}{2} \\ &= 200 \text{ MBit/s} \end{aligned} \quad (4.10)$$

From the simulation the Throughput TP is calculated from the peak data rate and the BLER:

$$TP = (1 - P_{block}) R_b \quad (4.11)$$

Figure 5.11 to Figure 5.15 show the throughput in AWGN and multipath channel environment

CM1-CM4 which show the decrease rate in throughput over the distance and define actual coverage for each data rate service as illustrated in Table 5.2.

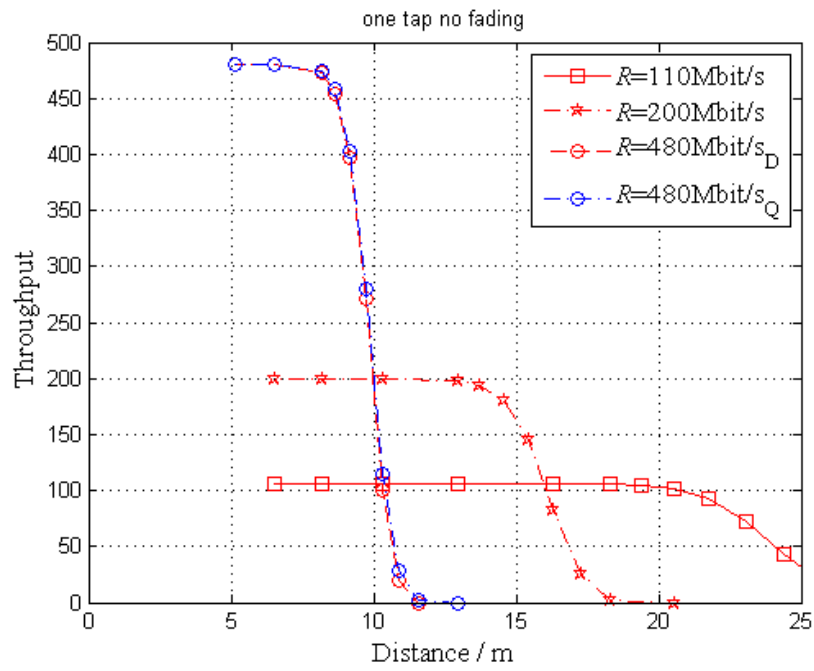


Figure 5.11: Throughput as a function of distance and data rate in AWGN environment.

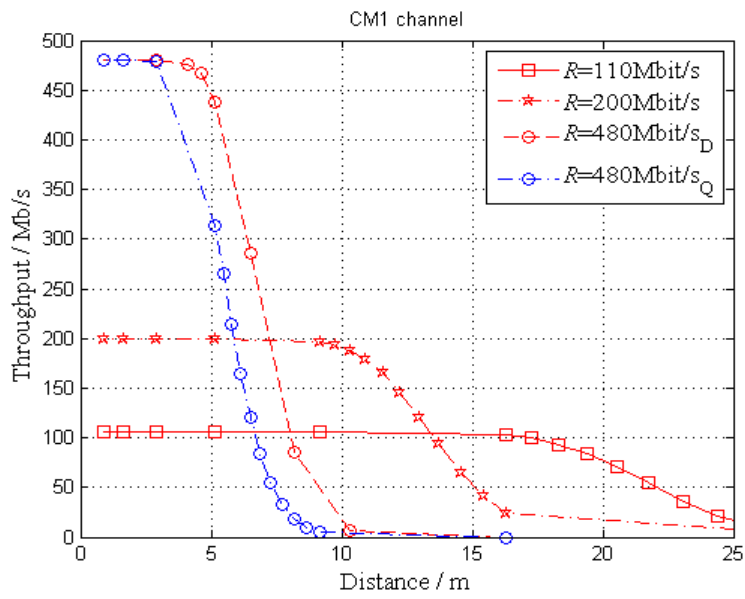


Figure 5.12: Throughput as a function of distance and data rate in CM1 environment.

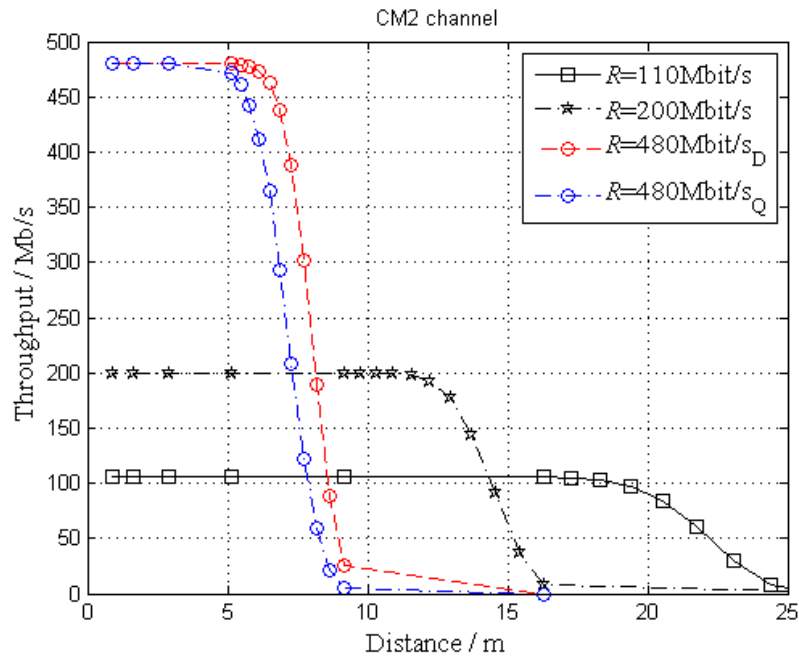


Figure 5.13: Throughput as a function of distance and data rata in CM2 environment.

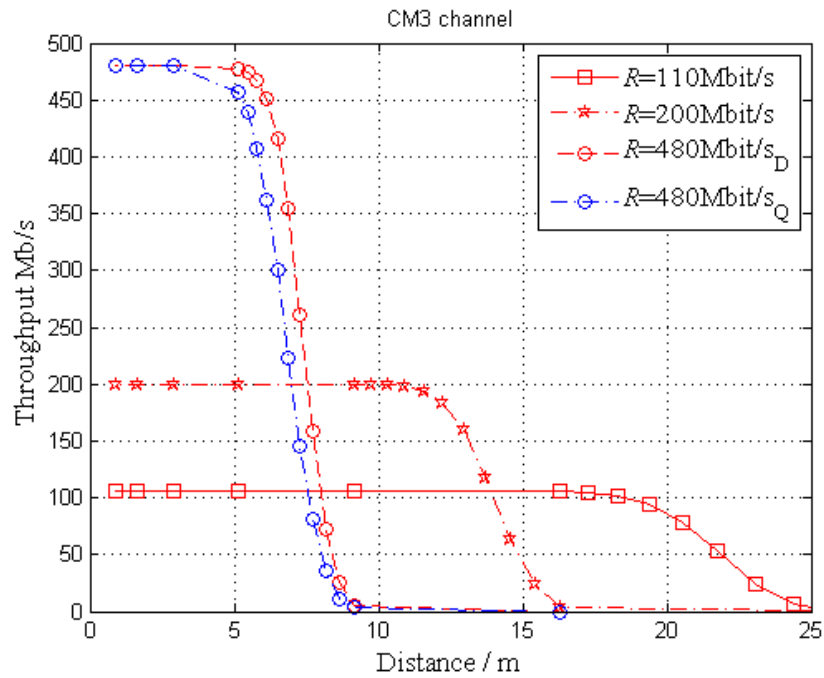


Figure 5.14: Throughput as a function of distance and data rata in CM3 environment.

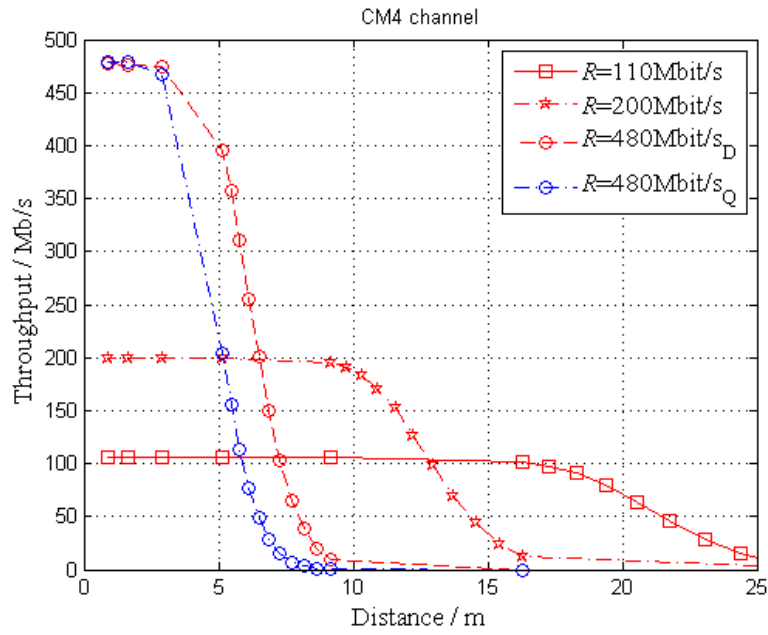


Figure 5.15: Throughput as a function of distance and data rate in CM4 environment.

The system performance of LDR transmission in AWGN channel is shown in Figure 5.16 to Figure 5.20. As defined in [3], the simulation is based on the IR-UWB with the DBPSK modulation. The information bits are spread with PN code of the length 12 in a first step and then modulated with DBPSK modulation scheme. The chip length, frame length and symbol length is 120 ns, 240 ns and 2.88 μs respectively. As a consequence the raw bit rate is 347 kbps. The deployed DBPSK modulation scheme provides a good immunity to clock drift. The spreading of the information bits improves the performance significantly and can compensate the shortcoming of DBPSK modulation.

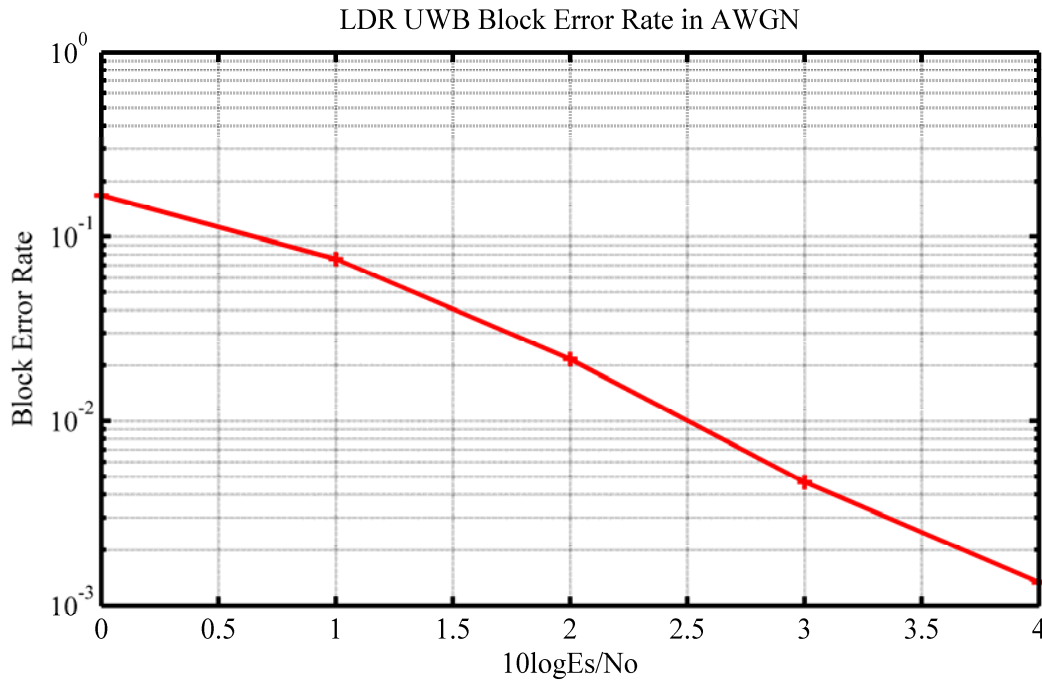


Figure 5.16: Block error rate vs Es/No in AWGN Channel

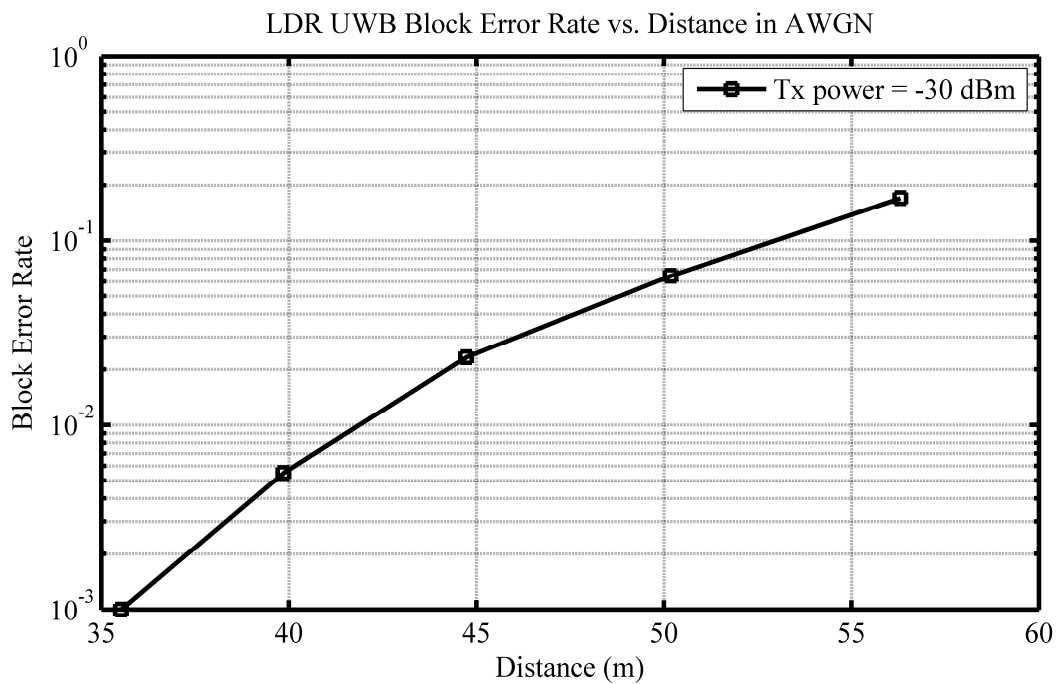


Figure 5.17: LDR Block error rate as a function of distance in AWGN channel with Tx power of -30 dBm

Figure 5.16 shows block error ratio simulation result in AWGN scenario. According to the function which is derived in the beginning of this chapter the relationship between block error ratio and distance can be found accordingly. Analogue the throughput as a function of distance could also be obtained. Figure 5.17 and Figure 5.18 show us the block error rate and the throughput with the relationship of distance at a given Tx-power of -30 dBm. In addition, Figure 5.19 Figure 5.20 show the results for a given Tx-power of -42 dBm.

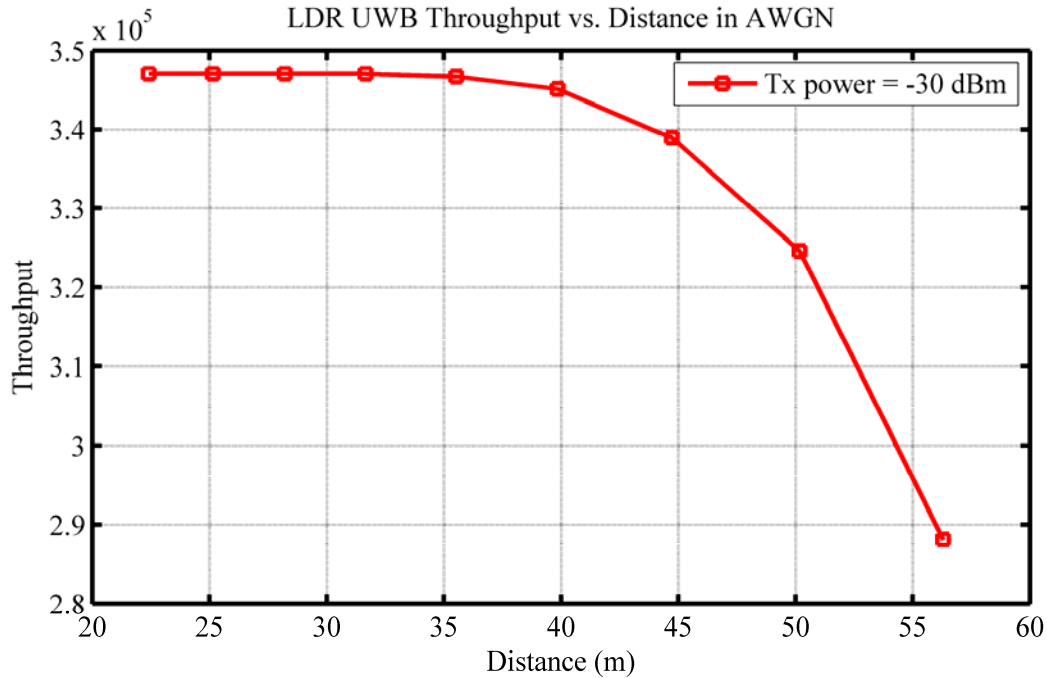


Figure 5.18: LDR Throughput as a function of distance in AWGN channel with Tx power of -30 dBm

A comparison of Figure 5.6 and Figure 5.17 is given first. Both Figures show the block error ratio in dependency of the transceiver distance but with different Tx-power. The average Tx-power of the HDR system is assumed to be -10.3 dBm while that of LDR in Figure 5.17 is -30 dBm. The simulation shows that the 110 MBit/s mode has less coverage than any LDR operation mode for the given transmit powers. As consequence, the LDR Tx-power could be decreased so that both systems show a similar coverage. The reduction of the Tx power to -42 dBm leads to the performance reported in Figure 5.19. It can be shown, that a power control can be used for interference avoidance and thus showing an improvement in the QoS of the system. To complete the performance investigation, troughput results for the LDR system in an AWGN scenario are reported in Figure 5.18 as well as for the well known UWB channel models CM1-CM2 in Figure 5.21 to Figure 5.23.

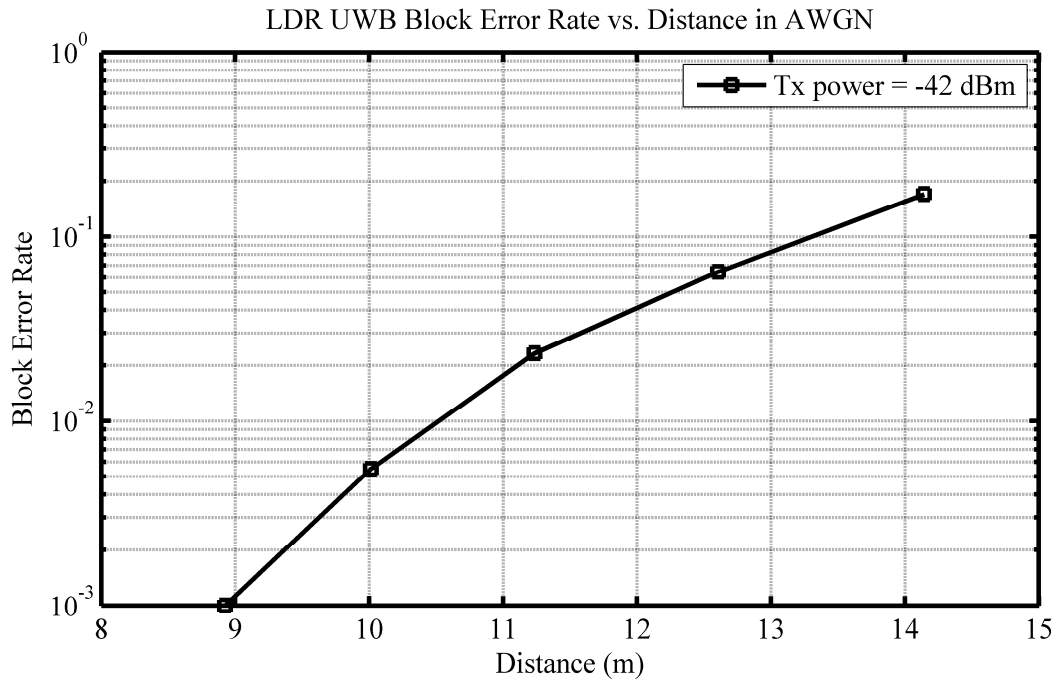


Figure 5.19: LDR Block error rate as a function of distance in AWGN channel with Tx power of -42 dBm

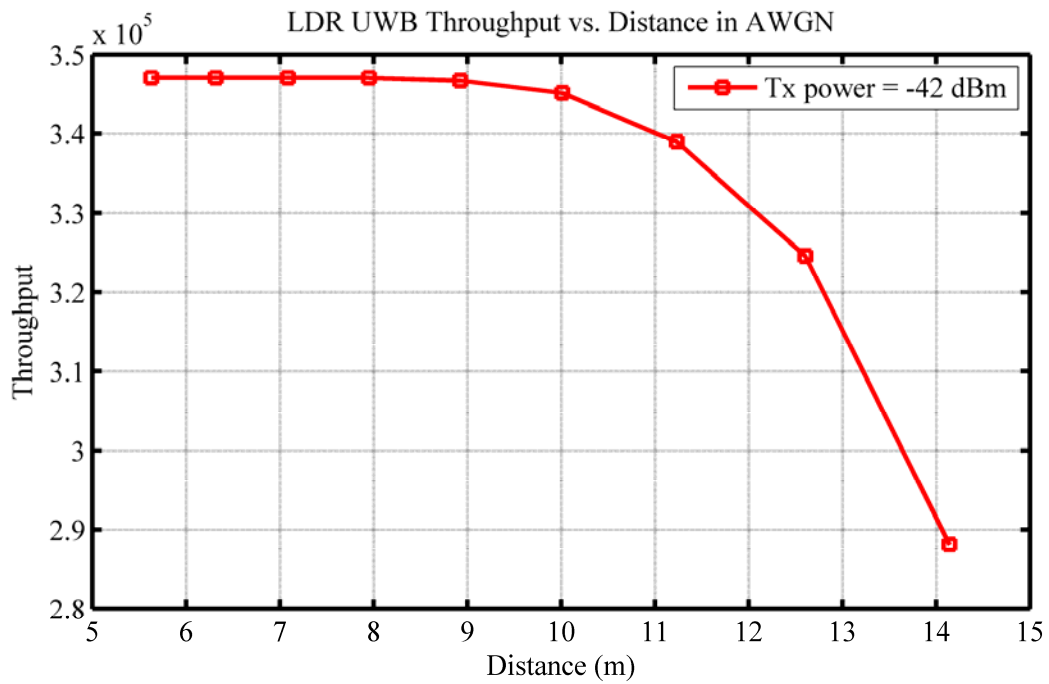


Figure 5.20: LDR Throughput as a function of distance in AWGN channel with Tx power of -42 dBm

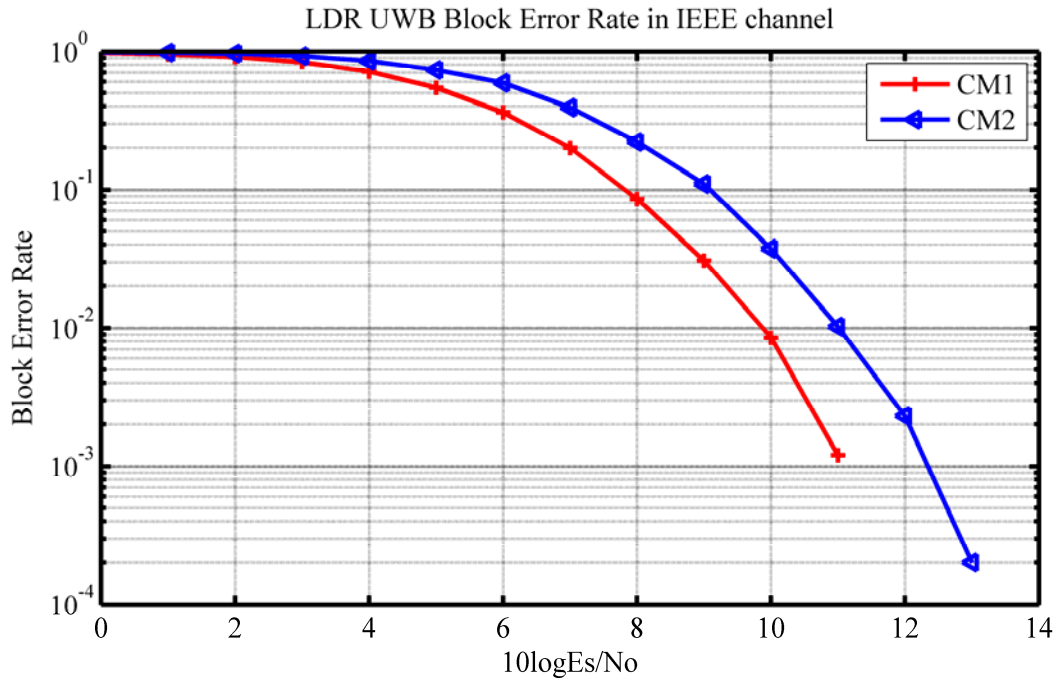


Figure 5.21: LDR block error rate in IEEE UWB channel

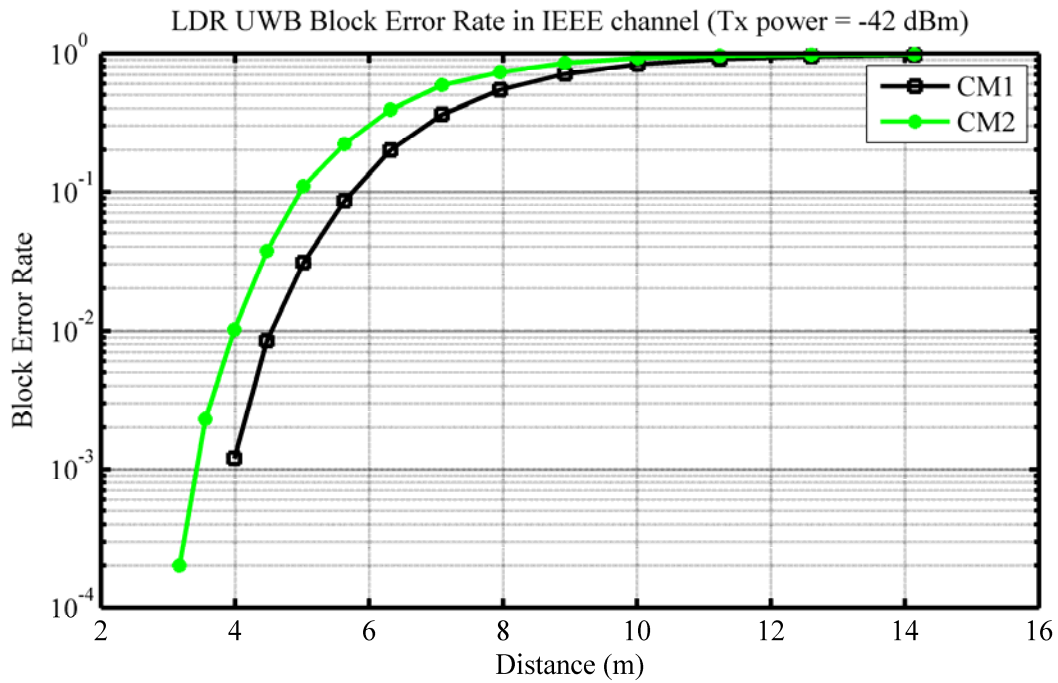


Figure 5.22: LDR block error rate in IEEE channel with Tx power -42 dBm

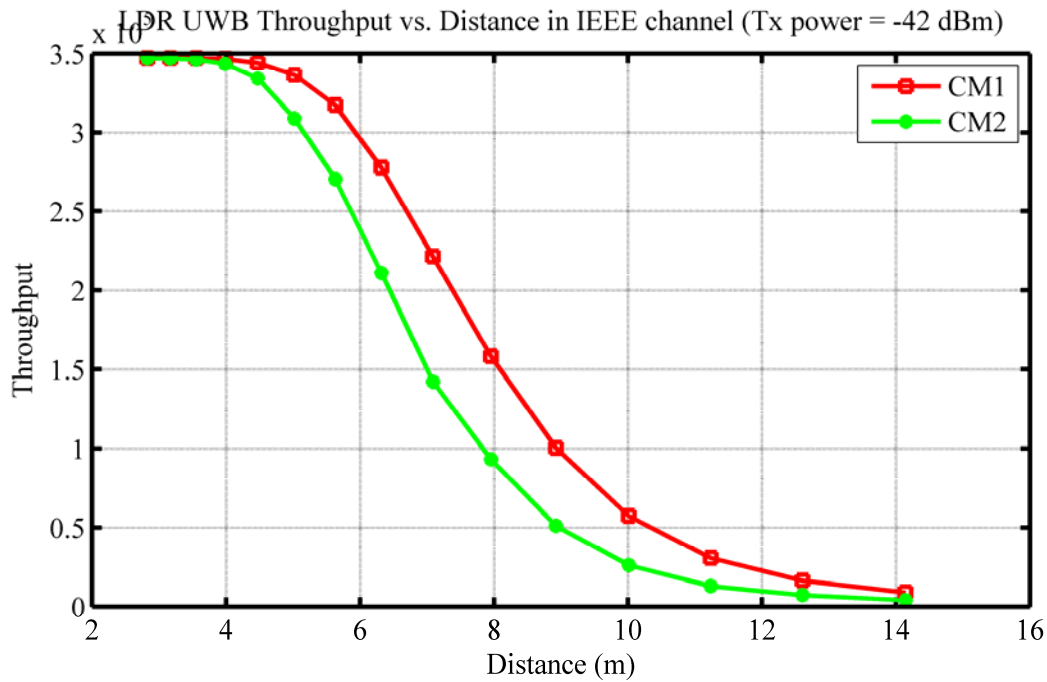


Figure 5.23: LDR throughput as function of distance in IEEE channel with Tx power -42 dBm

5.5 Power saving by combining HDR/LDR TRX

The simulation results demonstrate our concept of the combined LDR/HDR platform. The HDR transmission consumes more power than the LDR transmission but makes a higher throughput possible; it can be used to transmit the payload. In contrast, the LDR link can not reach the high throughput as the HDR link but it saves much more power and can be used to transmit the signalling frame which does not involve much information bits. Future work, which is carried out to show whether a combined HDR/LDR significantly saves power is carried out.

6 Conclusions

In this document, an architecture of a combined HDR/LDR device was proposed. After a brief introduction of the HDR and LDR UWB systems, potential applications of a combined hardware platform were presented.

The HDR/LDR system is classified into two categories. The categories are a fully combined device which can operate as HDR system and LDR system at the same time on the one hand and a combined system in which a major functionality is an HDR system operating and utilizing an LDR-UWB transceiver to enhance system efficiency. A core aspect in this combined architecture is the deployment of the energy efficient physical layer of the LDR device for low data-rate transmissions in the HDR system.

The investigation presented in this manuscript shows the necessity of an adaption layer which is designed to deal with routing, synchronization, and power control issues. For this layer, a new protocol coordinates the operation of two different devices using different protocols is proposed. This protocol allows having both system functionalities on the same device and a power control, which ensures similar coverage for both physical layers. This aspect is important for quality of service issues, in particular for interference avoidance.

In what follows, a state machine is introduced in order to regulate the operation mode of the combined HDR/LDR transceiver device and the transition states between HDR and LDR mode are defined. This functionality is also implemented by the adaption layer.

In the system performance investigation performance results and coverage simulations of the HDR and LDR systems are presented. The performance is quantified in terms of block error ratio and data-throughput. The simulation scenarios include the well known UWB channel-models CM1-CM4 including AWGN. According to those simulations it can be shown that a combined LDR/HDR architecture is desirable and an improvement in energy efficiency can be expected. Major improvements can be expected for the case of high data rate applications where the device is idle and only network signalling is carried out. The reason for this improvement is that the energy consumption of OFDM based systems does not scale with the data throughput very well. On the other hand, the energy consumption of pulse based systems scales very well with the throughput.

7 References

- [1] ECMA, “Standard ECMA-368: High Rate Ultra Wideband PHY and MAC Standard,” Dec. 2008org/publications/standards/Ecma.
- [2] Ghobad Heidari, WiMedia UWB for W-USB and Bluetooth Interpretation of standards, regulations and applications, Wiley & Sons, 2008.
- [3] IST PULSERS Phase II D3a3.3: LDR-LT Concept Specifications - PHY and MAC Layers, Jul. 2008.
- [4] Anantha P. Chandrakasan et.al, “Low-Power Impulse UWB Architectures and Circuits”, in Proceedings of the IEEE Vol. 97, No. 2,pp. 332-352, February 2009.
- [5] Multiband OFDM Physical Layer Specification (Rev1), Jan 14,2005. WiMedia Alliance; http://wimedia.org/en/resources/mboa_archives.asp
- [6] A. Batra, J. Balakrishnan, G. R. Aiello, J. R. Foerster, and A. Dabak, “Design of a multiband OFDM system for realistic UWB channel environments,” IEEE Trans. Microw. Theory and Tech., vol. 52, pp. 2123–2138, Sep. 2004.
- [7] Zeisberg, S., Schreiber, V.: “EUWB - Coexisting Short Range Radio by Advanced Ultra-Wideband RadioTechnology”, ICT Mobile and Wireless Communications Summit, Stockholm, June 2008, accepted for publication
- [8] URL of EUWB consortium: <http://www.euwb.eu>

8 Acknowledgement

The EUWB consortium would like to acknowledge the support of the European Commission partly funding the EUWB project under Grant Agreement FP7-ICT-215669 [8].