Integrated Project - EUWB

Contract No 215669

Deliverable

D2.6.3

CR-UWB based control unit

Contractual data:	**M36**
Actual data:	**M40**
Authors:	**CNET: Andrey Somov, Abdur Rahim Biswas**
Participants:	**CNET**
Work package:	**2**
Security:	**PU**
Nature:	**Report**
Version:	**1.0**
Total number of pages:	**31**

Abstract

This deliverable proposes the use of CR-UWB device as the control unit, wherever multiple air interfaces are co-located, to take over the usage of different communication modes in a device. For these purposes the node architecture with multiple air interfaces and control mechanism are proposed. In order to overcome the problem of interference and performance optimization, we develop two approaches mainly focused on the node power control.

Keywords

Ultra wide band communication, multi radio interface, beaconing, power control

Table of Contents

List of Figures

List of Tables

Abbreviations

AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
CN	Cognitive Network
CP	Control Point
CR	Cognitive Radio
DPSK	Differential Phase Shift Keying
DVB	Digital Video Broadcasting
FSK	Frequency Shift Keying
GPS	Global Positioning System
HDR	High Data Rate
ICT	Information and Communication Technologies
ID	Identification
IE	Information Element
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
LAN	Local Area Network
LDR	Low Data Rate
LL	Link Layer
LTE	Long Term Evolution
MAC	Media Access Control
OSI	Open Systems Interconnection
PHY	is an abbreviation for the PHYsical layer of the OSI model
PU	Primary User
QPSK	Quadrature Phase Shift Keying
RAT	Remote Access Technology
RSSI	Received Signal Strength Identification
SCN	Secondary Cognitive Network
SINR	Signal-to-Interference and Noise Ratio
SNR	Signal-to-Noise Ratio
SU	Secondary User
SUE	Spectrum Utilization Efficiency

UMTS	Universal Mobile Telecommunications System
UWB	Ultra Wide Band
WP	Work Package

Executive summary

This document investigates the use of a CR-UWB node as the control unit, wherever multiple air interfaces are co-located, to take over the usage of different communication modes in a device. Besides, we devise a control mechanism to support smooth operation of the nodes under restricted conditions like in an aeroplane. Finally, we present two approaches for interference mitigation and the nodes' performance optimization.

1 Introduction

In EUWB, key objective is to exploit the enormous potential of the innovative and disruptive radio technology embodied in UWB for key industrial sectors in Europe by innovation of cutting-edge short range radio solutions. Cognitive radios that are employed in a UWB network must operate efficiently in the presence of uncertainties and variations in the propagation characteristics of network's communication links. The efficient use of available radio resources in wireless communication system is the task of top priority.

The next generation wireless and mobile communications with increased data rates such as UMTS, LTE, Wi-Fi, DVB-H and Bluetooth etc. With multi radio interfaces foresees continuous and seamless connectivity. The state of the art however consumes high power for maintaining two or more radio interfaces and in addition with advanced imaging features such as camera, high-definition display, etc. and GPS/Galileo receivers the power consumption increases considerably in the next generation handsets. The technology progress towards energy efficient ICT technology is also being motivated strongly by the relevant bodies.

In this deliverable we present the architecture of CR-UWB node with multiple air interfaces. The control functions are performed by exchanging of beacons among neighbouring CR-UWB node. The general structure of beacon frame and its decapsulation mechanism is also presented in this work. Besides, we describe smooth operation modes for all nodes under restricted condition in an aeroplane. Finally, we propose two approaches for the nodes' performance optimization.

The deliverable is organized as follows: Section 2 will describe the CR-UWB node with multiple air interfaces architecture and protocol stack with CR-UWB layer. Section 3 will introduce beacon exchange mechanism and beacon frame structure. The CR-UWB nodes' operation optimization through interference mitigation is considered in Section 4. Finally, we conclude in Section 5.

2 CR-UWB node architecture

Recent advances in electronics and communications resulted in the opportunity of integration of various radio interfaces in a single device. This opportunity is presented in details in EUWB WP6 [1]. Figure 2.1 presents CR-UWB node which supports multiple radio interfaces. In this work we consider three communication technologies contained in the CR-UWB node: Bluetooth, WiMAX, UWB. In fact, two of them, i.e UWB and WiMAX, can interfere.

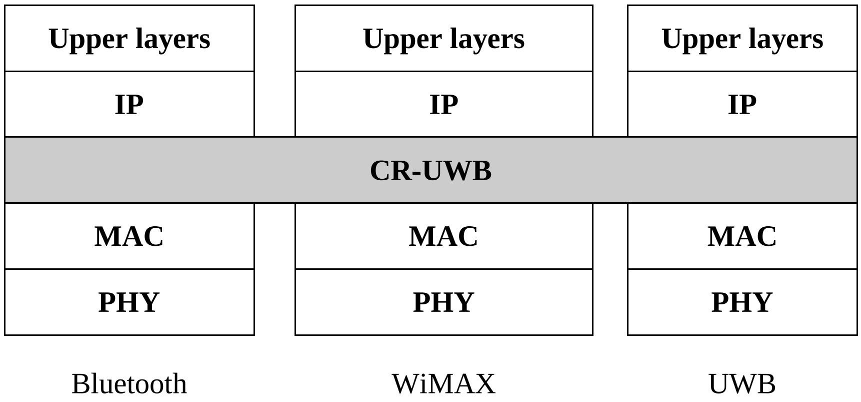

Figure 2.1 CR-UWB node with multiple air interfaces.

The main purpose of this unit is to provide control mechanisms and smooth operation modes for all co-located devices. Under the *smooth operation* we mean *energy-saving* (power control) in multi-standard mobile nodes. The *energy saving* gain is realized through cooperative networking, in particular, through the power control approaches described in Section 4.

The energy saving application is a part of CR-UWB control device, where it integrates with the device's protocol stack as shown in Figure 2.2. Such a modularization and representation makes it easier to analyze and evaluate interoperability in CR-UWB node, in particular interoperability of *energy saving* application functions with the existing protocol suite. From the figure one can recognize the fact that CR-UWB layer interconnects two layers of the OSI model: LL (Link Layer), which is typically dedicated to the underlying radio technology, and IP (Internet Protocol) layer, which characterizes most of the modern heterogeneous networking solutions. As it can be noted, *energy saving* application itself is independent from the underlying radio technology. However, *energy saving* functionality is very much related to that MAC layer in sense that it is required by CR-UWB layer to understand what type of frame the device has received, whether it is data frame or beacon frame, which determines further processing of the frame.

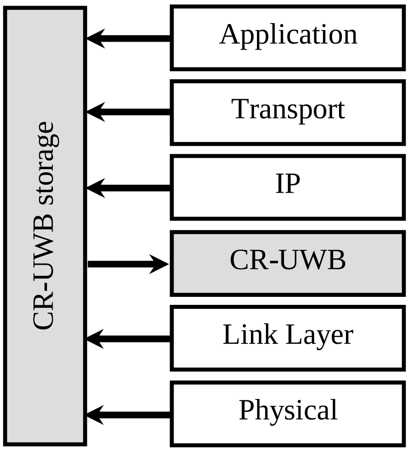

Figure 2.2 Protocol stack with CR-UWB layer.

Apart from the main application, which locates itself in the CR-UWB layer of the logic presented by OSI model, there is also an information storage ('CR-UWB storage', see Figure 2.2), which is reachable from every layer of the *energy saving* application. The purpose of this element is to receive various context information from other layers of the network devices protocol stack. The context information is then made available to the *energy saving* application which utilizes it during cooperation. Example context information extracted from the lower layers is composed of SNR or data rate of the received packet, or from higher layers the monetary cost of service. As noted previously, the *energy saving* application is independent from underlying RAT, thus as a consequence CR-UWB layer is capable of managing and having an interface to multiple radio technologies placed in one device (see Figure 2.1). Such knowledge enables *energy saving* application to effectively employ and manage cooperative schemes, e.g. multi-radio cooperative relaying or multi-radio cooperative scanning. As required by the 802.11 standard [2] the underlying IEEE radio interfaces shall appear to the upper layers the same as IEEE 802 LAN standard.

3 Beaconing

The CR-UWB cooperation is realized through the exchange of CR-UWB beacon frames among the neighbouring nodes. This approach is utilized to enable power control, performance optimization, cluster formation, and exchange of context information. In the following description we propose a general specification of CR-UWB beacon frame. The design of communication protocol for a node with multiple interfaces is out of scope of this work.

3.1 CR-UWB beacon frame

The proposed mechanism starts its operation from the discovering of neighbouring nodes. Then this information can be used to form clusters. We assume that all neighbouring nodes are available for cooperation. In this work we also assume:

- Each communication technology which performs beaconing may provide application specific payload in a beacon;
- Beacons within a network are exchanged periodically according to the priority set by its communication technology;
- A CR-UWB node can decode the application specific payload during the beacons' exchange among various communication technologies.

Respectively for different short-range systems beacon frames contain in their payload various types of Information Elements (IEs). The IEs are device and operation specific data that is being exchanged between different network entities. Every management frame consists of a number of IEs (some of them optional) and each class of IEs is dedicated to certain function. However, there is a particular class of IEs, namely vendor-specific IEs that enable the manufacturer or application developer to customize its payload. Each of the short-range technologies considered in CR-UWB provide such vendor-specific IEs:

- Application specific IE in WiMedia [3], which enables utilization of *n* payload octets, $\{n: (n>4) \wedge (n \leq 320\text{-length\_of\_other\_IEs})\}$.

The location of the IE in the management frame is pointed by Element ID (IEs are grouped in ascending order). Furthermore, each of the user specific IEs has its own vendor ID (in WiMedia vendor ID is named Specifier ID and consists of 2 Bytes), which is reserved at particular standardization body. It is envisioned that CR-UWB would use the same vendor ID regardless from the underlying technology (thus, vendor ID would be adapted to a specific technology by adding as a prefix FF octets, for instance), so that CR-UWB information could be extracted from the beacon and properly processed. Based on the above mentioned IEs, the CR-UWB specific IE structure is shown in Table 3.1.1 and it consists of control information, vendor ID and CR-UWB frame.

Table 3.1.1 CR-UWB IE

n bits			
Information Element ID	Length	CR-UWB ID	CR-UWB frame

*Dependent on the underlying technology, where *n* points to maximum value provided by the technology

The proposed IE contains CR-UWB frame, which is used as a cooperation-enabling frame between CR-UWB enabled mobile nodes. The CR-UWB frame is utilized for CR-UWB distributed management purposes, for example:

- communication technology status,
- Tx power level,
- cluster formation,
- cooperation.

The structure of the frame reflects variety of purposes it is used for. Table 3.1.2 presents the structure, which consists of the frame header

Table 3.1.2 Proposed CR-UWB frame structure.

n bits					
CR-UWB frame header				Destination address	Payload if any
Number of bits	Number of bits	Number of bits	Number of bits	Number of bits	Number of bits
Message type	Addressing type	Supported RATs	Supported optimization strategies*	MAC Address	Payload

*In this work we mainly focus on power control. The entry includes Tx power status of CR-UWB node and supported power optimization strategies (see Section 4).

3.2 Processing of beacons

Based on the presented layered model (see Figure 2.1), we propose the frame processing scheme for CR-UWB node with multiple air interfaces. At this point we have to recall that each layer of protocol stack encapsulates the on-going packet with its own header, thus connecting the same layers of other devices, which can further decode the received packet and read the included information. We have to note that CR-UWB node does not generate its own control frames instead it utilizes vendor specific payload of the beacon frames already available in the technology, as described in Section 3.1. In Figure 3.1 we present a frame processing scheme for CR-UWB node with multiple air interfaces.

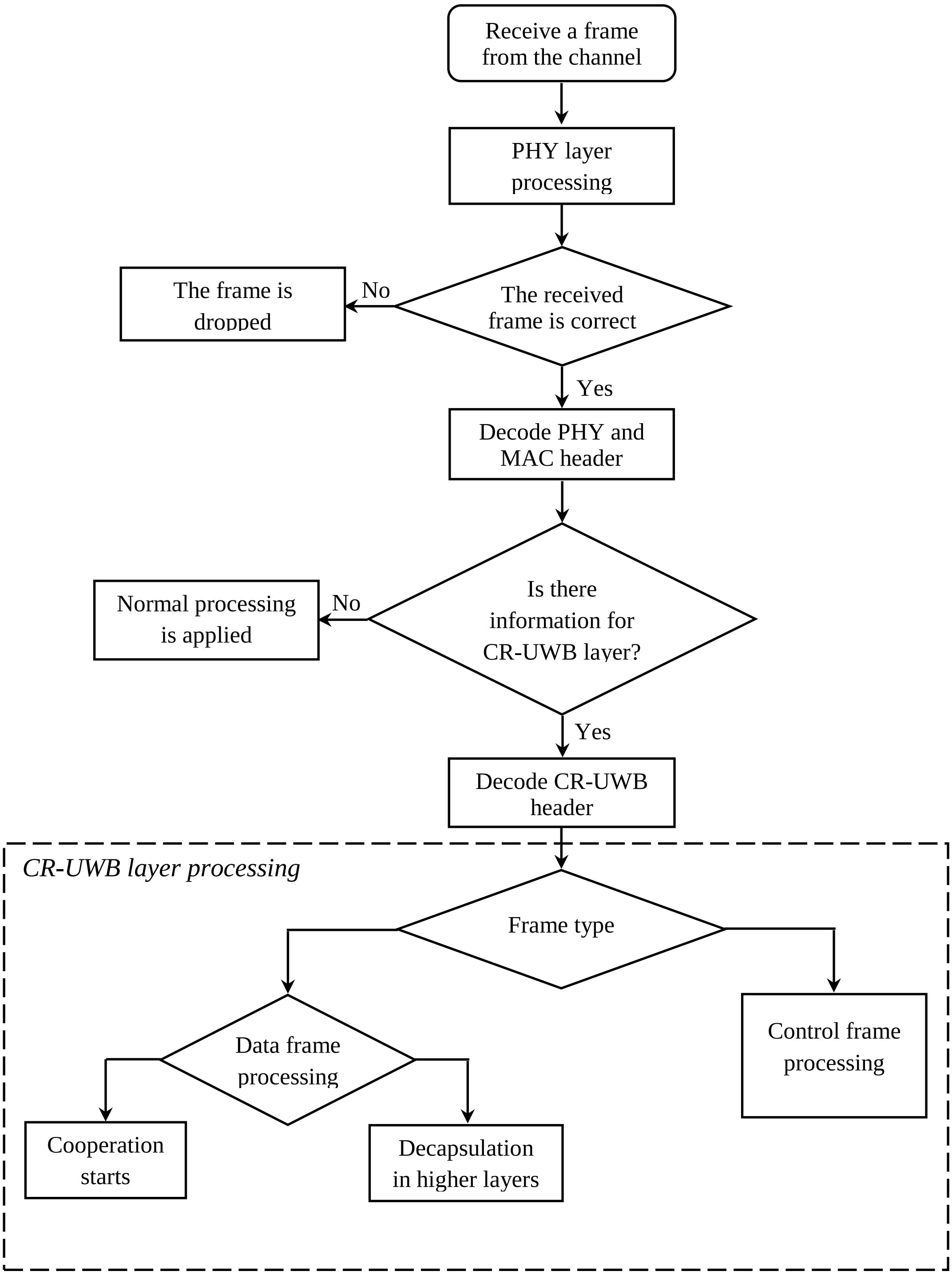

Figure 3.1 Frame processing in CR-UWB node with multiple air interfaces.

The algorithm shown in Figure 3.1 illustrates a set of key processing steps in the CR-UWB node when a new frame is received from the channel. Upon this receive the frame is being processed in PHY layer. In this case frame can be dropped due to RSSI below receiving threshold, unrecognized type or uncorrectable errors. The drop parameters are defined by technology used by the node at the moment. In case of correct frame its PHY and MAC frame are being decoded. During the decoding the frame needs to be checked whether it contains information for CR-UWB layer. The CR-UWB layer is interested in capturing CR-UWB control frames and relayed data frames. In the case that the received frame is Beacon Frame (which is indicated by MAC layer), the node seeks CR-UWB Information

Element and if found extracts it from the frame and further processes it as CR-UWB control frame. In its header each CR-UWB control frame (see Section 3.1) contains information about its purpose.

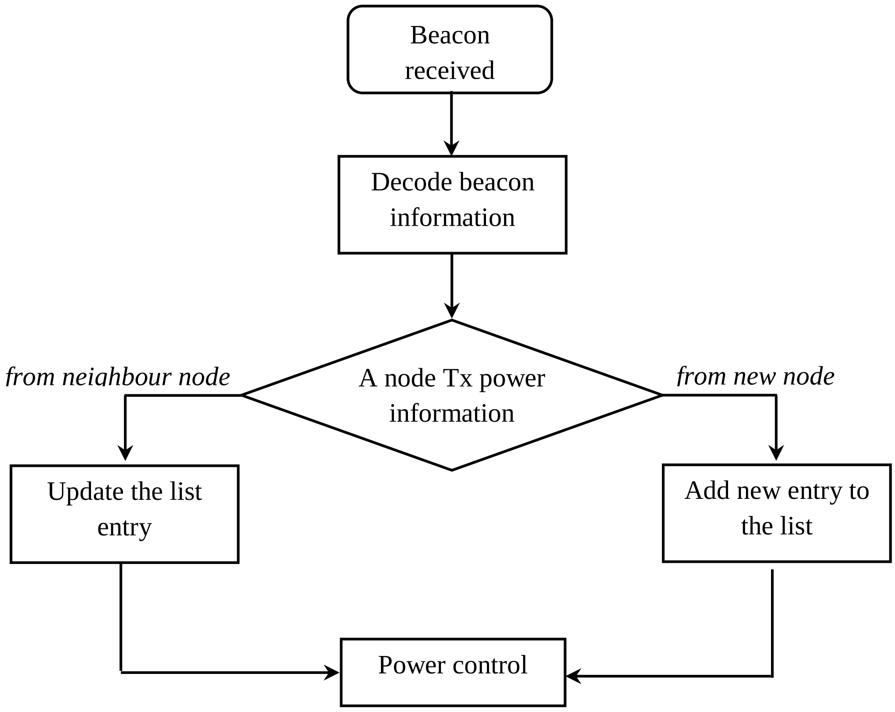

Figure 3.2 CR-UWB beacon reception.

Figure 3.2 shows how the CR-UWB node receives the beacon which contains the information on Tx power status from a node. As soon as the receiver decoded the beacon it performs the analysis if the information received from new node or from already known one. If the beacon is from new node the receiver creates a new entry in the list of Tx power status of neighbour nodes and starts power control mechanism. In the case when the beacon is from the neighbour node the receiver updates the entry and checks if power control is desired. We would like to node that the notions “receiver”, “node” in this section refer to CR-UWB node with multiple air interfaces. Power control mechanisms are described in Section 4.

4 Network Operation Optimization

In this section we present two performance optimization approaches for CR-UWB nodes with multiple air interfaces. These approaches are considered within public transport application. In the first approach we consider the case when all nodes support one communication technology, but interfere to each other. In order to find the highest utility we perform the searching of optimal parameters for each node.

In the second approach we assume that there are two communication technologies available for communication. These technologies occupy the same frequency band. To achieve interference mitigation we apply game theory paradigm.

4.1 Public transport application

In order to evaluate the proposed control mechanism for CR-UWB node with multiple air interfaces we consider public transport application, i.e. cabin management system, which is described in more details in EUWB WP8 [6].

The exploitation of wireless technologies in an aeroplane provide some advantages over wired ones: reduction of installation and maintenance time, flexible configuration, easy and fast reconfiguration, weight saving, etc. However, wireless communication must support a high level of reliability, dependability and system availability, providing the required quality of service to all the system components.

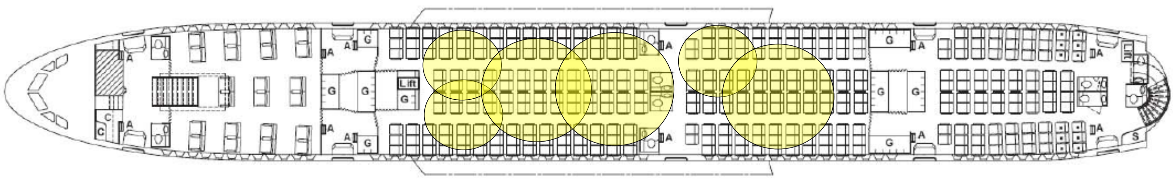

Figure 4.1 An example of operation of CR-UWB nodes in UWB mode in an aeroplane.

Figure 4.1 presents the cabin of aeroplane where some passengers use UWB devices. In this context we present a scenario where some users extensively use short range communication and in-flight entertainment facilities including all the services which are directly addressed to the passenger to enable an improved comfort experience like high definition video- or audio-on-demand. The performance optimization for this scenario is addressed in Section 4.2. We assume that CR-UWB nodes are switched to UWB communication mode by spreading beacons and find the communication parameters which provide the highest utility. Tx power status information is included into the beacon of each node, therefore, allowing each node to control its communication parameters, e.g. modulation, information rate, Tx power.

However, another communication technology interfering with UWB one may be available on board.

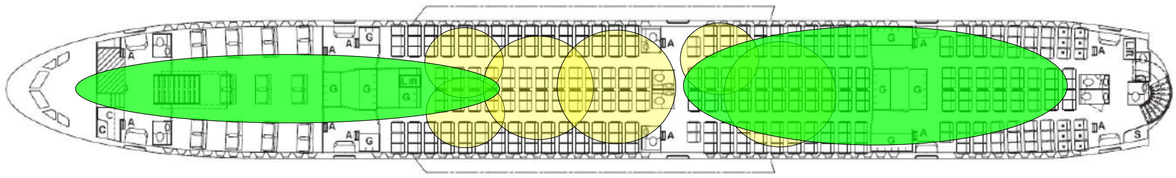

Figure 4.2 The example of coexistence of CR-UWB nodes operating in UWB mode (6 nodes) and WiMAX mode (2 nodes) in an aeroplane.

The example of two coexisting communication technologies on board, namely UWB and WiMAX, is shown in Figure 4.2. WiMAX can be used for improved communication services, e.g Internet. To overcome the interference and spectrum access problem we apply game theory paradigm in Section 4.3.

4.2 Optimization of communication parameters

In this section we consider a scenario when all nodes in the network support UWB technology, but some of them are LDR and another ones are HDR.

4.2.1 Network model

Let *Network 1*, *Network 2*, …, *Network i* be Secondary Cognitive Networks (SCN) where i=1, 2, …, N (see Figure 4.3). Each network contains transmitter (Tx) and receiver (Rx). The pair of nodes in a network can perform Tx and Rx functions interchangeably. We assume that both nodes do not perform Tx functions simultaneously. However, in our scenario we fix the operations of the nodes as it is shown in Figure 4.3. UWB links between Tx and Rx within each network are depicted in solid line, interference in dashed line. We assume the users in the network transmit data in the form of packets at a rate of R (bits/s) over a frequency bandwidth of B (Hz). We also assume that:

- the UWB nodes in the network may have different communication characteristics, e.g. be LDR or HDR;
- the UWB nodes have the same rights for spectrum utilization;
- the UWB nodes are rational: each node knows the system state information of other nodes, e.g location of transceivers, their Tx power level, etc.

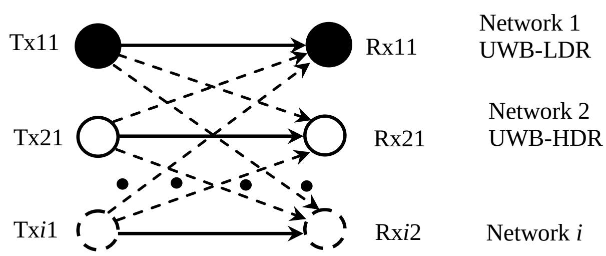

Figure 4.3 Scenarios for spectrum access among secondary cognitive networks.

The signal model is given by the following:

$$r_{i2} = \frac{s_{i1}}{L_{(i1 \to i2)}} + \nu + I_{i2} \qquad 4.1$$

where r_{i2} is received signal by the receiver in *i*-th network as in (4.3), s_{i1} is transmitted signal by the transmitter in *i*-th network, $L_{i1 \to i2}$ is a path loss in the channel between transmitter and receiver in *i*-th network as in (4.4), I_{i2} is interference at the receiver in *i*-th network, ν is Additive White Gaussian Noise (AWGN):

$$P_\nu = k \cdot T \cdot B \qquad 4.2$$

where k is the Boltzmann constant, T is the receiver's temperature, and B is the receiver's bandwidth.

In the proposed model Tx nodes Tx_{11}, …, Tx_{i1} may transmit UWB signals with the transmission power $P_{T,i1}$, …, $P_{T,i1}$ which may vary $P_{T,i1min} < P_{T,i1} < P_{T,i1,max}$ with ΔP_T step. The relationship between received and transmitted power (in dBm) can be expressed as:

$$P_{R,i1}(dBm) = P_{T,i2} - PL(d_{ij,ij`}) \qquad 4.3$$

where $P_{R,i1}$ is useful signal received by *i2*-nd receiver from *i1*-st transmitter, $P_{T,i2}$ is transmitted power to *i2*-nd receiver from *i1*-st transmitter, *PL* is path loss, $d_{ij,ij`}$ is the distance between *ij*-th and *ij`*-th nodes.

Path loss (in dB) can be determined as:

$$PL(d_{ij,ij`}) = PL_0 + 10\alpha \log_{10}\left(\frac{d_{ij,ij`}}{d_0}\right) \qquad 4.4$$

where the value of PL_0 is based on a free space assumption from the transmitter to d_0 and is defined by (4.5), α is the path loss exponent, d_0 is the reference distance.

$$PL_0 = 10\log_{10}\left(\frac{4\pi d_0 f_c}{c}\right)^2 \qquad 4.5$$

where f_c is the transmit frequency and c is the speed of light.

Due to the assumption that nodes in the network may change its function (be either Tx or Rx) within one network, it is obvious that the interference levels will be changed as well. In the following we assume that CN knows the respective coordinates of the nodes. Thus the distance between two nodes can be defined as following:

$$d_{ij,ij`} = \sqrt{(x_{ij} - x_{ij`})^2 + (y_{ij} - y_{ij`})^2} \qquad 4.6$$

where x_{ij}, y_{ij}, $x_{ij`}$, $y_{ij`}$ are the coordinates of *ij*-th and *ij`*-th nodes respectively.

To avoid harmful interference the *Tx* nodes must support their transmission power rates in accordance to the specified Signal-to-Interference-plus-Noise Ratio (SINR), γ_n, which is known to all nodes. The SINR in AWGN channel (where interference is Gaussian distribution) is:

$$\gamma_{i2} = SINR_{i2} = \frac{P_{R,i1}}{P_\nu + I_{i2}}$$
$$\begin{cases} I_{i2} \sim N(0, \hat{I}_{i2}) \\ \nu \sim N(0, P_\nu) \end{cases} \quad 4.7$$

where, $P_{R,i1}$ is useful signal received by i2-nd receiver from *i1*-st transmitter, I_{i2} is the interference at the *i2*-nd receiver, $\hat{I}_{i2}$ is the mean value of interference as in (4.8), and ν is AWGN noise as in (4.2).

$$\hat{I}_{i2} = \sum_{\substack{k=1 \\ k\neq i}}^{N} P_R(k1) = \sum_{\substack{k=1 \\ k\neq i}}^{N} \left[P_T(k1) - L(k1 \rightarrow i2) \right] \quad 4.8$$

where $P_R(k1)$ is the received power (interference) from *k1*-st transmitter, $P_T(k1)$ is the emitted power from *k1*-st transmitter, $L(k1 \rightarrow i2)$ is path loss in the channel.

The nodes can adjust their own transmission power $P_{T,i1}$ to fulfil SINR threshold requirements of $\gamma_{i2,th}$.

4.2.2 Performance metrics

In this section we evaluate the performance of proposed model. For the analysis of the model we apply an optimization technique based on utility function. We show, how the utility function is calculated using performance metrics.

Performance metrics aimed at the evaluation of CR performance at the node, network, and application levels.

To evaluate the proposed model we use the following metrics: SUE and BER.

4.2.2.1 SUE metric

It is proposed that the SUE metric – the unit of measure of spectrum-space use – be defined as the product (bandwidth)×(relevant physical space)×(time) that is denied to other potential users [4].

In this work we consider *technical spectral efficiency* [5] which would consider the theoretical capacity of the wireless components to carry traffic using the least amount of spectrum. This would be somewhat different from a notion of *operational spectral efficiency* which would measure the practical efficiency of a system under operational conditions.

A measure of SUE can be described in general form:

SUE=(information delivered)/(spectrum space used) 4.9

We define SUE as a complex metric:

$$SUE = \frac{R_b}{B \cdot S} \quad 4.10$$

where R_b is a raw bit rate (bits/s) at the modulator input as in (4.11), B is a frequency bandwidth, S is a relevant physical space.

$$R_b = \log_2 M \cdot R_s \quad 4.11$$

where R_s is resulting symbol rate (symbols/s), M is the number of encoding levels of modulation. For BPSK, FSK, DPSK $M = 2$. For QPSK M = 4.

Analysis of radio spectrum assumes benefits for a CR which will be able:

- To fit into the spectral footprint of other CRs;
- To minimize the CR`s own footprint.

The corresponding iterative algorithm has five steps:

1. Set initial values of R and B;
2. Calculate SUE_{ni} If $SUE_{ni} > SUE_{ni,th}$ go to step 5, else go to step 3;
3. Choose next *input R x B* vector;
4. Continue with step 2;
5. End.

4.2.2.2 BER metric

Bit Error Rate (BER) is an important objective for all digital communications' needs. It provides a baseline for the amount of information transferred, and so understanding it in light of the design of a waveform under certain channel conditions is therefore necessary. Unfortunately, BER calculations depend heavily on the type of channel and type of modulation, and so the cognitive engine must know the formula for each modulation type the radio is capable of using and the channel types it is likely to see during operation. In this section, we have collected a number of bit error rate formulas (see Table 4.2.1).

Table 4.2.1 Probability of bit error.

Modulation type	**Probability of error**
BPSK	$Q\left(\sqrt{\frac{2 \cdot E_b}{N_0 + I_0}}\right)$
DPSK	$\frac{1}{2} \cdot \exp\left(-\frac{E_b}{N_0 + I_0}\right)$
QPSK	$Q\left(\sqrt{\frac{2 \cdot E_b}{N_0 + I_0}}\right)$
Coherent FSK	$Q\left(\sqrt{\frac{E_b}{N_0 + I_0}}\right)$

where N_0 is noise power spectral density, I0 is the interference power spectral density

The BER is a number of received bits that have errors divided by the total number of transferred bits during specified time interval. The BER (P_e) depends on the digital modulation scheme deployed by the system (Table 4.2.1) and is expressed in terms of γ_{i2}:

$$\gamma_{i2} = SINR = \frac{E_b}{N_0 + I_0} \qquad 4.12$$

where E_b is the energy per bit, N_0 is the noise power spectral density, and Io is interference power spectral density. *Q*-function in Table 4.2.1 is defined as:

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_{x}^{+\infty} e^{-\frac{x^2}{2}} dx \qquad 4.13$$

where *x* is the SINR.

Thus, the BER value in Table 4.2.1 is calculated by using the SINR value from (4.7) and using (4.13).

The corresponding iterative algorithm for BER calculation comprises 5 steps:

1. Set initial $P_{T,ij}$, *d*, values and modulation type for each corresponding CR;
2. Calculate the *BER* according to (4.7) and Table 4.2.1. If $BER_{ni} < BER_{ni,th}$ go to step 5; else go to step 3;
3. Choose one *input* vector from Cartesian product;
4. Continue with step 2;
5. End.

4.2.3 Utility function

The utility function maps the current state of the CR, usually represented by an array of chosen metrics, to a value for indicating how close the state is towards the desired (optimal) CR state. The utility function is defined as following:

$$u_{ni} = \sum_{i=1}^{N} \frac{\beta_{SUEi} \cdot SUE_i}{\beta_{BERi} \cdot BER_i} \qquad 4.14$$

where β_{SUE} and β_{BER} are the weightings of importance of respective performance metric.

Obviously, to improve the overall utility one has to increase the SUE and decrease the BER of each CR. QoS can be defined in terms of minimum utility u_{ni} for a given CR_{ni} and may be expressed as:

$$u_{ni} \geq u_{ni}^{*} \qquad \forall ni \qquad 4.15$$

The value u^{*}_{ni} is a threshold which ensures CR_{ni} performance quality, and may be determined from the BER and SUE requirements.

4.2.4 Simulation results

For the model proposed in Section 4.2.1 we carried out the simulation of two networks. We refer the networks to LDR and HDR. It is assumed that the HDR network has higher both transmission power level and potential data rate. Each network supports four modulation types as well as four transmission levels and data rate (see Table 4.2.2). In simulation we assume equal metrics importance with β_i = 50%. In order to calculate the overall utility we follow the methodology described in Section 4.2.2 and 4.2.3.

Table 4.2.2 Simulation parameters

LDR network	**HDR network**
P_T = -17, -15, -13, -11 [dBm]	P_T = -14, -12, -10, -8 [dBm]
R_s = 40, 80, 100, 250 [ksymbols/s]	R_s = 11, 22, 33, 44 [Msymbols/s]
Bandwidth, *B*, 500 [MHz]	
Transmission frequency, *f*, 3.2 [GHz]	
Relevant physical space, *S*, 10 [m^2]	
Path loss fading, *α*, 3.5	
Available types of modulation: BPSK, DPSK, QPSK, FSK	

The purpose of the simulation is to find the optimal parameters in order to achieve the highest utility function.

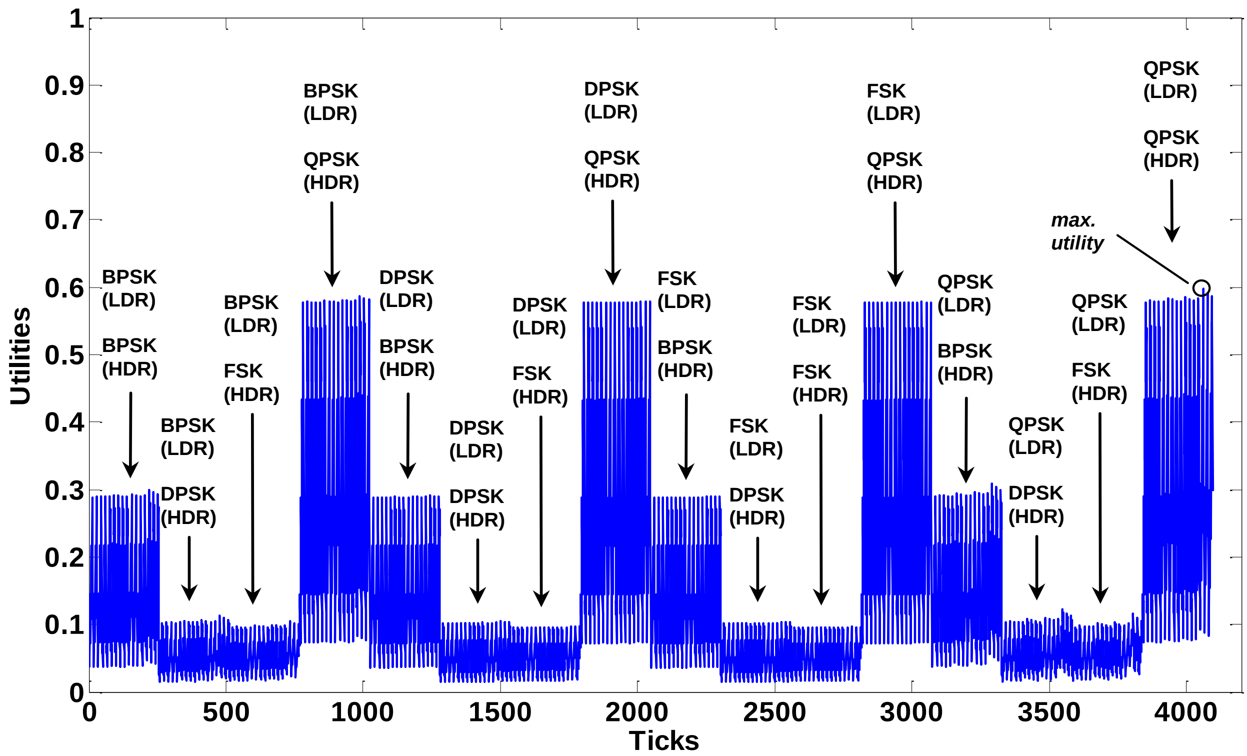

Figure 4.4 The search of the highest utility.

To do so we set up initial communication parameters for each network (see Figure 4.4) and start iterations. Each combination of appropriate modulations provides us with 256 iterations (marked as ‘Ticks’ on the *x* axis) of total utility. The search of the highest utility shows that the best utility is gained with QPSK modulation at LDR network and QPSK modulation at HDR network.

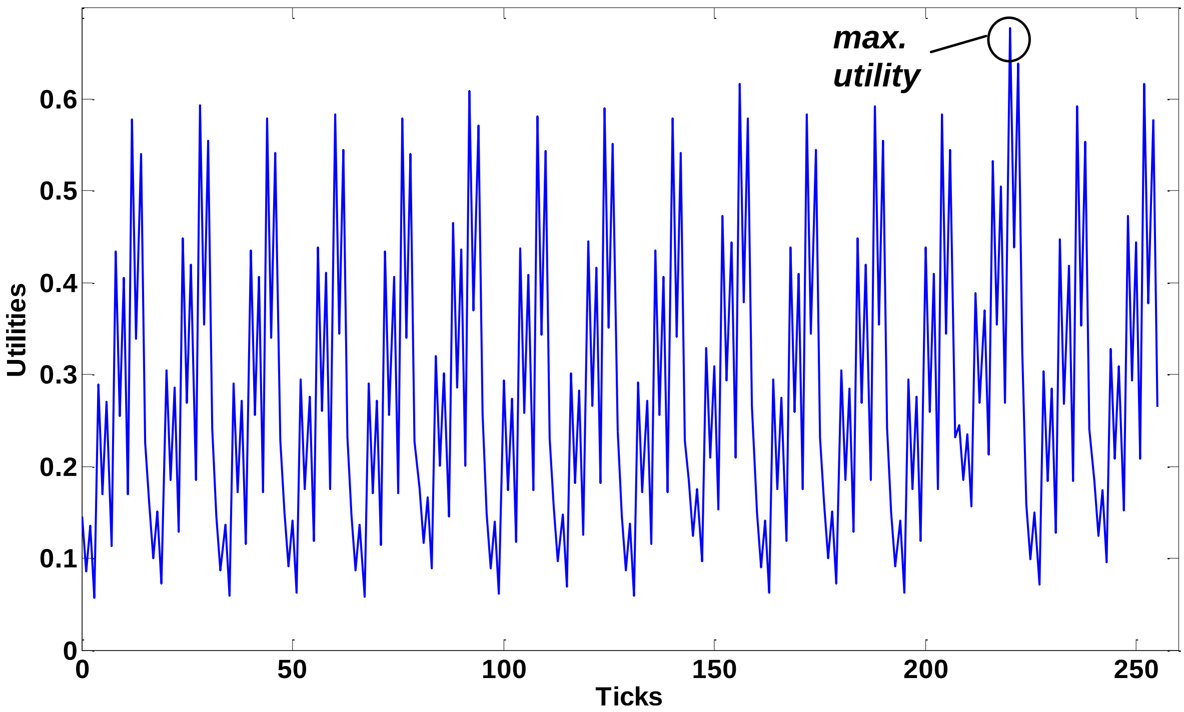

Figure 4.5 256 iterations: QPSK modulation at LDR and HDR networks.

Figure 4.5 shows the 256 zoomed iterations of the highest utility search when both networks support QPSK modulation. The highest utility is being provided by 218-th iteration which is composed of fourth value of data rate (250 ksymbols/s) and the second value of transmission power (-15 dBm) at LDR network and the third value of data rate (33 Msymbols/s) and the second value of power transmission (-12 dBm) at HDR network.

Analyzing the simulation results we may summarize that the networks achieve the best performance when HDR network uses QPSK modulation. That happens due to low BER and high SUE at QPSK modulation. The modulation type and the level of transmission power of LDR network do not significantly affect the overall utility.

4.3 Power control using game theory

In this scenario we assume that there are primary users in the network which support WiMAX and the secondary users which support UWB technology (see the model shown in Figure 4.6). We consider the model when PUs impose the interference temperature restriction which cannot be exceeded. Power control of the SUs is implemented using the *game theory* paradigm. In order to fulfill the game we use the utility function which both maximizes SINR and minimizes the transmit power of a SU in real time.

4.3.1 Spectrum access model

In this scenario we use the same spectrum sharing model as in previous scenario, but assume that PUs (WiMAX) appeared and impose the interference temperature restriction which cannot be violated by SUs. This restriction is expressed by WiMAX Control Point (CP). This point monitors the power level of each SU's transmitter and requests to adjust the corresponding power in accordance with the restriction. The centralized power control algorithm is focused in finding a trade-off between the minimal transmit power and the highest rate of each user.

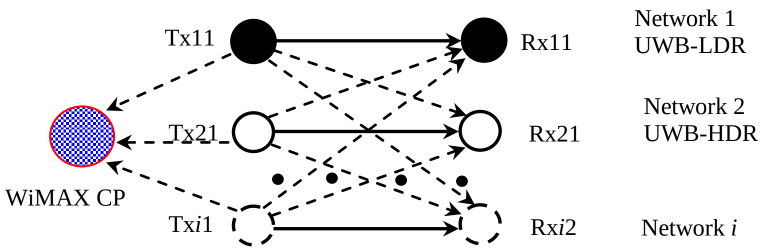

Figure 4.6 Scenarios of spectrum access.

The equations (4.1) – (4.6) used in Section 4.2.1 can be adopted for network analysis. However, to avoid harmful interference we protect the PUs by placing CP. CP monitors interference level not to exceed maximal interference (I_{max}) and request a SU to decrease its Tx power in the case when condition in (4.16) is violated.

$$P_{R,i1,CP} \leq \frac{I_{\max}}{n_{Tx_{i1}}} \tag{4.16}$$

where n_{Txi1} is the number of active transmitters in neighbouring networks. The mean value of interference measured at the CP ($\hat{I}_{CP}$) is expressed as

$$\hat{I}_{CP}(dBm) = 10\log_{10}\sum_{\substack{k=1\\k\neq i}}^{N} P_R(k1) = 10\log_{10}\sum_{\substack{k=1\\k\neq i}}^{N} \frac{P_T(k1)}{PL(k1 \to CP)} \tag{4.17}$$

Where $P_R(k1)$ is the received power (or interference) from k1-st transmitter by CP, $P_T(k1)$ is the emitted power by k1-st transmitter, and PL(k1 -> CP) is path loss in the channel.

4.3.2 Game model development

Thanks to the game theory, the network designers are equipped with the tools required for the application of balanced network resources. The game theory is based on the concept of a game defined in normal form: $G = \langle N, A, \{u_i\}\rangle$ where G is a particular game, N = {1, 2…, n} is a finite set of players (decision makers), A_i is the adaptation space available to player i, $A = A_1 \times A_2 \times ... \times A_n$, and $\{u_i\} = \{u_1, u_2, ..., u_3\}$ is the set of utility (objective) functions that the players wish to maximize.

The network described in Section 4.3.1 can be modelled as a game as follows:

- *Players*: The set of all decision making CRs in the collaborating networks $N = \{Tx_{11}, Tx_{21}, \ldots, Tx_{i1}\}$;
- *Actions*: The set of available inputs, Q_i (in our case $P_{T,i1}$);
- *Utility function*: In this scenario we use the utility function described in the following subsection;

4.3.2.1 Utility function

Utility is an assignment of values to the current operating state such that the closer the CR comes to satisfying some goal, the greater the value assigned to the operating state. Here we design a utility function with which we achieve the following objectives:

1) maximize the SINR or equivalently maximizing the information rate, R, formally given by the Shannon's law R = log2(1 + SINR); note that in our case we consider the SINR at the Rx end which we assume to be communicated by the Rx to Tx by some signaling means;

2) minimize the transmit power, $P_{T,i2}$, to save power as well as reduce interference to the environment.

Hence, the utility function can be expressed as

$$U(P_{T,i1}, P_{T,i2}) = \exp(-P_{T,i1})[1 + SINR_{i2}] \quad 4.18$$

where maximizing U will jointly minimize the power usage and maximize the information rate to a certain extent. $SINR_{i2}$ is expressed in (4.7).

Then our overall objective is to maximize $U(P_T, P_I)$ with respect to P_T given by

$$\hat{P}_T = \arg\max_{P_T} \{u; P_{R,i1-CP} + P_{R,i2-CP} \le I_{\max}\} \quad 4.19$$

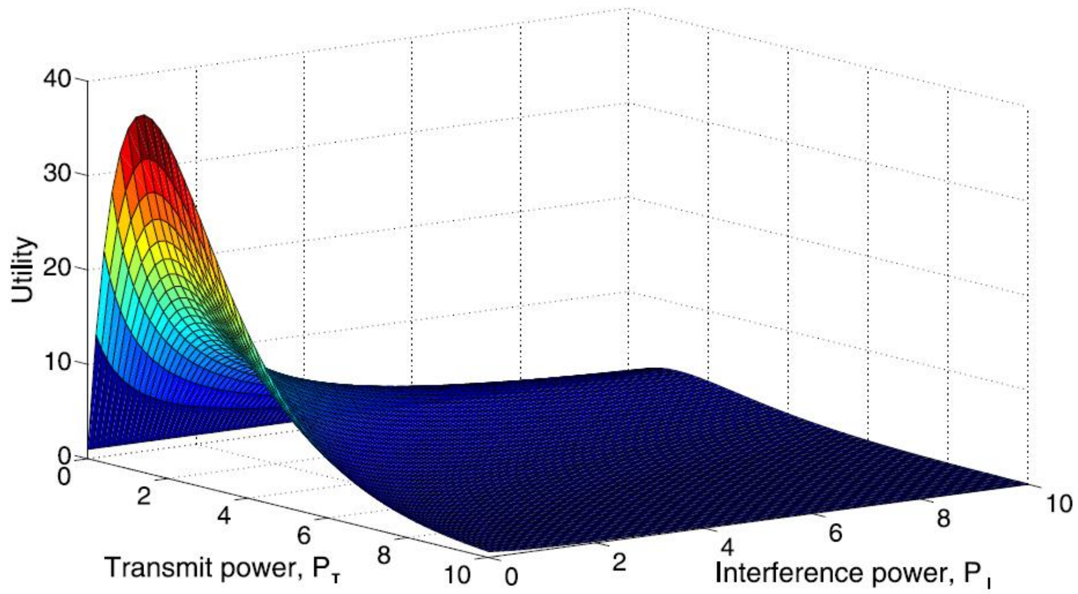

Figure 4.7 An example of user's utility function.

Figure 4.7 shows the example of utility function which finds the optimum operating region depending on P_T and P_I.

4.3.2.2 Transmit power optimization

Based on the above mentioned utility function $U(P_{T,i1}, P_{I,i2})$ we derive the optimal point for the transmit power level at a particular transmitter in this section. Let us redefine the utility function in general terms without considering the subscripts, given by $U = \exp(-P)[1 + P/(LP_0)]$, where, P is the transmit power, L is the pathloss and P_0 is the aggergated interference and noise power levels.

To derive the optimum transmit power level we consider the first order partial derivative of *U* with respect to *P*, given by,

$$\frac{\partial U}{\partial P} = U' = \frac{1}{LP_0}\exp(-P)[1 - P - LP_0] \qquad 4.20$$

The optimum point is achieved when $U' = 0$ and from (4.20) we see that it is obtained when $P_{opt} = 1 - LP_0$. Moreover, in order to prove that our strategy proposed in (4.19) is optimum, we consider the second derivative of *U* and prove that $U(P_{opt})$ is a global maxima of *U*. the second order derivative is given by,

$$\frac{\partial^2 U}{\partial P^2} = U'' = \frac{1}{LP_0}\exp(-P)[P - 2 + LP_0] \qquad 4.21$$

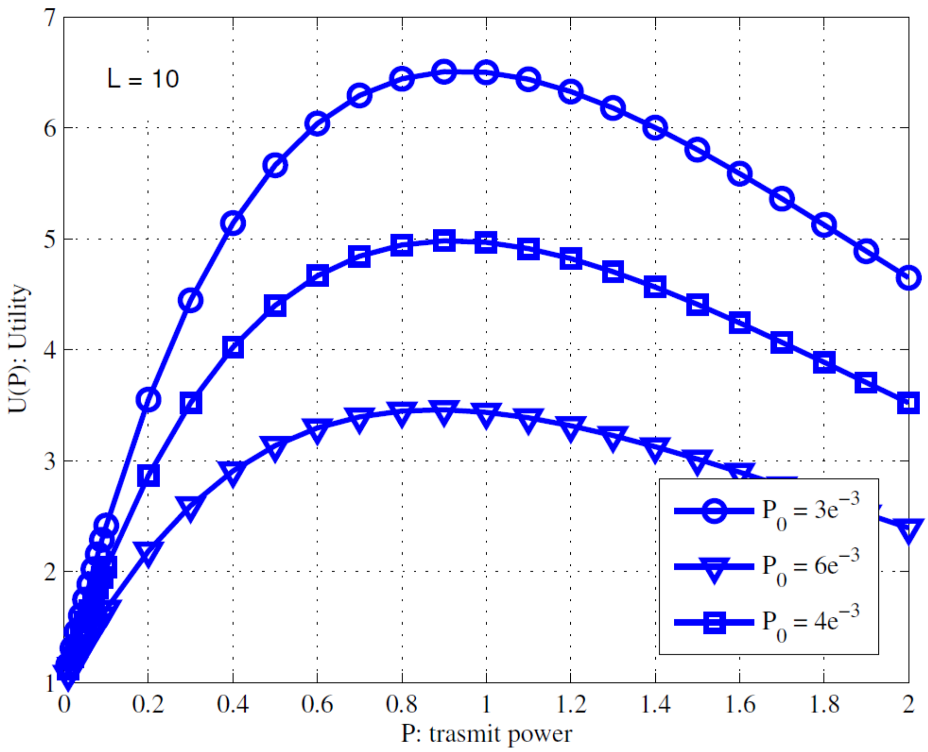

Figure 4.8 Utility function displaying the optimum transmit power levels at $1 - LP_0$, for various values of P_0.

Therefore, from (4.21) we observe that $U''(P_{opt}) < 0$, $\forall P \in R^+$, hence giving us a global maxima.

4.3.2.3 Power control algorithm

Figure 4.9 represents the example of algorithm which finds an equilibrium operation point for two networks. However, it can be easily upgraded for *n* networks. Formally, the algorithm provides each player in the game model with the highest possible utility with respect to transmit and interference power.

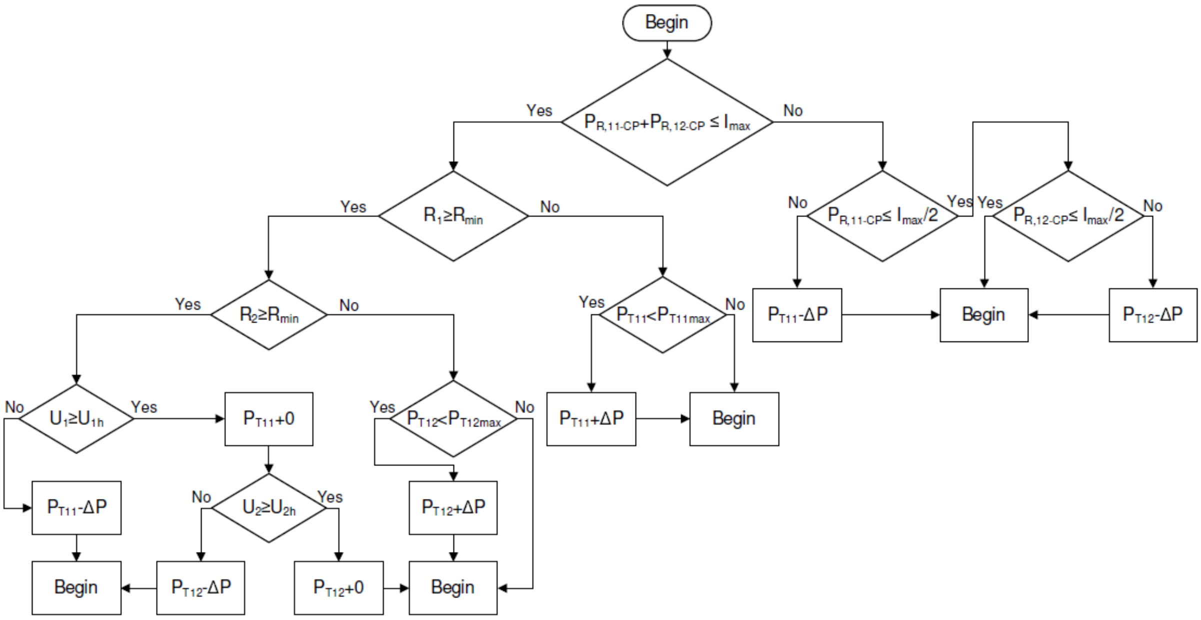

Figure 4.9 Power control algorithm.

In fact, the proposed power control algorithm has three main conditions which have to be met.

The total interference (I_{max}) in the network must be less or equal than its maximum level. CP performs this task and when this condition is violated it analyses which transmitter interferes too much: $P_{R,i1-CP} \leq \frac{I_{\max}}{2}$. As soon as CP reveals this transmitter it requests to decrease its Tx power for ΔP value.

Information rate (R) in the network must be high enough to support the minimal value, R_{min}, in order to provide a user with a desirable performance. If a transmitter can not follow this condition with established transmit power the dedicated receiver requests to improve it on ΔP value.

The highest possible utility could be obtained at low transmit power level. However, with the decrease of power level we also decrease the information rate. To avoid the infinite loop which adjusts the power in order to support desirable information rate and utility we introduce the notion of *historical utility* (U_h). This value is the information based on the past calculations. U_h informs the algorithm regarding the power rates at which a user achieves an acceptable utility. In case when utility of a corresponding transmitter is less than historical value it requests the transmitter to decrease its transmit power for ΔP value. Otherwise, the algorithm keeps the last value of utility until a parameter changed in the network.

4.3.3 Simulation results

To evaluate the network and game models we simulate three scenarios for two networks. The simulation parameters are presented in Table 4.3.1. Figure 4.10 shows how two networks adjust the transmit power in Scenario 1. Tx1 achieves smooth operation in thirty ticks and does not adjust its parameters anymore. Transmitters are 3.5 m far from each other as well as CP is 3.5 m far from each transmitter.

Table 4.3.1 Simulation parameters.

	Scenario 1	Scenario 2	Scenario 3
Transmit power, dBm	3/11*	3/11	3/11
ΔP_T, dBm	0.1	1	1
Distance CP-Tx_{i1}, m	3.5	3.5	7
Min. information rate, Mbits/s	320	320	320
Transmission frequency,GHz	3.2	3.2	3.2
Bandwidth, MHz	500	500	500
Path loss exponent	3/2	3/2	3/2

* - The numbers separated by "/" in Table 4.3.1 are referred as the values of Tx_{11} / Tx_{21} respectively.

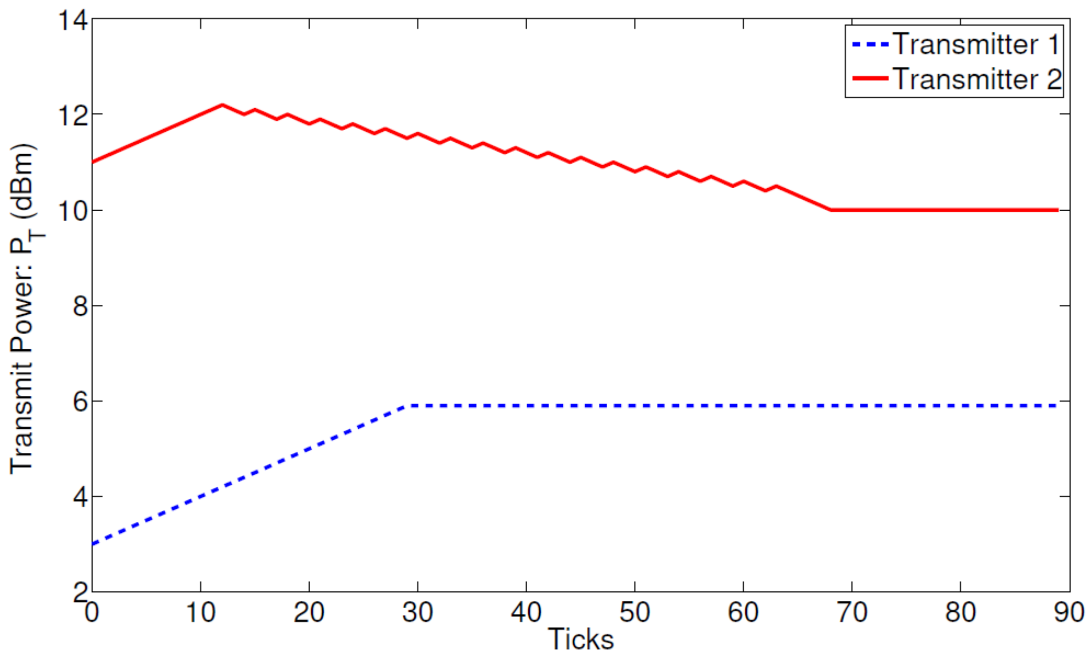

Figure 4.10 Tx power adjustment for scenario 1.

Figure 4.11 shows the power adjustment similar to Scenario 1. However, ΔP_T value is 1 dBm for Scenario 2. The transmitters reach stable operation faster in comparison to Scenario 2. Transmit power in stable mode coincides with the previous case, but there is no connection between proportional increase in ΔP_T and equal stable Tx power values delayed in time.

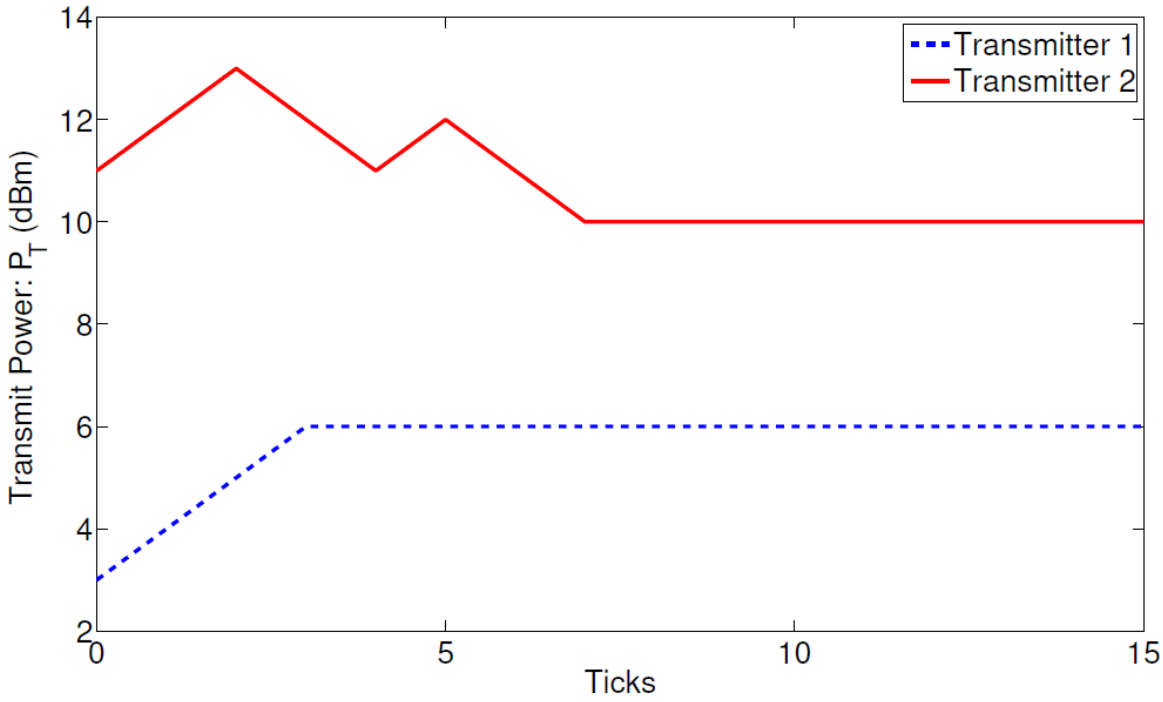

Figure 4.11 Tx power adjustment for scenario 2.

In Scenario 3 we keep all the network parameters like in previous simulation, but increase the distance among three nodes up to 7 m. It takes more time to find balanced operation and requires more power to support stable operation (see Figure 4.12).

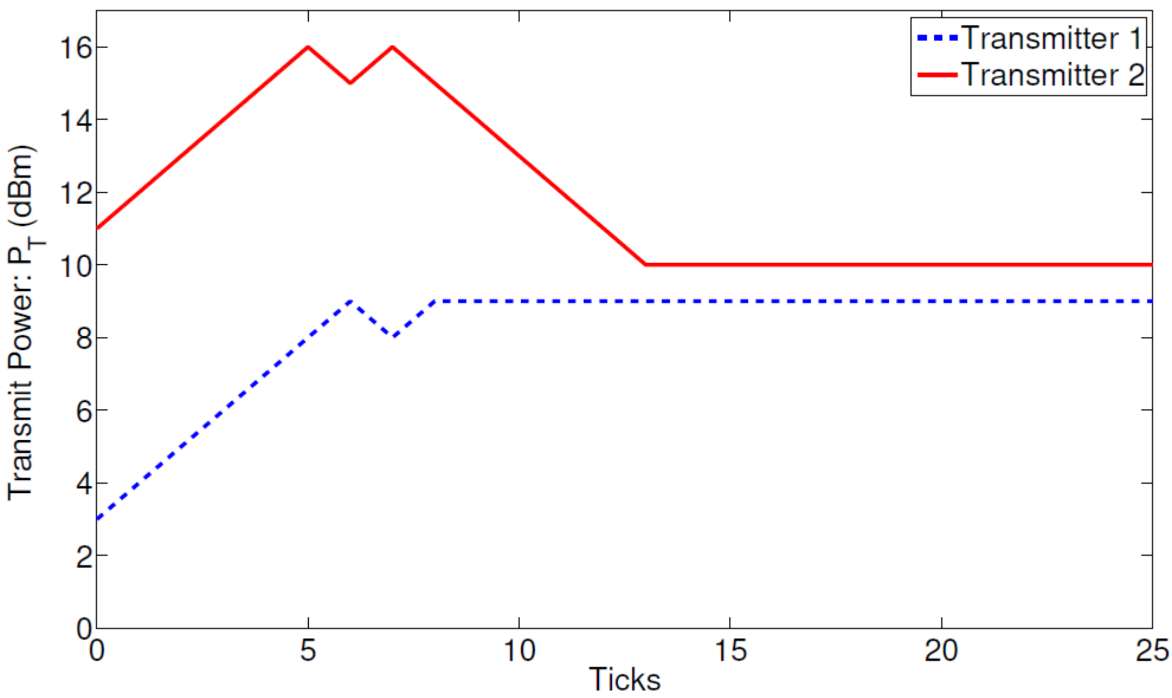

Figure 4.12 Tx power adjustment for scenario 3.

5 Conclusions

This deliverable investigates the use of a CR-UWB node with multiple air interfaces as the control unit, wherever multiple air interfaces are co-located. This work starts with the development of the architecture of the node with multiple air interfaces. In order to support control functions in the node we propose beaconing mechanism where each beacon includes the information about co-located nodes and their parameters, therefore, giving a chance to optimize the performance of each node.

Within this deliverable we also propose two approaches for interference mitigation for all nodes under restricted conditions. We would like to note that we considered public transport application, namely aeroplane environment, for the evaluation of the proposed techniques. The first technique is based on the iteration of communication parameters to find the highest utility for the nodes. This technique overcomes the problem of power control in the cabin of an aeroplane when a number of the nodes operate in UWB mode and interfere to each other. The second technique adopts game theory paradigm to address the problem of the coexistence of WiMAX and UWB communication technologies. This approach allows one to find a trade-off for using both WiMAX and UWB at the same time.

References

[1] A. Siera et. al, Project Report – D6.1.2: 'Description of First Family of Multi-radio Interface User Devices,' EUWB Integrated Project, European funded project (EC: FP7-ICT-215669), May 2011, http://www.euwb.eu

[2] "IEEE Standard for Information technology-Telecommunications and information exchange between systems-Local and metropolitan area networks-Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," *IEEE Std 802.11-2007 (Revision of IEEE Std 802.11-1999)*, 2007, pp. C1-1184.

[3] G. Heidari, *WiMedia UWB: technology of choice for wireless USB and Bluetooth*, Wiley Publishing, 2008.

[4] L. A. Berry, "Spectrum metrics and spectrum efficiency: Proposed definitions," *IEEE Trans. Electromagnetic Compatibility*, vol. EMC-19, no. 3, pp. 254–260, Aug. 1977.

[5] "Definition of spectrum use and efficiency of a radio system", ITU-R Rec. SM-1046-2.

[6] S. Bovelli and F. Leipold, Project report – D8a.1: 'Scenario description for public transport application,' EUWB Integrated Project, European funded project (EC: FP7-ICT-215669), June 2011, http://www.euwb.eu

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.