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Coexistence Analysis of the Subsystems at Radio Signal Level

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This report will expose the theoretical analysis processes as input to the spectrum measurements that result, e.g. in the detection of mutual interference effects, output power deteriorations, etc... Various possible configurations are taken into account for different radio environments (indoor or outdoor) and installations as defined in task 5.4. Fraunhofer IIS leads the measurement phase with contributions of ANA and INOV with respect to possible conflicts to be tested.

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1 Introduction to Coexistence of Radio Systems

Various radio systems – irrespective if used for communication or localization purpose – share their transmission medium, the air spectrum. Like considering many other natural resources, the availability of this radio spectrum is limited for the electronic devices depending on it. Hence, sometimes resource conflicts between coexisting systems arise and the systems can distort each other up. This distortion reaches from unremarkable and resolvable impacts up to hindering totally the intended communication functionality. Although the distortion is usually mutual, this text makes the separation of a system of interest (SOI) and the potential source of distortion, the radio interferer (RIF). Target of the work is to identify conflicts or coexistence issues between systems and to quantify this impact on the SOI and its performance in order to compile a list of advice for the deployment of radio systems.

1.1 General Overview

Especially, in ISM band (for *industrial, scientific, and medical*) between 2.4 GHz to 2.5 GHz and between 5.725 GHz and 5.875 GHz regulating authorities (ECC, FCC) allow for unlicensed access to the respective frequency band. In these bands various communication networks and localization systems – also denoted as real time locating systems (RTLS) – compete for the utilization of the air interface. Examples for localization systems of the LocON partners in the ISM bands are the LPR system from Symeo in the 5.8 GHz band, the WisMIT/Goniometer platform from Fraunhofer IIS, and the WLAN-Tag based system from CIT both in the 2.4 GHz range. The ISM band above 5 GHz is extended in the US by the U-NII (*unlicensed national information infrastructure*) spectral region from 5.15 to 5.35 GHz and from 5.470 to 5.825 GHz. There, the unlicensed channel use underlies slightly stricter regulations with respect to the allowed power levels and the channel access mechanisms. In the Europe regulation some stricter requirements than in the US (see Section 3.1.7) are defined.

Conflicts arise per definition with ultra wideband (UWB) systems that make access to large parts of the already employed radio spectrum. Consequently, for UWB only a extremely low power spectral density is allowed in order not to distort coexisting primary users. In Europe the mainly foreseen spectrum reaches from 6 GHz to 8.5 GHz, in the US from 3.1 GHz to 10.6 GHz. There, UWB systems are allowed to transmit with a maximum power spectral density of -41.3 dBm/MHz and a peak power of 0 dBm. An example for UWB based systems is the localization system by the LocON partner CEA/LETI working however as a laboratory prototype with 500 MHz bandwidth at a center frequency of 4.2 GHz.

In other spectral ranges, licensed users have exclusive access to the spectrum. Examples represent the 0.9 GHz and 1.8 GHz bands for GSM, the 2 GHz band for UMTS and the 450 MHz band for CDMA450. With the exception of the largest player – the global navigation satellite systems (GNSS) with global coverage (1.2 GHz and 1.7 GHz) –, there do not exist localization systems with even region- or nationwide networks – except for those of course that base their service on the nationwide communication networks. Consequently, their market and their business model is more manufacturer and application centred contradicting a strict licensing of a part of the spectrum. Therefore, the ground and infrastructure based localization systems have mainly unlicensed spectrum access (ISM or UWB). With the expected introduction of cognitive radio systems in the years to come, the strict separation will become softer. Target of cognitive radio research is to exploit the temporally unused spectrum of primary (licensed) users like GSM, UMTS, etc. for the cause and profit of a secondary cognitive network.

Radio systems may distort each other if they transmit in the same or nearby ranges of the radio spectrum and if their radio cells overlap. The latter occurs when the distance between the interfering transmitter and the victim device is that small that a remarkable part of the signal energy leaks into the signal of interest. Concerning to signal propagation, this happens when the respective path loss is weak and/or the respective radiated power is strong.

With regard to communication systems, then, the reception of bits or whole frames fails because of a low signal to interference and noise ratio (SINR). Thus, the communication may be hindered entirely. Similarly, for radio localisation systems especially for RTT systems, the localisation will fail if the data packets cannot be detected and identified correctly due to the enhanced distortion level.

If real-time locating systems (RTLS) transmit in the same overlapping band, the localisation accuracy may suffer from the mutual interference to that extent that the potential gains due to sensor fusion diminish or are even turned into losses in accuracy, coverage and reliability. As a worst case, the localisation fails completely and no reliable position estimate is obtained from both systems. This represents the main motivation of the report and its underlying research in the course of the LocON project. Therein, the interconnection between a set of heterogeneous localization systems is considered and implemented via a middleware platform in order to profit from their individual strengths in different scenarios and to avoid their weaknesses in other situations with a carefully designed data fusion. Additionally, this enables LocON to provide seamless localization of persons, vehicles and objects in complex infrastructures like airports.

Several works have done research on the topic of interference, e.g. [2],[4]. Also the standardization committees at the Institute of Electronics and Electrical Engineers (IEEE) have realized the importance of the coexistence for the implementation of new standards. The IEEE has set up a group that is supposed to bring forward a standard for the coexistence and interference analysis, enumerated IEEE P1900.2 [3] in the standards coordinating committee SCC 41 working in the area of cognitive radios.

The remaining text is outlined as follows: at first in Chapter 2, the effects and their describing parameters are discussed that determine the classification and the degree of a coexistence issue. Then, a theoretical analysis introduced providing initial results. Afterwards, in Chapter 3 introduces several methods that may help to prevent or reduce the unwanted interference effects. Chapter 4 provides a spectral mask for Faro airport, and discusses the impact on the issue of coexistence. Chapter 0 introduces a measurement procedure trying to verify the theoretical findings, and presents the measurements results.

1.2 On the LocON Project

The LocON project aims at integrating embedded localisation systems and embedded wireless communication in an open, standardised way. Thus, the project partners develop a new platform in order to control and manage large scale infrastructures, like airports, more efficient, secure, robust and flexible.

With the implementation of new security control services, the added values of LocON will be shown on a Portuguese airport site at Faro in autumn 2010. The *LocON platform* is a key enabling technology for new services in various markets. Via an open *position information layer*, all kinds of localisation systems using the LocON standard can be integrated. Therefore, the LocON concept is attractive to all types of large infrastructures which require localisation as a tool for new or better adapted monitoring and control services.

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Partners of LocON are Fraunhofer IIS, ANA – Aeroportos de Portugal, perLocus, Symeo, Bijo Data, CEA-LETI, CIT – Cork Institute of Technology (CIT), INOV, Artesis University College.

2 THEORETICAL TREATMENT

In the context of coexistence even if only looked at from the PHY, multiple parameters influence the impact the coexistence of two or more systems have. The next subchapter introduces the identified parameters and analyses them afterwards in detail. Afterwards an analytical methodology for the coexistence analysis follows.

2.1 COEXISTENCE PARAMETERS

Some parameters are decisive for the judging of possible conflicts and coexistence issues as introduce above:

- the spectrum / the radio band determined by
  - the bandwidth and
  - the carrier/centre frequency
- the radio propagation
  - radiated power,
  - the hop length,
  - the domain
- the channel access,
  - the duty cycle or the system load,
  - the access scheme
  - the signal modulation,
- the receiver structure.

These parameters are specific to each communication system, and thus each system – even each implementation of a device – behaves very individually to distortions from other systems. The respective parameters of the regarded radio localization systems are presented in the Annex as they are part of the assembled data base. Communication systems that are covered by the theoretical part of the study are GSM, EDGE, UMTS, HSDPA, CDMA450, IEEE802.11a/h, b and g (WLAN), IEEE802.16d/e (WiMAX), Bluetooth, ZigBee, MB-OFDM (UWB),

The following sections discuss the impact of these parameters on the coexistence in more detail. In the following a concept for evaluating coexistence issues is developed from these considerations.

2.1.1 SPECTRUM AND RADIO BAND

The most prominent separation of coexisting radio systems comes with the frequency division in frequency domain according to the spectrum plans of the national and international regulating authorities. Therein, the spectral ranges are allocated to dedicated systems either on basis of licensing like for the GSM and UMTS spectra or simply based on decisions of the authorities like for GPS, the ISM bands or the UWB spectrum. Licensed spectral ranges are usually exclusively used by the licensee with a spectral separation to neighbouring systems in order to avoid affecting other systems and to avoid being affected by spurious or out-of-band radiations from other systems.

However, especially in the ISM band several unlicensed radio communication and localization systems share the same part of the radio spectrum and in some of the employed bands the spectra of the heterogeneous systems overlap to a varying extent. The varying overlap is decisively influenced by the very different bandwidths of the systems.

For a discussion, we introduce an interference classification. Since in the case of a spectrum overlap both systems are affected differently, it is important to define the system of interest (SOI) and the interfering system (IFS)

- class 1: bands overlap
    - class 1a: complete overlap > 75 % of the bandwidth of the SoI
    - class 1b: strong overlap > 25 % of the bandwidth of the SoI
    - class 1c: weak overlap < 25 % of the bandwidth of the SoI
- class 2: bands are edge to edge (spacing less than one bandwidth of the IFS)
    - class 2a: remarkable spurious interference detectable
    - class 2b: interference negligible
- class 3: bands are distant (spacing more than one bandwidth of the IFS)
    - class 3a: potential weak interference due to OBO, carrier harmonics, etc.
    - class 3b: no interference effects to be expected

In contrast to class 1, the definition of class 2 comprises the bandwidth of the IFS instead of the SOI. This is because the descent of band limiting filters at the transmitter is relative to this bandwidth, i.e. presuming the same effort filters of large bandwidths tend to decay at a lower rate. Hence, the amount of energy that leaks into the SOI spectrum depends more likely on the bandwidth of the interferer than on the SOI.

Complex cellular systems with multiple network providers like GSM or UMTS employ a larger set of frequency bands. On the one hand, this is caused alone by the multitude of providers, on the other hand, frequency reuse and capacity reasons make employed subbands within the FDM network of a single provider necessary in order to best serve many base stations and subscribers. Additionally, several cellular systems (GSM, UMTS) work in different frequency bands for uplink and downlink, known as frequency division duplex (FDD). Hence, they need at least two bands per definition.

2.1.2 Radio Propagation

Main propagation parameters are the radiated power of all coexisting systems, the hop distances and the differentiations between indoors and outdoors, as well as line-of-sight (LOS) and non-line-of-sight (NLOS) propagation channels. Other strongly influencing parameters like the antenna gain are not investigated here also as they are fixed once the system is setup. Additionally, the high variety of realizations and of their properties will drastically extend the exploration space beyond the manageable amount.

2.1.2.1 Radiated Power

The radiated signal power or more reasonably the received signal energy is the most vital parameter for the operation of the transmission system. In order to maintain a minimum signal to noise ratio (SNR) in the receiver the received signal power of the system must not drop below a threshold given by the noise power and the system design as, e.g., spreading, interleaving and coding gain. In many system specifications, the radiated power is adjustable, according to a power stepping and a power control scheme. However, always a maximum power exists that must not be exceeded. Eventually, the transmit power level should be adapted due to coexistence reasoning. A power adaptation may be the only way to mitigate once the fixed infrastructure is installed and a coexistence issue has been detected.

Sometimes different maximum output levels exist for infrastructure and handheld devices of cellular systems. Because of health and battery runtime issues, the power limit for the mobiles is often significantly lower than that of a basestation, e.g. for GSM or UMTS. But also the practical consideration of one basestation serving many mobile devices supports this observation – irrespective if employing CDMA, (O)FDMA, TDMA, SDMA[1] or combinations of them. Thus, a mobile interferer may certainly be closer, but due to its lower output level it may distort still much less.

2.1.2.2 System distance

Beneath the radiated power, the propagation path between the SOI and the potential interferer serves as a flexible parameter that influences the received signal power. If coexisting system exist, their interfering signals obey the same rules as the signal of interest, i.e the transmit power, the line-of-sight scenario and the distance between the coexisting transmitter and the SOI are the main parameters that enter the computation of the path loss.

2.1.2.3 Application Domain

Additionally, the domain of the system has a large impact on the path loss. Possible classifications are indoor, outdoor, wireless personal area network (WPAN) for short range indoor usage or even body area networks that are influenced, on the one hand, by the coupling of the electromagnetic waves to the human body, and on the other hand, by its attenuating behaviour.

2.1.2.4 Path Loss Model

The path loss model as used here has been taken from the IEEE 802.4a channel modelling report [4] for low rate UWB systems in order to be able to cover also very broadband signals, and because narrowband channels are only a non-frequency selective special case of wideband channels. Also for UWB channels and frequency hopping systems only a single path loss is computed by averaging over subbbands respectively the complete (ultra wideband) frequency spectrum.

The pathloss is based on a reference pathloss $PL_0 = PL(d_0,f_0)$ at a reference distance d_0, and at a reference frequency f_0. With these parameters the path loss yields in logarithmic domain

$$PL(d,f) = PL_0 + 10n\log_{10}(d/d_0) + 10(2\kappa+2)\log_{10}(f/f_0) \quad [\mathrm{dB}], \tag{1}$$

i.e. the distance dependency of the attenuation is modelled via the exponent n and in frequency domain via the exponent κ. If averaging the pathloss from the lower bound f_{lo} to the upper bound f_{hi} of the used spectrum

$$\begin{aligned} PL(d,f) = \quad & PL_0 + 10n\log_{10}\left(\frac{d}{d_0}\right) + 10\log_{10}\left(\left(\frac{f_{hi}}{f_0}\right)^{-2\kappa-1} - \left(\frac{f_{lo}}{f_0}\right)^{-2\kappa-1}\right) \\ & -10\log_{10}\left(\frac{f_0}{f_{hi}-f_{lo}}\right) \qquad [\mathrm{dB}]. \end{aligned} \tag{2}$$

Additionally, a statistical shadowing coefficient alters the magnitude of the incoming data. Measurement indicate that it is lognormal distributed for some distance with a variance σ_X^2 The introduced parameters for an outdoor scenario, indoor office and industry environments

[1] code division multiple access – CDMA. (orthogonal) frequency division multiple access – (O)FDMA , time division multiple access – TDMA, space division multiple access – SDMA,

for line-of-sight (LOS) as well as for non-line-of-sight (NLOS) are assembled in Tab. 1. The antennas are not included in this path loss model due to the multiple possibilities. The measured or concluded path loss parameters for the application domains are displayed for the reference scenarios at a reference frequency f_0 = 5 GHz.

	indoor (office)		outdoor		industrial		freespace
	LOS	NLOS	LOS	NLOS	LOS	NLOS	
PL_0 in dB	36.6	51.4	43.29	43.29	56.7	56.7	46.42
n	1.63	3.07	1.76	2.5	1.2	2.15	2
κ	-0.175	0.265	-1.6	0.4	-0.31	-0.433	0
σ_X	1.9	3.9	0.83	2.0	2.00	2.00	

Tab. 1: Path loss parameters according to [4] to be employed for Eq. (1) and (2) and determined for a reference frequency of f_0 = 5 GHz.

2.1.3 Channel Access

2.1.3.1 Duty Cycle

Even if systems transmit in the same spectral range, their signals do not necessarily have to interfere with each other because most systems do not make continuous use of the transmission medium, but transmit in regular or irregular time intervals. The duty cycle is the ratio between active time periods, where the system accesses the channel, and the total observation interval length.

Duty cycles below 100% cause transmitted signals of coexisting systems to collide on a statistical basis. If both systems access the channel independently, the respective relative temporal overlap of the transmitted signals is given by the duty cycle of the respective other system. If $x_1(t)$ ($x_2(t)$) is the event that systems 1 (system 2) transmits a data packet during time instance t, it is possible to write the probability of a collision of packets at time t as

$$\begin{aligned} p(\text{collision} \mid x_1(t)) &= p(x_2(t) \mid x_1(t)) = p(x_2(t)), \\ p(\text{collision} \mid x_2(t)) &= p(x_1(t) \mid x_2(t)) = p(x_1(t)) \end{aligned} \quad (3)$$

where we have used the presumed independence of the transmit signals.

However, this formula is not correct for more dedicated channel access schemes that observe the channel and base their decision to transmit or to remain mute on this observation, e.g. listen before talk (LBT) and carrier sense multiple access (CSMA) like described in Section 3.1. Then, the access probability to the channel $p(x_{1/2}(t))$ at time t, in fact, depends on the other channel accesses. In order to keep work and analysis brief and manageable, this is neglected in the analysis. Nevertheless, it is possible to say that in the case of high duty cycles beyond 50 %, two CSMA systems will jam and thus blockade each other. Thus both functionalities become at least limited because both systems will not be able to obtain their desired share of the channel, but a *graceful degradation* in terms of a reduced throughput of communication systems or a reduced measurement update rate of location systems can be expected.

The number of colliding packets may also be an interesting measure if a collision can be assumed to lead to a complete packet loss. In contrast to the pure investigation of collision time, long packets are affected more probably from collisions then short ones, so that systems transmitting relatively long packets suffer more from coexistent competing systems. However, packet sizes in most modern telecommunications standards are highly variable and additionally the load which determines the duty cycle is not really constant in time. Thus, in a first shot, simulated packet collisions are not looked at.

2.1.3.2 Channel Access Scheme

The channel access has been neglected in the previous paragraph. Modern radio systems do not only show flexibility in the time of transmission (TDMA and CSMA), but also in frequency domain (FDMA, OFDMA) and code domain (CDMA). An example for frequency domain flexibility is adaptive and non-adaptive *frequency hopping* in Bluetooth or adaptive band selection (DFS) in WLAN in the 5 GHz U-NII band (IEEE 802.11h); for more information refer to Section 3.1.

Compared to the previous paragraph, similar observations of the probability of spectral collisions result from the investigation of frequency hopping systems. An equal distribution of the signal power on all frequency hopping bands is assumed here. Then the probability of a collision in subband i of *system 1* is given by the quotient of all colliding bands of the interfering *system* 2 with subband i and the total number of subbands of this *system* 2, i.e. mathematically

$$P\left(\text{collision}\mid\text{system 1 in subband } i\right)=\frac{\text{No. of colliding subbands of system 2 with subband } i}{\text{total No. of subbands of system 2}}\quad .$$

Then the total probability of collisions in all bands is given by the weighted sum over all subbands

$$\begin{aligned} P(\text{collision}) &= \sum_{i=1}^{N} P(\text{system 1 in subband } i)\cdot P(\text{collision}\mid\text{system 1 in subband } i) \\ &= {}^{1}\!/_{N}\cdot\sum_{i=1}^{N} P(\text{collision}\mid\text{system 1 in subband } i) \end{aligned} \tag{4}$$

Fortunately, the formulas directly also apply if one – or both – of the systems operate in a single band mode by setting the respective number of bands to N = 1. This directly impacts the individual conditional probabilities. Together with the temporal probability, the overall ratio of collisions in time and frequency simply yields from the product of the time (3) and frequency (4) related probabilities.

2.1.3.3 Modulation

Not every system is affected by interference from coexisting systems in the same way. The impact is also influenced by the type of modulation of the system, often related to the channel access scheme. For instance, *spread spectrum* (SS) systems – or *code division multiple access* (CDMA) systems – allow for mitigating interference effects. However, the realizations of spread spectrum systems and therefore the involved mechanisms are quite different. They all provide a spreading or – since it is achieved in the inner receiver – processing gain *S*. Usually then, 1/*S* is the factor by which the spread spectrum system suppresses the interference signal. Realizations are direct sequence spread spectrum (DSSS often equivalently used to CDMA), chirp spectrum spread spectrum (CSSS) and Frequency hopping (FHSS). The mechanisms are in more detail in Section 3.1.7.

A subtype of spread spectrum techniques employs chirp signals to transmit data. For instance an up-chirp equals a data value of **1**, and the down-chirp symbolises a **0** data bit) e.g. [8]. These chirp signals are very robust against frequency selective distortions like multipath or narrowband interference due to their concentration of instantaneous signal energy in time and frequency, while exploiting a high degree of time-frequency diversity.

Several *frequency hopping spread spectrum* (FHSS) systems adapt to an interference situation like e.g. Bluetooth. They try to avoid frequency ranges where strong distortion is expected. Bluetooth from its revision 1.2 [11] excludes interference contaminated subbands from its hopping sequence. For UWB, a similar *detect and avoid* (DAA) scheme is proposed for the frequency range between 3.4 and 4.2 GHz. Other proposals are notch filters that suppress transmission and reception in a defined part of the spectrum. For single carrier systems these excision filters are the only possibility to suppress narrowband interference. For broadband interference notch filters are not reasonable as they suppress also the energy of the wanted signal. For more detailed view on this topic please refer to the next chapter.

For the spread spectrum systems the *spreading* or *processing gain* can be computed from the time bandwidth product

$$G_P = 10\log_{10}(S) = 10\log_{10}(BTs)\ . \qquad (5)$$

Therein, B is the bandwidth of the spread signal and Ts is the duration of the symbols that are spread. This computation can therefore be easily extended to all different spread spectrum flavours. Considering a chirp signal with the chirp bandwidth B_{chirp} and a chirp duration of T_{chirp}, the gain becomes

$$G_{P,chirp} = 10\log_{10}(B_{chirp}T_{chirp}) \qquad (6)$$

and for a FHSS system with a total bandwidth B comprising all subbands and a subband bandwidth B_{sb}, the spreading gain computes as

$$G_{P,FH} = 10\log_{10}(B/B_{sb})\ . \qquad (7)$$

However, in order to obtain the full spreading gain in a FHSS system, the information on each bit would have to be spread over all subbands which would add a considerable amount of redundancy if the number of subbands is large. Given a low coding rate $R = N_{uncoded\ bits}/N_{coded\ bits}$, novel coding schemes like LDPC and Turbo codes may approach this distribution on all subbands with their property of distributing the information and considering all data in the decoding of each single bit.

Orthogonal frequency division multiplex (OFDM) as well as the corresponding *multiple access* scheme OFDMA are highly flexible in terms of the frequency usage by separating the spectrum into subbands (ther called subcarriers) that are modulated individually and concurrently. Exploiting this flexibility, subbands with detected spectrum collisions with other narrowband systems can be suppressed, or, assuming a sufficient diversity added by the forward error correction (FEC), neglected in the receiver or refused already in the transmitter.

2.1.4 RECEIVER STRUCTURE

A direct impact of interference on a receiver is that LNA or ADC are driven into saturation masking the desired signal. The ADC may also have insufficient dynamic range in order to resolve the desired signal in the presence of a potentially stronger interferer. In general, the receiver is harmed by the radio interference on several system levels or layers. Regarding to the digital receiver design for the *physical layer* (PHY), three stages of interference impact can be defined

1. the burst acquisition fails (plus detection of the burst beginning),
2. the synchronisation of the symbol time interval or of the carrier frequency is lost,
3. bit errors, and respectively, frame errors occur (ARQ).

The three have a decreasing hierarchy, i.e., on the one hand, a frame error will automatically occur if the synchronisation of receiver and transmitter is not established or lost. On the other hand, the synchronisation will fail without any doubt if the existence and the beginning of the burst are not detected correctly in the first place.

Obviously, the synchronization accuracy degrades with a decreasing SINR. But when the SNR falls below a certain threshold[2], cycle slips occur frequently in frequency and timing clock synchronization. On the one hand, a more "graceful degradation" results if the SINR is reduced with the synchronization still acceptable, on the other hand, modern *forward error corrections* (FEC) like Turbo of LDPC codes also show threshold behaviour. When the distortion level rises beyond that threshold the *frame error rate* (FER) grows immediately from almost zero[3], which is the operating point, to close to 1. Most RTLS operate and relatively high SINR.

As a best case, receivers directly detect interference and instantly suppress it – or cancel it out – as early as possible in the receiver chain, i.e. before the ADC, or even better, before the analog amplifiers and filters. However, receiver designs are not standardized and the interference handling is, thus, an implementation issue that may differ for multiple devices according to the same standard or for even for the same cell, system, or network.

2.1.5 Noise Floor

Although it is not a system parameter[4] as such the noise floor is an important feature in the analysis of radio systems, mainly because it determines the SNR of the received signal. However, implementation specific parameters impact decisively the SNR, e.g. the noise figure of the analog front end and the implementation loss of the digital post processing. On the one hand, these implementation specific parameters are often unknown to the user, and, on the other hand, may differ rather strongly from device to device. The thermal noise floor of the SOI with the active bandwidth B [5] at a temperature T_F in Kelvin (K) computes according to

$$N_{Floor} = 10\log_{10}(k_B B T_F) \ , \tag{8}$$

employing the Boltzmann constant k_B = 1.38065×10^{-23} J/K.

2.2 Methodology of the Theoretical Analysis

2.2.1 Overview

The methodology is a mathematical evaluation of the signal to interference power in five scenarios defined by the application domain, indoor, outdoor and freespace, and by the existence of the direct path, LOS or NLOS according to the parameters from Tab. 1. The computations and comparisons are implemented in the developed coexistent evaluation software in Matlab like described in Section 2.3. The data on the covered systems and standards are stored in two data base files, one for the localisation systems and the other for wireless communication standards. However with respect to the analysis the data sets for

[2] The threshold depends on the synchronisation algorithms and on the signal model respectively on the constellations of training and user data.

[3] FER values in the order of 10^{-6} or 10^{-7} are realizable even at moderate Eb/N0.

[4] The noise floor is more likely an environmental parameter.

[5] For non-spreading system the correct choice of the bandwidth is trivial. For DSSS this is the bandwidth after spreading, for CSSS again the total bandwidth, and for FHSS systems this is either the total bandwidth or the bandwidth of the subbands. If for FHSS the subband bandwidth is picked, the (reduced) noise floor already comprises the spreading gain.

localisation and communication systems differ only in the impact of the interference and in the extra information on the communication channel of localisation systems – and in some parameters on the signal exchange (see Annex 8.2). These system parameters are stored in the two data bases.

Aim of the software is to analyse the various radio systems from the data bases with respect to coexistence, to manage the data bases and to visualize the computed analysis results in a set of plots. Main focus is the comparison of signal and interference power in dependence of the distance of an interferer and the own *hop length*, i.e. the distance between transmitter and receiver.

2.2.2 DATA BASE ANALYSIS

Firstly, the spectrum overlap of the system of interest (SOI) with the other systems of choice is analysed for all of their selected subbands. For all those subbands, the potential interference is classified according to the classes in Subsection 2.2.2. Afterwards, for the systems with detected potential coexistence issues – those are the classes 1 and 2 – the following steps are performed.

The path loss is computed for each system and for the scenarios indoor or outdoor and LOS or NLOS transmission and a variety of distances. The distances have logarithmic scale according to the coverage range of each system. If the system is ultra-wideband the path loss is averaged according to eq. (2). If the system employs frequency hopping an average over all bands is applied. The shadowing, a statistical, position dependent signal strength variation, is not considered in the first version of the software.

The effect of channel access schemes is modelled depending on the channel access schemes as taken from the data base of each system:

1. the duplex mode:
    a) frequency division duplex (FDD): if two maximum transmit powers exist, the first one fits for the basestation and the second one for the mobiles. The same is valid for the first half of the frequency bands.
    b) time division duplex (TDD): no special consideration are necessary.
    c) heterogeneous duplex modes like different signal modulation for uplink and downlink are not considered.
2. the transmit power
    a) of the interferer is directly proportional to the received interference power.
    b) of the SOI is directly proportional to the received signal power.
3. the duty cycle
    a) of the interferer is directly proportional to the received interference power.
    b) of the SOI helps to identify the probability of frame collisions with the interference, which becomes very important for low SIR, because then collided frames translate to packet errors. However this computation needs additional data: frame length of SOI and interferer, which usually varies strongly.
4. frequency hopping (FH): all the "hopping subbands" are accessed with equal probability, i.e. the rate of collisions (4) within each of the N bands can be scaled by the probability factor: $P(\text{system in subband } i) = 1/N$.
5. the modulation (not implemented in a first version):

a) CDMA/spread spectrum allows for a spreading gain S (identical with the spreading factor) increasing the received signal power compared to interference and noise – spreading of the interferer has no further effect for this investigation

b) OFDM does not allow for spreading gains, but offers high degrees of flexibility and diversity that is covered here by ignoring signal power on disturbed subcarriers: that is equivalent to scaling the SIR with the bandwidth factor $(B - B_{\text{overlap}})/B$, which assumes that no information but only signal power is lost. In effect this is the same as for frequency hopping.

c) Pure single carrier modulation usually does not allow for these choices, such that interference directly adds up to the system noise level.

6. the coding: the channel coding schemes (or FEC) is not considered in a first step, however it adds a decisive amount of diversity to the system, that is immensely important.

7. receiver implementation issues that may lead to additional results (not implemented till now) are if an interference detection with active interference processing is employed.

From these computation the following results are computed, that are however focussed on the effect on the localization systems of the partners and the employed communication networks.

2.3 DESCRIPTION OF THE IMPLEMENTED ANALYSIS TOOL

In this section, the developed MATLAB software for the computation and detection of interference issues is presented in some detail. The main program represents a (non-graphical) user interface called *Interference Designer*. Other main parts are the extendable data bases for location and communication systems and the visualization engine. The system structure around the user interface (UI) of the software is depicted in Fig. 1. A second central component is the coexistence data file, where all selected and processed data is stored according to the current process status.

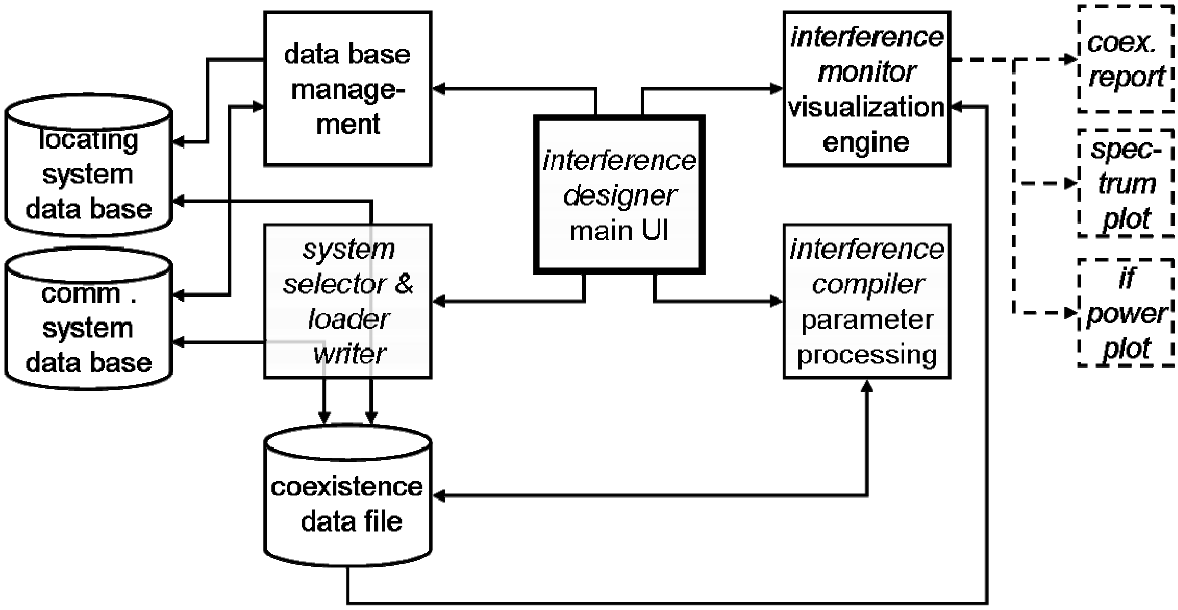

Fig. 1: Software tool structure diagram.

2.3.1 INTERFERENCE DESIGNER - THE MAIN INTERFACE

From, this prompt based interface, all actions are started, i.e. the data bases (location systems and communication systems) and the data sets are loaded, the systems are selected from the data bases for the coexistence analysis, the interference effects are computed and the visualization is started. The help display allows then to view all options and the start screen shows the progress of the coexistence analysis as shown in Fig. 2, where all achievable progress stages are displayed. The usual user process is as follows the data bases are loaded (`ll` for location systems and `lc` for communication systems). Then, the systems of interest are selected from the data bases and configured and the current unit under test (UUT) is chosen with the *System Selector*. Afterwards, computations of the path loss and of the transmission coefficients are started with the *Interference Compiler*, before the visualization of the results and the post analysis can be started in the *Interference Monitor*. The present state of the process can be stored (and reloaded) in a coexistence data file with the command `sd` (respectively

```
Welcome to Interference Designer
(c) Fraunhofer IIS

Location system(s) loaded!
Communication system(s) loaded!
SOI selected!
Location system(s) selected!
Communication system(s) selected!
Data prepared for visualization!

ifD/ >>
```

Fig. 2: Start screen indicating process progress

`ld`), such that not all configurations and computations have to be restarted.

Commands and executions of program module are performed by entering introduced 2-letter abbreviations as displayed in the help display in Fig. 3. The filenames can be changed centrally via the menus.

An additional option is to view (*System Viewer*, `sv`) and change (*System Editor*, `se`) all systems parameters of the systems.

```
Help display

?? : this info
in : program info
cs : clear screen - update progress data
gu : start graphical user interface

gn : get file names
nl : alter name of data base for location systems
nc : alter name of data base for commnication systems
nd : alter coexistence file name
ls : display directory (relevant files/directories)
cd : change directory

ll : load location system data base
lc : load communication system data base
ld : load coexistence data file
sl : save location system data base
sc : save communication system data base
sd : save coexistence data file
rl : remove location system data base
rc : remove communication system data base
rd : remove coexistence data file

ss : System Selector
sv : System Viewer
se : System Editor
ic : Interference Compiler
im : Interference Monitor

qs : quit with saving data
qq : quit without saving
```

Fig. 3: Option list from the help menu

2.3.2 Data Bases and Data Selection

2.3.2.1 *The System Data Bases*

The data bases for location systems and location systems have rather similar entries, however some specialities, e.g. for a communication system, the communication interface with the exterior is relatively clear. Additionally, bidirectional communication between a basestation or a communication node and a mobile device is the usual operation mode, while for an RTLS a communication channel between the tag and the node beyond the identification is not necessarily needed.

The entries for a locating system are: *name*, *manufacturer*, *info* (additional information on the system provided to the user), *modulation* (e.g. dsss, uwb, psk, ofdm, qam), *channel access* (e.g. csma, lbt, cdma, ofdma, frequency hopping, fdd, tdd), *spectrum bandwidth* [MHz], *carrier frequency* [GHz], *localisation method* (e.g. rtt, toa, tdoa, doa), *duty cycle* [%], *radiated power* [dBm], *range* [m], *communication* (onedirectional, bidirectional), *interface* (wlan, ethernet), *domain* (e.g. indoor, outdoor, wpan).

Equivalently, for the communication systems: *name*, *organization*, *info* (see above), *modulation* (see above), *channel access* (see above), *receiver structure* (e.g. rake, mlse, dft), *symbol rate* [MSps], *bandwidth* [MHz], *carrier frequency* [GHz], *duty cycle [%]*, *radiated Power* [dBm], *range* [m], *structure* (e.g. basestation, master, cell), *domain* (see above).

2.3.2.2 *Data Base Handling*

The system allows entering different values for mobile and basestation respectively anchor nodes and tags. Communication data base entries exist for a wide set of communication standards. The location data base concentrates on the systems of the project, but can be easily extended given the knowledge of the respective systems.

2.3.2.3 *System Editor*

For handling the data base a *System Editor*, a loader and a storing function for the location data base and for the communication data base are available. Additionally it is possible to design an own user data base that can be used in the analysis. However, when editing the data base, the user must relate to the keywords for the fields as printed above in the examples of the previous section for the data fields.

2.3.2.4 The System Selector

After the data bases have been loaded, the user can choose the systems of interest (SOI also UUT in the tool) and the coexisting systems to test against with the *System Selector* provided by the tool. During the process a configuration of the system is chose e.g. the WLAN channel or the allowed transmit power in the (political) region of interest. The data of all systems is then written to a coexistence data file.

2.3.3 THE COMPUTATION

After selecting the systems the data must be pre-processed before visualisation of the coexistence issues can begin. The result of the computations is written to the above coexistence data file that can be stored to disk.

2.3.3.1 Interference Classifier

In preprocessing firstly, the coexistence situation is classified based on each subband of the system. That considers different subbands in FDD systems as well as the sub bands for frequency hopping systems. These subbands are classified according to the list in Section 2.1.1. An overall classification based on the precomputed data from the *Interference Power Compiler* below is then straight forward.

2.3.3.2 Pathloss Compiler

Then, the pathloss is computed preliminarily according to different channel scenarios, i.e. freespace, indoor LOS and NLOS as well as outdoor LOS and NLOS.

2.3.3.3 Interference Power Compiler

Based on this data and on the various radiated power values (basestation/mobile, anchor node/tag) and the relative subchannel overlaps the interference power of uplinks and downlinks are computed separately if existent. Additionally, low collision probabilities for the signals reduce the expected average, interference power if the duty cycle is low. For high probability and high duty cycles (ca. 90 %) the power is reduced only very little.

2.3.4 THE INTERFERENCE MONITOR

Three software variants for the visualization of the coexistence analysis have been implemented. They make use of the data base and of the pre-computed interference data situated in the coexistence data file. Additionally, the user interface allows managing the created plots.

2.3.4.1 The Coexistence Report

The *coexistence report* serves as an entry into the analysis. It generates automatically a test report of the coexistence issues between the SOI and the other systems that. Thereby, the band-overlaps are explicitly analysed and the classification (see above) is displayed for each sub-band. An extract from a coexistence report is plotted below for the WISMIT/Goniometer system in Fig. 4.

```
Conflict and coexistence report
-------------------------------
The defined UUT is WiSmIt_Goniometer according to IIS.
------------------------------------------------------
The system has cellular node-tag structure.
The employed bands are at 2.440000 GHz and have a bandwitdth of 80.000000.
The radiated power is 0.000000 dBm.
The duty cycle is 50.000000 %.
The UUT has been tested against the following systems:
Location systems:
none
Communication systems:
(1) 802.11b WLAN Channel 1 (IEEE)
(2) 802.11g WLAN channel 7 (IEEE)
(3) 802.11g WLAN channel 12 (IEEE)
(4) 802.15.4 ZigBee channel 1 (IEEE)
(5) 802.15.4 ZigBee channel 16 (IEEE)
The following conflicts may arise between the UUT
and the chosen location systems:
none
The following conflicts may arise between the UUT
and the chosen communication systems:

From system 802.11b WLAN Channel 1 on UUT:
------------------------------------------
For 1 (sub-) band(s) a class 1 conflict has been detected.
> 75 % system spectrum overlap in UUT bands at 2.440000 GHz.
This interference stems from system bands at 2.412000 GHz.
...
```

Fig. 4: Extract from an exemplary generated coexistence report.

2.3.4.2 The Spectrum Plot

The spectrum plot collects the spectrum data – i.e. the bandwidths, the center frequencies and the transmit power recomputed as maximum power spectral density – of the selected radio systems. It displays this data in a plot of the power spectral density in dBm/MHz vs. the frequency in GHz. This diagram allows for a quick overview over the possible conflicts that

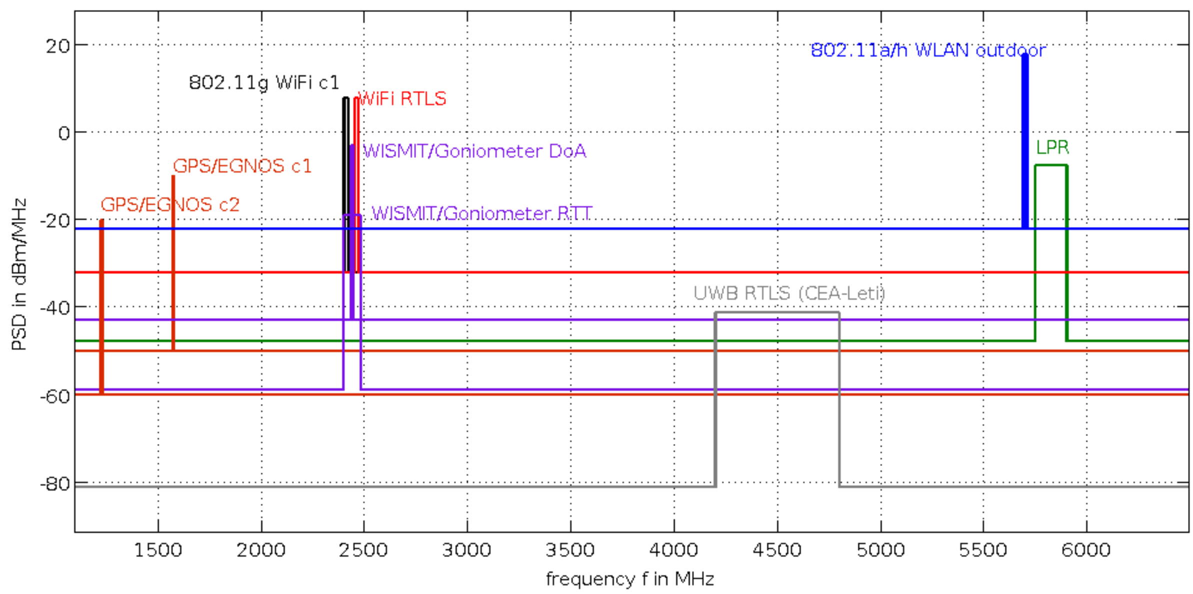

Fig. 5: Spectral plot of the RTLS from the Locon project.

however should have been clear when selecting the systems, otherwise the diagram becomes crowded and unfocussed very quickly. This will especially happen if considering frequency hopping system with a multitude of subbands like Bluetooth. In order to highlight the coexistence issues, it is possible to mark the band overlaps and add a path loss scale. The latter shows the effect of the channel loss in the distance range of interest for the SOI. Beyond the defined signal spectrum, the spectrum plot is continued at a reduced power level (40 dB lower) in order to serve as a placeholder for the out-off-band radiation that is common to all radio systems. An example for a generated spectrum plot is displayed in Fig. 5. It contains the spectra of all location systems to be integrated in the LocON installation at Faro Airport.

2.3.4.3 The Interference Power Plot

In the last implemented visualisation tool, the signal power of the SOI is compared to the interference power from the coexisting systems independently for all systems uplink and downlinks. The powers are compared either with a varying distance or a varying duty cycle. The computation of the signal considers the processing or spreading gain of spread spectrum systems. However, since in many systems it is variable the spreading or processing gain has to be entered manually according to (5). Additionally, the selectable duty cycles D_C of SOI (or uut in the software) and of the potential interferers introduce flexibility into the results. It is possible to display in scale at the edge of the diagram, how a variation of the duty cycle alters the plots. Furthermore, the option has been implemented to show the thermal noise floor (8) of the SOI at T_F = 20° C in the diagram. Consequently with that inputs in the diagram, a graphical analysis of the coexistence is possible.

2.3.5 OUTLOOK ON UTILIZATION FUTURE DEVELOPMENT

Given a further development especially with respect to the user interface and of the analysis and visualisation tools, the software tool may be used in various contexts beyond LocON. Everywhere, where coexistence is supposed to be checked quickly against a large set of potentially distorting devices, the tool may help to identify early (even in the system design) potential coexistence issues, such that system design or deployment of the respective hardware can be adapted accordingly.

Main future extensions should comprise:

- a graphical user interface (GUI)
- further visualization engines.
- direct computation of spreading gains.
- direct realization of OFDM impact.
- variance analysis for location systems based on loadable SNR characteristics.
- consideration of impact of coexistence mitigation techniques beyond spreading.

2.4 Results of the Theoretical Analysis

In the following paragraphs, the relevant location and communication systems are described briefly including the basic PHY features relevant for the coexistence analysis. A more detailed parameter set for the real time locating systems (RTLS) can be extracted from the LocON deliverable D1.2 on the *LocON Platform Requirements*. Afterwards, the spectrum of the respective systems as extracted from the *Coexistence Report* of the developed software tool (see last section) is investigated. Then, the power from the relevant systems leaking into the spectrum of the SOI is displayed. In the end, the obtained results are discussed. Nevertheless, this section starts discussing the overview over the spectra of the LocON systems in Fig. 5.

2.4.1 Spectrum Overview

At the end of the previous Section, the spectra of the location systems in Fig. 5 are depicted as generated from the tool. Additionally displayed are an indoor communication channel via WLAN channel 1 (f_{center} = 2.412 GHz) according to IEEE 802.11g, and for outdoors an IEEE 802.11a/h device in channel 140 (f_{center} = 5.7 GHz). For the WLAN locating system arbitrarily also channel 11 has been chosen[6]. In the figure, a concentration of systems in the 2.4 GHz band is well visible, such that any analysis is supposed to concentrate on this range. The involved systems are WISMIT/Goniometer with RTT and DoA bursts, WLAN according to IEEE 802.11 in the 2.4 GHz range, and with it, the WiFi RTLS. Furthermore, other potentially coexisting systems reside within this range. This will be discussed in detail in the respective paragraphs following below.

The 5 GHz range is used much more scarcely, and thus, the spectrum of the LPR system will be hardly used. In many parts of Europe, for instance, also the last channels in the 5 GHz band are dedicated to notifiable WiFi access only (*Fixed Broadband Wireless Access*).

2.4.2 Location Systems

2.4.2.1 WISMIT/Goniometer (Fraunhofer IIS)

2.4.2.1.1 Description

The WISMIT/Goniometer platform estimates the position of the WISMIT transceivers (or tags) comprising also a set of other functionalities like *radio frequency identification* (RFID) reader and *intertia sensors* (INS). To do so, the system employs the two-way ranging capability of the nanoLoc [8] chipset from Nanotron with a set of nodes and a direction of arrival measurement with the Goniometer nodes. These Goniometer nodes are equipped with an antenna array for measuring the angle of an incident wave. The general locating structure is cell-based and in principle each cell may support 2^{48} objects – the limiting factor is the achievable update rate. The positions are computed in a PC based central unit that is connected to the LocON server by Ethernet.

The ranging uses a *round trip time* (RTT) measurement on the 80 MHz chirp spread spectrum (CSS) signals (nanoLoc). They have the symbol interval length 1 µs at an adaptable center frequency around 2.44 GHz[7]. Hence, the spreading factor becomes 80 MHz x 1 µs = 80. The ranging is initiated once from the WISMIT tag and once from the anchor nodes, i.e. for one distance estimate four transmissions are necessary and for one 2-dimensional position 12

[6] Though, it is well understood in here that there is no extra WLAN access point for the WLAN locating system. It makes use of the existing infrastructure.

[7] The exact center frequency (also fort he DoA signal) is tuneable between 2.438 GHz and 2.443 GHz.

channel accesses have to be carried out by the concerned devices (three anchor node and one tag). The relation can be reduced by restricting to one-way ranging to two transmissions per distance and minimally six per position.

The direction of arrival (DoA) measurements are based on a single narrowband signal of 2 MHz transmitted by the WISMIT device. It is generated abusing the nanoLoc chip to send an (instable) carrier signal at approximately 2.44 GHz. The narrowband signal follows an FMCW burst triggering the DoA estimation devices (Goniometer) such that only one narrowband signal is needed for all Goniometers. The range of the transmission is between 100 and 150 meters in open area and around 30 m to 50 m in buildings depending on the penetration properties of the structure (e.g. a wall) of interest in the spectrum of interest.

For both, transmission modes, i.e. RTT and DoA, the radiated power is limited at 0 dBm EIRP for both infrastructure nodes and the tag. The nanoLoc chipset is capable of the listen before talk (LBT) technique (see Chapter 3), in two exclusive variants, measuring the channel power and detecting for other chirp signals. Furthermore, the transceiver chipset is capable of a transmit power control (TPC) that allows to reduce the transmit power for short links. The TPC may help to limit the interference on other coexisting radio systems by reducing the average transmitted power. However, it is not implemented till now.

2.4.2.1.2 Spectral analysis

In Fig. 5, now a multitude of spectra of radio systems potentially distorting the WISMIT/Goniometer platform is displayed. However, in order to ease the overview, only a set of three WiFi users is displayed[8], Bluetooth with its 79 carrier frequencies in the band is completely omitted, and for ZigBee only the leftmost and the rightmost of the 16 bands (on

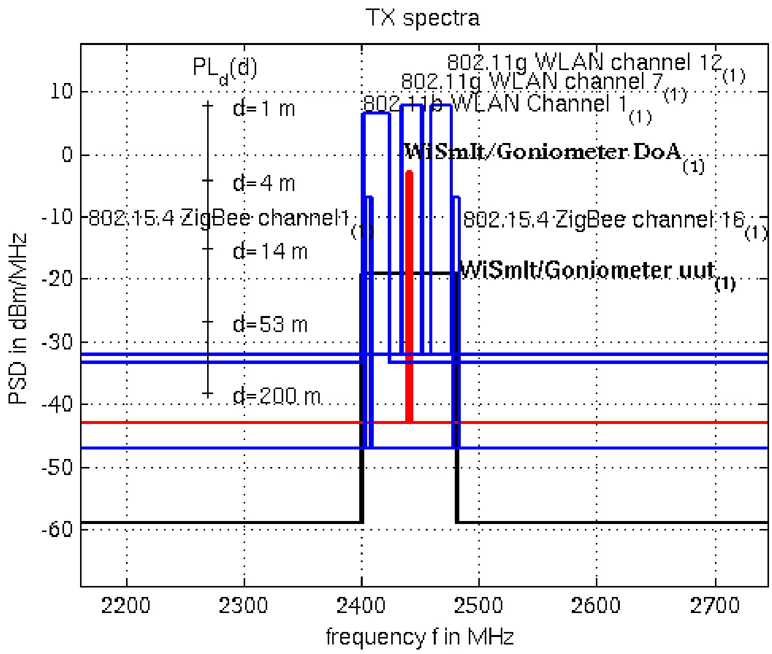

Fig. 6: Spectral analysis for the WISMIT/Goniometer system

[8] There are plenty of other overlapping WiFi channels in the 2.4 GHz band. The depicted version is just an example of three non-overlapping bands.

the frequency axis) is presented. For the WiFi systems to variants have been chosen: IEEE 802.11b and IEEE 802.11g. The latter needs slightly less bandwidth causing a higher PSD level if starting from the same maximum power. Additionally, the figure distinguishes between the WISMIT RTT and the DoA burst. Both inhibit the same power, which is thus much more concentrated for the DoA signals. Additionally, the DoA burst emerges more rarely than the RTT signalling as one RTT burst suffices for all devices measuring the DoA (the Goniometer).

The DoA signalling is only affected by the frequently used WiFi bands 6 and 7 at 2.437 GHz respectively 2.442 GHz. An impact of Bluetooth, on the DoA burst is improbable. Zigbee devices are scarcely used anyway: they suffer from severe coexistence issues with the Bluetooth and WiFi/WLAN. However, investigations proposed that DoA measurements fail mainly because the trigger by the wideband signal is missed, as experience has shown.

The wideband RTT signal suffers from WiFi, Bluetooth and ZigBee interference from all subchannels in the complete 2.4 GHz band. However, e.g. assuming marginal WLAN traffic due to a low network load, collisions are scarce and the channel capacity suffices for the RTT measurements. Due to their relatively low power Zigbee signals distort the chirp little and due to the sweeping frequency signal, they interfere on an irregular basis.

2.4.2.2 Interference Power analysis

In Fig. 7, the estimated mean received signal power of the WISMIT system is displayed together with expected, predominant interference sources: a WiFi system[9] and a Bluetooth class 2 device[10]. The duty cycle of the anchor node is assumed to D_C = 40 % as it serves several tags and D_C = 10 % for the tag itself. However this definition is completely arbitrary in order to cover a higher range of duty cycle values, because also the tag communicates individually with each anchor node of the cell. For the WiFi system, an extreme case of an ongoing download with almost full load is displayed, i.e. D_C = 90 % for the downstream from the access point with a mobile device filling the remainder of the channel with the duty cycle D_C = 10 %. The Bluetooth traffic is displayed for a network load of D_C = 100 %. The signal power of the chirp signals already considers the spreading gain of

$$10\log_{10}(S(\mathrm{WISMIT})) = 10\log_{10}(BTs) = 10\log_{10}(80\mathrm{MHz}\cdot 1\mu\mathrm{s}) \approx 19\mathrm{dB}. \quad (9)$$

When inspecting Fig. 7, it is obvious that the WLAN channel with high network load poses a severe threat to the correct detection of the chirp signal.

Presuming the same distance between node and tag and between the anchor node and the WiFi access point, the interference power is only 3 dB weaker than that of the received chirp signals even *after the dispreading*. This signal to interference and noise ratio (SINR)[11] will hardly be sufficient neither for a secure communication nor for accurate RTT measurements via the chirp signals. Furthermore, the diagram shows the impact of the different products of duty cycles of the respective transmitters.

---

[9] Since the interference power and the bandwidth are approximately the same for all WiFi standards with the exception of the new IEEE 802.11n stnadard, the effect of the WiFi interference can be expected to be approximately the same. Hence, here a IEEE 802.11b device is taken for computations

[10] The class 2 device has an EIRP of 4 dBm, certainly the class 1 device will distort the the chirp signal to higher extent due to ist superior 20 dBm EIRP.

[11] The displayed noise floor is far away. Thus only the potential interference power plays a role.

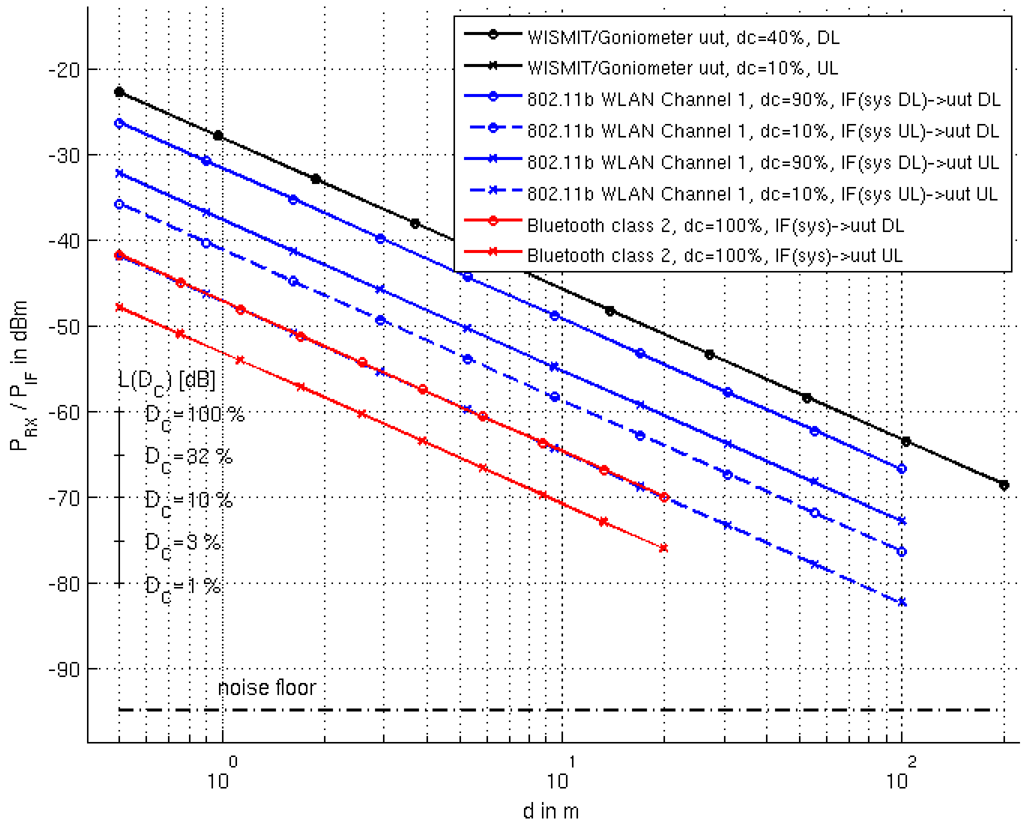

Fig. 7: Interference power vs. the distance for the WISMIT/Anchor system employing 80 MHz chirp signals with the duration of 1µs (outdoor channel with LOS)

The red lines in the diagram in Fig. 7 indicate that Bluetooth class 2 interference will not limit the location performance of the RTLS if the Bluetooth device is not quasi collocated with WISMIT anchor nodes while the tag is more than 10 m away. This changes however if the 16 dB stronger Bluetooth class 1 devices. However, the duty cycle of D_C = 100 % is hardly a realistic operating point for Bluetooth traffic, that is additionally only bursty, i.e. not continuous over a longer time period.

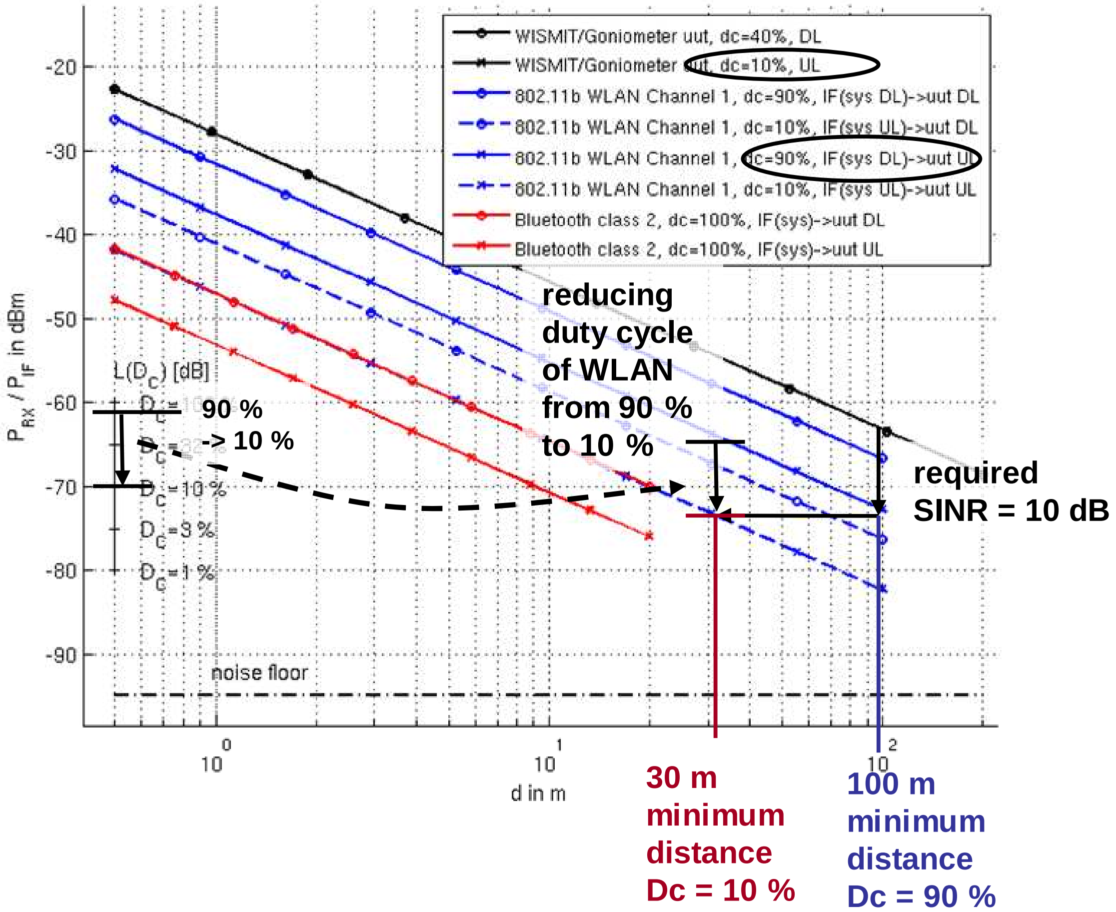

Fig. 8: Example for using the diagram

Fig. 8, now shows an example for using the diagram for a locating distance of 100 m. A target SINR = 10 dB is aimed at for the links. The link as of interest here has a duty cycle of D_C = 10 %. We can read from the diagram that the minimum distance of a WLAN access point is also 100 m at 90 % duty cycle. If we reduce now the duty cycle from 80 % to D_C = 10 %, then a separation of 30 m becomes sufficient.

Considering the DoA burst transmission as concerned with in Fig. 9, again a WLAN transmission, here with a more realistic duty cycle of D_C = 30 % in the WLAN channel 7, leads to the major coexistence issue. However, D_C = 10 % duty cycle of the DoA signalling is still pretty high. More likely D_C = 1 % may be realistic. In the diagram this provides a relative gain of 10 dB in the SINR that is also needed since the DoA signal does not provide a spreading gain. The Bluetooth traffic has almost no impact since it is rather improbable that the instantaneous hopping subband will overlap with 2 MHz band of the DoA burst.

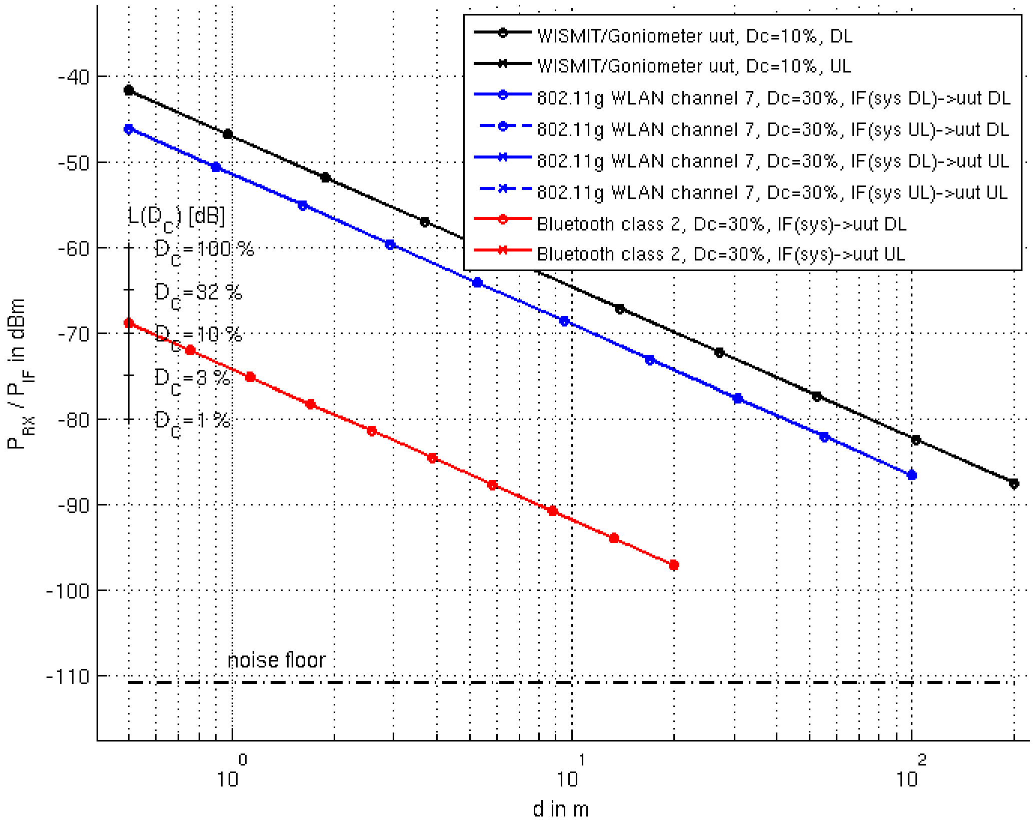

Fig. 9: Interference power analysis vs. the distance for the DoA-Goniometer system employing 80 MHz chirp signals with the duration of 1µs (outdoor channel with LOS).

2.4.2.2.1 Discussion

The implantation of WLAN coexisting techniques like *alternating wireless medium access* (AWMA) and *packet traffic arbitration* (PTA) might be a realistic idea in order to prevent packet collisions on a MAC level if a WLAN node is integrated into the anchor nodes. Otherwise the WiFi devices in the 2.4 GHz range pose a severe threat on the RTLS. Otherwise, it can be said that quite some separation to WiFi nodes is advisable irrespective if for RTT or for DoA calculation. "Fortunately", the LocON demonstration intends to use WiFi in the 2.4 GHz bands only indoors (5 GHz WiFi outdoors), while the RTLS nodes are deployed outdoors.

2.4.2.3 LPR (Local Positioning Radar, Symeo)

2.4.2.3.1 Description

The main difference to the above WISMIT system is that the LPR system by Symeo is based on tag centered localisation estimating the position based on RTT measurements or, otherwise, on time difference of arrival (TDoA) measurements in the tag. Thus for the first method (RTT), the tag transmit to some wall-mounted transponders that reply after a fixed delay. This requires a bidirectional transmitting tag. For the second mode (TDoA), the strictly synchronized transponders transmit a beacon signal that is received in the tag and the difference of the arrival times is used to compute the position. Thus, the tag operates in the *listen only* mode. However then, an independent, wireless communication channel has to be established if the position data is required remote from the tag location. For LocON the connectivity is achieved via the GPS box by INOV that communicates with the LocON Sever via WLAN functionality. The LPR system is cell based and the total bandwidth depends on the number of nodes per cell. However, an operation in cells of six nodes is considered as the standard mode. For determining the position, 30 tags or objects are supported per cell.

The system also employs chirp signals, but these sweep the spectrum range between 5.75 and 5.85 GHz for five transponders. This spectrum is extended to approximately 5.9 GHz for six transponders per cell. At 5.87 GHz, a narrowband communication channel employing B-FSK signalling[12] is situated. Hence, the full configuration employs a bandwidth of 120 MHz in that setting, but usually the communication channel is embedded in the 150 MHz of the chirp signalling. Each signal consists of an upchirp and a downchirp both of duration of approximately 1 ms, i.e. totally with 2 ms. Thus, the spreading factor becomes 2 ms x 150 MHz = 300,000 for 6 nodes (or 2 ms x 100 MHz = 200,000 for 5 nodes).

The radiated power is limited to a level 14 dBm EIRP and is adjustable by software. The LPR system will work together with the GPS device by INOV and in general its coexistence will be considered in WP6 on the intra-node sensor fusion (task T6.5, deliverable D6.4). The maximum ranging distance is approximately 400 m according to the data sheet. As can be concluded from these distances the usual application scenario for the LPR system is outdoors.

2.4.2.3.2 Spectral analysis

Two plots for the LPR system are included. The first one, Fig. 10, includes UWB systems – in this case, the only relevant UWB system is MB-OFDM employing band group 2; all bands of IEEE 802.15.4a are beyond 6 GHz. It is well visible that, in theory, MB-OFDM has the potential to distort an LPR system with two overlapping subbands of MB-OFDM. However, the difference between the power of the signal and the residual interference power components is very obvious. Additionally, while the application field of the LPR system is mainly outdoors, that of

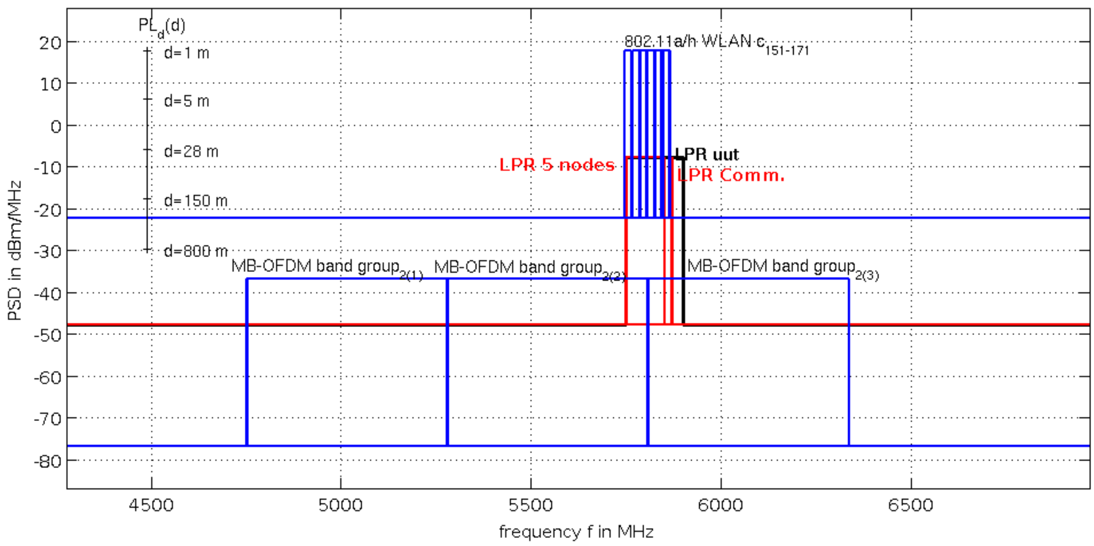

Fig. 10: Spectral analysis for LPR system.

[12] It signals with two alternating carrier signals carrying the respective information.

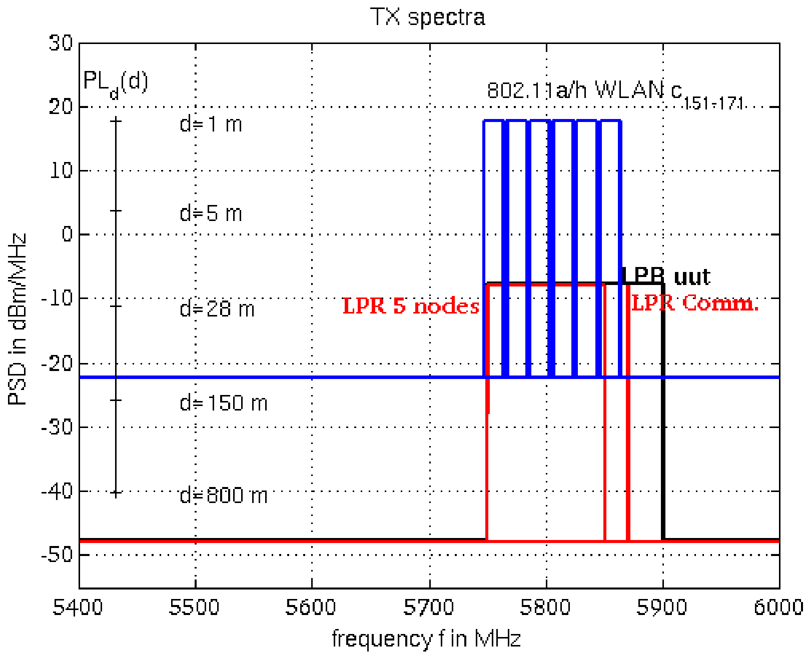

Fig. 11: Close up of the LPR spectral analysis.

MB-OFDM is clearly inside of buildings. Thus, in addition to the large power difference also the attenuation due to walls and windows is helpful for our cause.

The second diagram in Fig. 11 is a close up of the first focussing on the WiFi channels 151 – 171 and on the LPR system. The WiFi channels only distort that part of the spectrum in use for "five-node/transponder" operation. The additional bandwidth required if utilizing six transponders remains unaffected by WiFi distortion. Also, the communication channel of the LPR system is outside this range.

2.4.2.3.3 Interference Power analysis

WLAN systems in the 5 GHz range pose the greatest threat for the coexistence of the LPR system, as can be directly concluded from Fig. 12. However, the low duty cycle of D_C = 10 % and the huge processing gain of $\log_{10}(300{,}000)$ = 54.7 dB (resp. 53 dB for 5 active nodes per cell) cause a tremendous separation from the WLAN signals. Additionally, in comparison to the nanoLoc powered WISMIT/Goniometer system, the transmit power is higher by 14 dB.

A coexistence analysis for a distance of 400 m then works as follows: Assuming an SINR of 10 dB a minimum separation to the WLAN system must be 300 m for the duty cycle of D_C (WiFi) = 40 %. This minimum separation can be decreased to ca. 120 m for 10 % duty cycle.

The interference from the MB-OFDM system as displayed with red lines in Fig. 12 can be obviously neglected. At the same distance, the calculated interference is more than 70 dB weaker than the LPR signal transmission itself and is hidden in the noise floor at less than 30 m anyway.

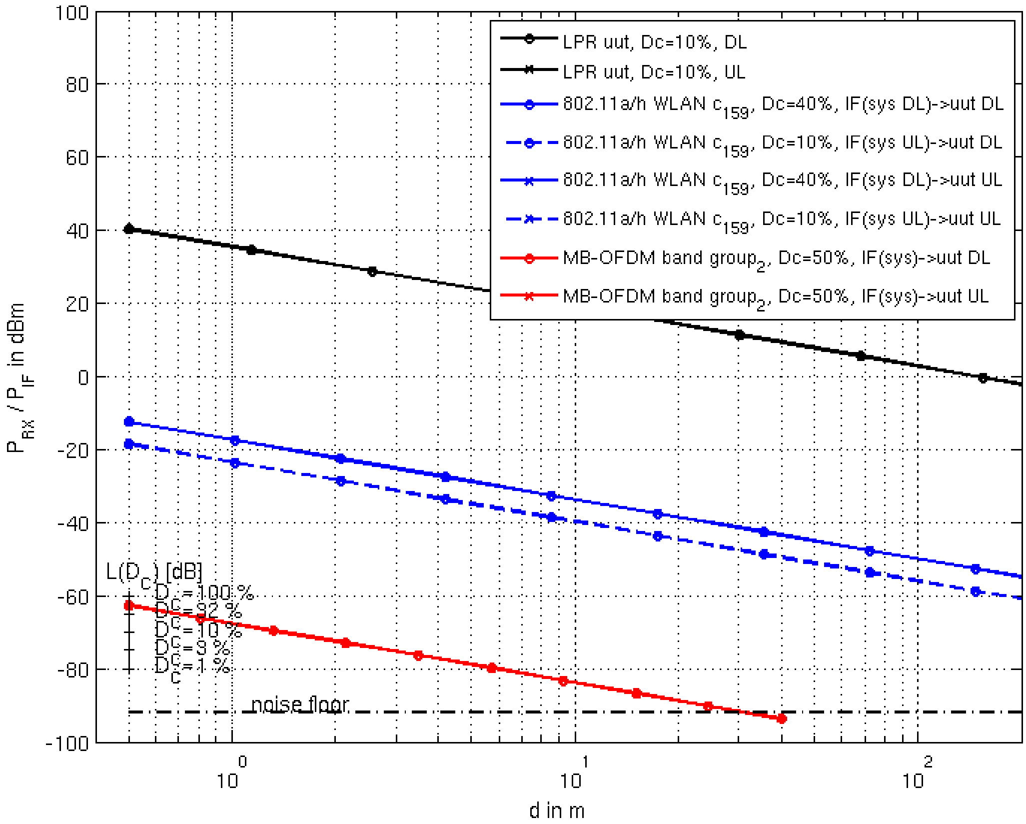

Fig. 12: Interference power vs. the distance for LPR system employing 150 MHz chirp signals with the duration of 2ms (indoor channel with LOS).

2.4.2.3.4 Discussion

If one or several of the WiFi channels 159 – 171 are in use it seems more reasonable for the "five-transponder-operation" to use the upper part of the spectrum. Then, the chances of occurring signal collisions with the WiFi interferers would be much smaller – the bands 159 and 163 would remain out off the selected transmission band. However, usually these high channel numbers are scarcely in use for WiFi anyway according to the extra obligation to notify the regulating authorities.

2.4.2.4 UWB RTLS (CEA-LETI)

2.4.2.4.1 Description

The locating system by CEA-Leti uses short UWB pulses of 500 MHz bandwidth in order to perform TDoA measurements on them. Those are used to estimate the position of UWB tags with a minimum of four, fixedly mounted UWB receiver nodes. One of them serves as master and reference for the other fixed receivers that synchronize wirelessly via the UWB link. Additionally, the master performs the bidirectional communication with the tag. In principle, the system has been designed for both locating and communication application.

The center frequency of the transmission band can be found at 4.2 GHz corresponding to a lower cut-off frequency of 3.95 and an upper cut-off frequency of 4.45 GHz. Since, without extra regulation and with the PSD limit of -41.3 dBm, that frequency range is only available in the US, the employed frequency range of the Leti UWB system will move to the 6 to 8.5 GHz range available in Europe in a medium time horizon.

The maximum radiated power achieves -14.3 dBm, which corresponds approximately to the maximum power spectral density of -41.3 dBm/MHz for UWB devices. The connectivity to the LocON network is via Ethernet cabling. The maximum distance between tag and antennas is 20 m. The main application scenario is LOS indoor localisation.

2.4.2.4.2 Spectral analysis

The UWB system from CEA-Leti mainly competes with other UWB systems for the spectrum as it is depicted in Fig. 13. This is the case for momentary spectral range around 4.5 GHz. But this is still true, once the signal spectrum has been transferred to the frequency range beyond the 6 GHz, where it is allowed to operate without restrictions according to the European regulation. The only difference is that other frequency bands of the UWB counterparts are susceptible to coexistence issues with the LETI system.

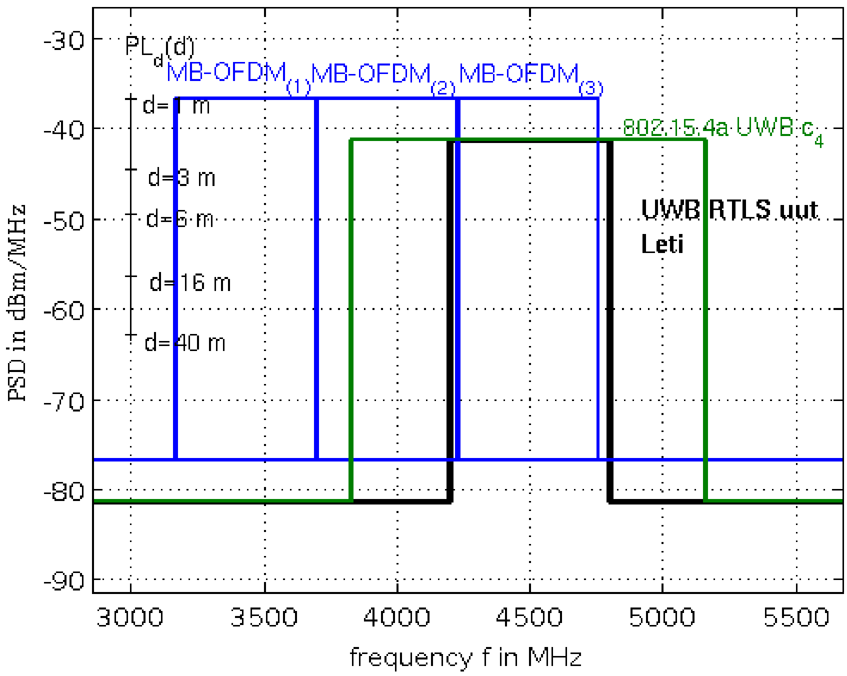

Fig. 13: Spectral analysis generated for the UWB system by Leti.

The signal PSDs of UWB systems have the same level anyway as that is the measure of the regulation by the CEPT or the FCC. The PSD level seems different for the MB-OFDM PSD in Fig. 13 because the peak PSD has been plotted in the diagram. Hence, the frequency hopping nature of the MB-OFDM system allows to increase the PSD level by 10 $\log_{10}(3)$ = 4.8 dB. For more information read the description of MB-OFDM in Paragraph 2.4.3.4.

Other systems are not in the respective frequency band, but the main concern for UWB coexistence in the 6 – 8 .5 GHz range is the distortion of radio-astronomy applications. This is however rather improbable for the indoor localisation and communication system. Usually, it will be kilometres (at least >100 m) away from a radio-astronomy operation, such that the path loss will be very large, plus the attenuation of walls and windows.

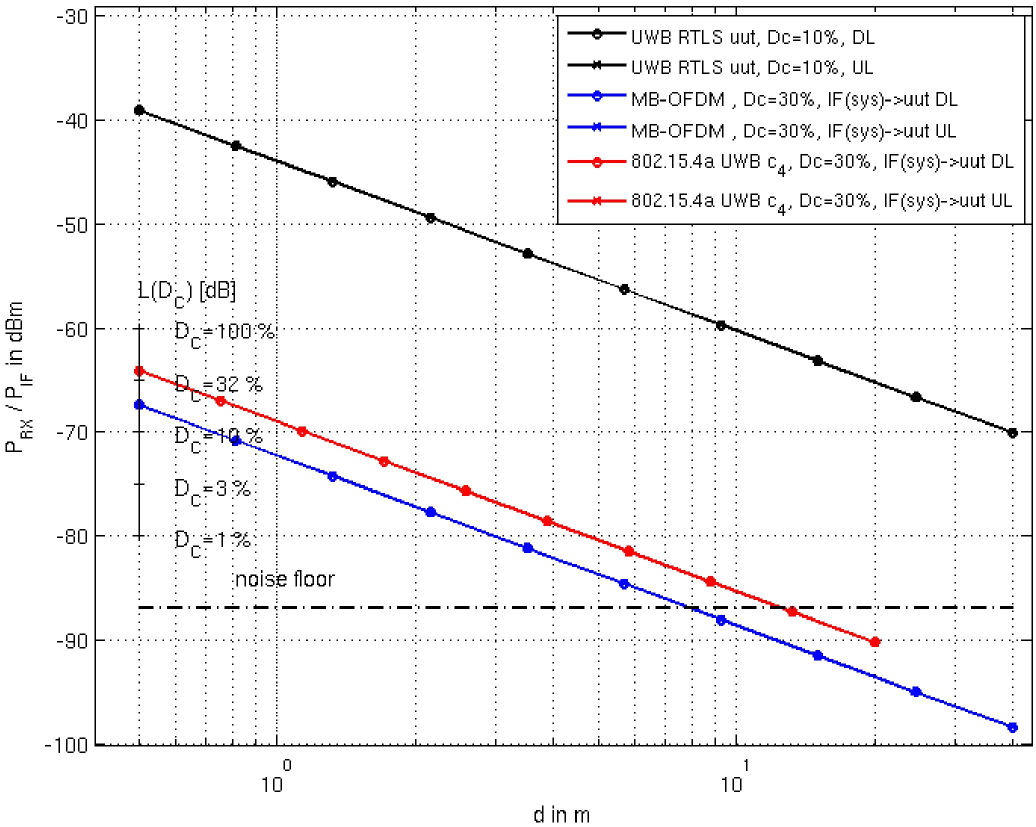

Fig. 14: Interference power analysis vs. the distance for the UWB-RTLS by Leti.

2.4.2.4.3 Interference Power analysis

Owing to the spreading gain, the impact of the interference from the other UWB devices is relatively weak as it is underlined by Fig. 14. The interference components in the despread signal is strongest for the IEEE 802.15.4a UWB device with its 1.3 GHz bandwidth as it distorts at the same time the full bandwidth of the UWB system by Leti. In contrast, one of the subbands of the MB-OFDM device does not overlap with this UWB RTLS, which reduces the effective PSD level by another 1.75 dB. Additionally, always only a part of the spectrum is harmed, such that the harmed (by the interference) part of the signal spectrum can be suppressed in the receiver in theory.

2.4.2.4.4 Discussion

The main source for interference is from UWB systems. Due to their short reach, UWB networks will usually distort each other only marginally. However, a temporal synchronisation or arbitration (AWMA or PTA) may be a reasonable option, once the market penetration of UWB devices has become stronger.

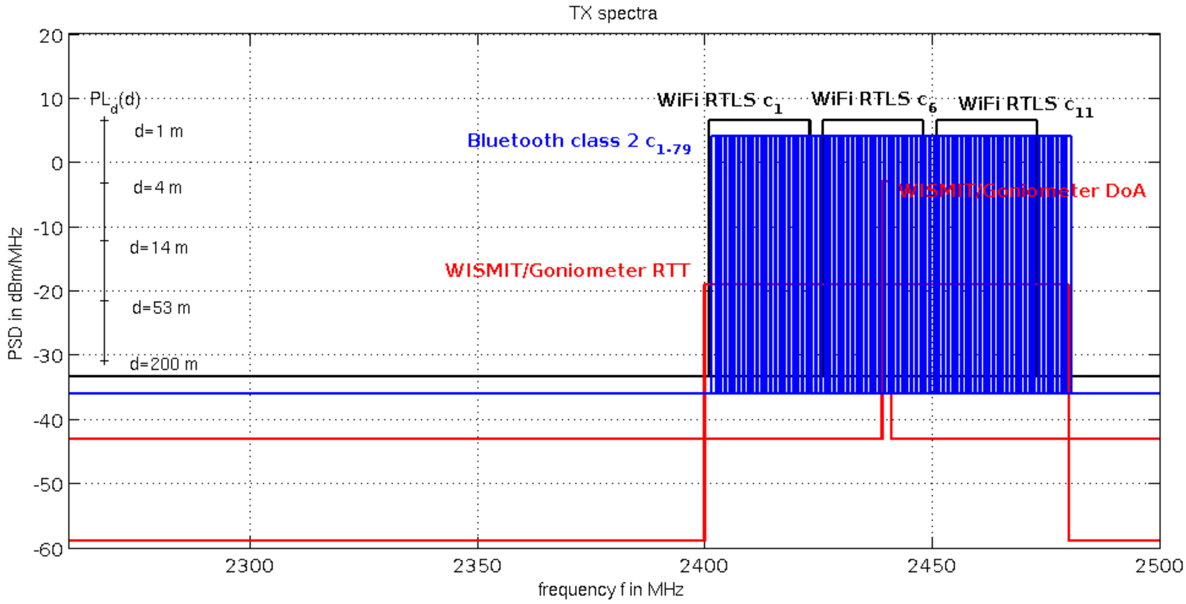

Fig. 15: Spectral analysis generated for the WiFi RTLS.

2.4.2.5 WLAN RTLS (CIT)

2.4.2.5.1 Description

The WLAN RTLS by CIT uses fingerprinting in order to obtain position estimates. These estimates derive from comparing measured data vectors with a map of reference measurements. In this case, the data vector consists of a *received signal strength indicator* (RSSI) for a set of different WLAN access points that are identified via their MAC address. In other configurations, i.e. not in LocON, also RTT measurements are used to perform fingerprinting. In order to have the data vectors approximately unambiguous, a minimum number of access points is needed. But especially for the RSS measurements utilized in LocON, this number is hard to identify theoretically. It can be determined by educated guesses based on experience of the operator. However, fingerprinting can cope with extreme multipath and extreme non-line of sight conditions. Since RSSI fingerprinting is based on measurements within the mobile device (i.e. the tag), the number of additional channel accesses is marginal.

Given a tag that is capable of multiple WLAN standards, each of the supported standards can be used to measure the RSSI values. In principle, the measurements may be performed either in the tag or in the infrastructure. The first choice seems advantageous because of the renunciation of tag transmissions according to each standard. The estimated position may then be conveyed to the LocON server by the WLAN capability.

The transmitted power and the interference mitigation techniques depend on the used WLAN standards and devices – not every feature of a standard is implemented in all devices. In the 2.4 GHz range WLAN is allowed to transmit with 20 dBm EIRP, in the 5 GHz range up to 30 dBm are possible. Usual ranges of WLAN systems are 50 m in building, and 200 m outsides.

2.4.2.5.2 Spectral analysis

The spectral analysis for the WLAN system if operated in the RSSI based fingerprinting mode is the same as for all used WLAN/WiFi communication systems and depends just on the infrastructure that is available. Fig. 15 now displays the generated spectra for WiFi localisation based on access points operating in the WiFi frequency bands 1, 6, and 11. These are the carrier frequencies 2.412 GHz, 2.437 GHz and 2.462 GHz.

The displayed peak spectra of Bluetooth class 2 devices have an allowed transmit power of 4 dBm, which is relatively low compared to WLAN – even the transmit PSD is below that of the WLAN devices despite the much lower bandwidth. Therefore, it is not probable that a complete WLAN transmission is distorted by the Bluetooth transmission neither for spread spectrum realisations of the WLAN PHY (IEEE 802.11b) nor for WLAN standards employing OFDM (IEEE 802.11a, g, h, n). The IEEE 802.1a standard and its modification h operate in the 5 GHz range anyway, where no Bluetooth traffic can be expected.

Furthermore, the depicted spectra for the WISMIT/Goniometer system on the nanoLoc basis show that the potential harm for the WLAN system can be assumed low. However, the FMCW or chirp nature of the wideband signal is not covered by that diagram, because the signal power is concentrated at distinct time instances. If considering the opposite direction, given a large network load due to additional data traffic, the WiFi systems will do severe harm to the FMCW signal of the WISMIT and its network nodes.

2.4.2.5.3 Interference Power analysis

The diagram in Fig. 16 affirms the observation from the previous paragraph that Bluetooth is the most severe source of interference for WLAN systems in the 2.4 GHz ISM band. The chances that the WiFi transmissions are sustainably distorted by the chirp signals or the narrowband carrier signal of the WISMIT device and of the Goniometer nodes are remote.

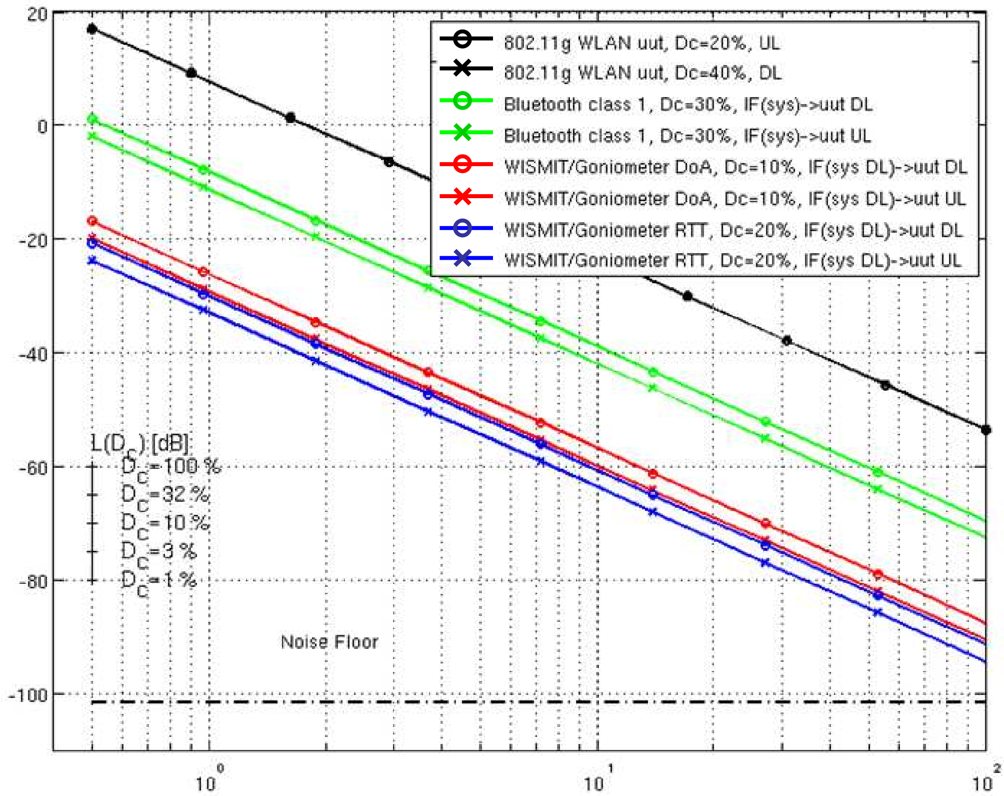

Fig. 16: Interference power vs. the distance for a 2.4 GHz WiFi device in channel 7 for indoor NLOS channels.

2.4.2.5.4 Discussion

As such the WiFi localisation system is just parasitic device (used in here without any negative intention) exploiting the available infrastructure and the independently transmitted signals. It does not harm the systems or reduce their capacity decisively because it just measures the signal strength from existent data packages.

Another advantage if seen from coexistence point of view is that these WiFi RTLS automatically make use of all coexistence mechanisms that are already implemented in the infrastructure. Further mitigation of coexistence issues can be achieved by careful choice of the positions of the access points and by choosing the channels that are most improbably harmed by e.g. the other devices. Other devices should be capable of LBT and should access the channel not to frequently, if the network load of the WiFi system is high. If observing the coexistence from the other direction, the load of the WiFi system should also leave enough time slots for coexisting devices.

2.4.2.6 GPS

2.4.2.6.1 Description

The best known localisation and navigation system is the Global Positioning System (GPS) that will be in near future assisted by the European Galileo system and by the re-strengthened Russian GLONASS. Since GPS is currently the only freely available of the three in Western Europe, this report concentrates on it. GPS employs a 1 MHz frequency subband of the L5 band at 1.575 GHz for acquisition and a second frequency band of 10.2 MHz at 1.228 GHz in the L2 band. The set-top box by INOV is connected to the LPR tag by Symeo and is able to connect to the LocON server via WLAN, in later updates perhaps also by the public *CDMA-450* network.

2.4.2.6.2 Discussion

The GPS carrier frequencies are securely separated from the other spectrum users at 1.5750 and 1.2280 GHz with bandwidths of 1 MHz and 10.2 MHz, respectively. Especially, the US government has made a lot of effort in order to keep interference away from the GPS bands due to the general importance of GPS to current and future military operation. The closest users – from spectral perspective – in the future will be the new European Galileo system. There has been performed a lot of research on the topic prior to the specification of Galileo. Hence, the present system design of Galileo will lead to a band overlap of Galileo and GPS of 8 %. The three frequency bands for Galileo are 1164 – 1214 MHz (L1), 1260 – 1300 MHz, 1563 – 1591 MHz. Like the LPR system, coexistence will be tested within WP6. Thus, the analysis in here may remain brief.

2.4.2.7 Ubisense RTLS

One of the first commercial implementation of a UWB locating system has been provided by Ubisense [20]. It has not been tested in detail in terms of the study and the available technical data on the PHY is incomplete. Nevertheless the main features as known will be described below.

2.4.2.7.1 Description

The system works based on TDoA and AoA measurements of UWB pulse sequences of 2 GHz bandwidth between 6 and 8 GHz. The angles of arrival of the signals are determined by evaluating the differences of the arrival times at the four[13] involved receive antennas per sensor node. One of the four sensor nodes per cell acts as a master device for the wired synchronization network. Additionally, the master establishes the wireless, bi-directional communication with the tags via the more narrowband telemetry channel at 2.40 GHz. The recommended minimum configuration for 3D-localisation is four sensor nodes.

Together, with the regulation of the European authorities that accounts for a maximum EIRP of -8.3 dBm in the UWB band. According to the regulation, the maximum signalling power for location systems in the 2.4 GHz band must be around 0 dBm EIRP. Typical ranges for the RTLS will be 100 m outsides and 30 m insides.

2.4.2.7.2 Spectral analysis

It is well visible in Fig. 17 that WiFi in channel 1 is critical for the telemetry channel and that only the other UWB systems reside in the same transmission band as the Ubisense system. The coexistence with the other UWB users may be achieved if each of the systems has a relatively low channel load. However, even a thin wall between two systems will reduce the potential interference power sufficiently.

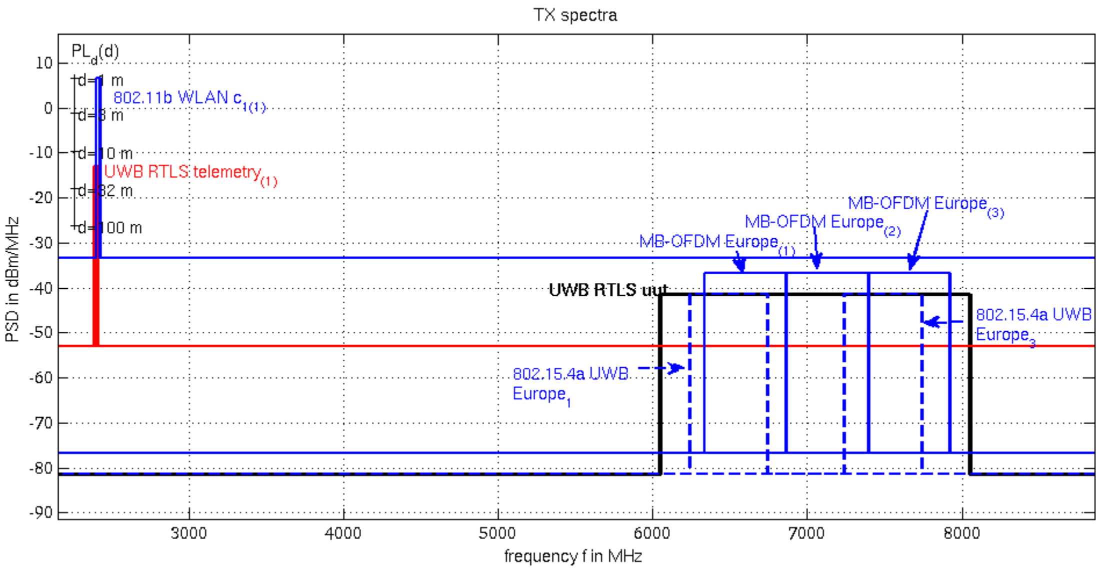

Fig. 17: Spectral analysis generated for the Ubisense RTLS (indoor path loss).

2.4.2.7.3 Discussion

For the Ubisense RTLS like for the Leti UWB system, the most critical other spectrum users are again other UWB users. However, the Ubisense system has the speciality that it also has a signal at 2.4 GHz that is essential for the operation – the tags receive their authorization to transmit via that telemetry channel. Thus, also a strong protection of this channel is essential. However, it is unclear how this issue is solved or if it is solved at all for the Ubisense devices.

[13] The antennas are arranged in a trapezoid in order to obtain horizontal and vertical directions.

2.4.3 Communications Systems

2.4.3.1 Wireless and Mobile Phone Standards

In the past, many mobile phone standards have emerged and several have already vanished. Currently in Europe, only a subset is realistically in use, these are mainly GSM, EDGE, CDMA-450 (Portugal), UMTS-WCDMA, LTE and DECT. As a special case, the latter specifies personal network for cordless phones.

Their spectra do not overlap with those from the considered RTLS, they are not even close to each other in the (inter-)national band plans. Thus, direct coexistence issues can hardly be expected and the description in this report can remain short. Also their packet based extension like GPRS, EV-DO, and HSDPA/HSUPA[14] will not have any impact on the location systems.

2.4.3.1.1 Description

GSM is the most common standard for mobile phones. GSM devices employ Gaussian minimum shift keying (GMSK) modulated channels of 200 kHz in three global frequency bands, namely the original 900 MHz band, its extension around 1800 MHz and the 1900 MHz band. The first two are available almost worldwide with the exception of the USA, while the last is restricted to the USA. The transmit power is limited to 39 dBm for basestations and 33 dBm (2 W) for handheld devices. The duplex mode is *frequency domain duplex* (FDD) and TDMA and naturally FDMA are the multiple access schemes. In principle, GSM allows frequency hopping, which is however not used in practice. EDGE is a *higher-rate* extension to GSM and its packet switched service GPRS. EDGE increases the available data rate by replacing the (bipolar) GMSK by a higher order modulation (8-PSK). Otherwise, the main features like radiated power, bandwidth, and the dedicated carrier frequencies remain the same.

CDMA-450 (as part of the CDMA2000 specification) is originally the CDMA implementation considered in the 3G standards project for the USA. According to its name, it is situated in the 450 MHz band (CDMA2000 also specifies bands at 950 MHz, 1.8 GHz and 2.1 GHz) and is based on DSSS respectively CDMA. In many countries the 450 MHz band is – or has been formerly – used for terrestrial television transmissions. CDMA2000 bands are 1.25 MHz wide (in the US 1.23 MHz) and allows for data traffic up to 153 kBps.

Like the former, **UMTS** (*universal mobile communication standard*) is a third generation (3G) communications standard that is mainly in use in European countries. It is also based on the CDMA technique with 5 MHz bands[15] and operates in Europe mainly in a band around 2 GHz with a maximum radiated power of 33 dBm EIRP of the basestations and mobiles. The duplex mode is FDD. However, an active power control tries to limit the interference between mobile users[16]. Hence, the power level of mobile devices is reduces where possible.

LTE for *long term evolution* is the fourth generation of cell phone standards. It tries to reuse many parts of the UMTS analogue hardware and will be consequently restricted to the same frequency bands. Currently, the first real networks are deployed. The standard enables a larger amount of freedoms on bandwidths and transmission modes as its predecessors and

[14]GPRS relates to GSM, EV-DO to CDMA-2000 (and CDMA-450), HSDPA/HSUPA (sometimes combined as HSPA) to UMTS. LTE will be implemented as HSDPA from the start, for DECT no such extension exists.

[15] 3.84 MHz are ultimately used the remainder is guard bands.

[16] CDMA in the uplink is interference limited.

introduces again a completely new PHY layer. The intended downlink is based on OFDMA. Since OFDM suffers from a high *peak to average ratio* (PAR) and with it large power back-offs of amplifiers, in the uplink, the related technology *single carrier FDMA* (SC-FDMA) is envisioned. The supported bandwidths will range from 1 MHz to 20 MHz. Due to the same underlying regulation, the maximum radiated power will be in the same order as that of UMTS. Again different frequency bands are envisioned for uplink and downlink.

The cordless phone standard **DECT** is the most distributed in its application field. In Europe, the 1.9 GHz band is mostly used. The peaky DECT signalling consist of short time slots or bursts with a peak power of 24 dBm and an average of 10 dBm EIRP, i.e. the duty cycle is rather low far below 10 %. Modern DECT telephone sometimes allow to reduce the transmit power, when the distance between station and mobile is small. The data symbols are modulated with Gaussian frequency shift keying. DECT employs *time domain duplex* (TDD).

2.4.3.1.2 Discussion

In principal, for the mobile phone standards no coexistence issues should arise because they are licensed and, consequently, exclusive (perhaps except for DECT) in their respective spectral range. Considering non-linearities and intermodulation products in receivers may lead to distortions of other channels.

2.4.3.2 WLAN or WiFi

The development of wireless local area network (WLAN), synonymously called WiFi, has created over the last 10 years a large set of different standards mainly incorporated in the IEEE 802.11 standards group (a, b, g and n). They are discussed in this single section because they are all based on the same frequency grid of 22 MHz bands in the 2.4 GHz and in 5 GHz bands. Additionally, they have the basic channel access schemes (CSMA) in common and all WLAN standards of the IEEE 802.11 family divide uplink to and downlink from an access point in time domain (TDD). Mainly, the standards differ in the type of modulation.

2.4.3.2.1 Description

Its first instantiation of IEEE 802.11 lead directly to today's **IEEE 802.11b** standard that is based on DSSS and complimentary code keying [13]. Its signal spectrum has a bandwidth of 22 MHz is shaped like a cosine half wave. Thus, its power spectral density is decreasing rather slowly versus the band edges. 11b is implemented as a fallback solution for devices supporting other WLAN standards.

The other implementations (**IEEE 802.11a, g,** and **n**) are based on OFDM. The first two divide the spectrum into with 52 subcarriers and the *a-standard* is designed for the 5 GHz band, while the *g-standard* mainly comprises the transformation of that one to the more common 2.4 GHz band. Both standards implemented adaptive coding and modulation (ACM) in order to achieve maximum data rates up to 54 MBit/s. In principle the employed bandwidth for both is 16.7 MHz if considering only the used subcarriers. The **IEEE 802.11n**, then is a supplement to the former standards (in both frequency ranges) allowing to unite two channels and increase the bandwidth to 40 MHz. Hence in principle, it allows for data rates up to 600 MBit/s.

IEEE 802.11h covers only the required coexistence techniques for using the 5 GHz band in Europe [14], namely implementing dynamic frequency selection (DFS) and transmit power control (TPC) (see Section 3.1.7).

In the 2.4 GHz band, there are 14 channels defined with grid of 5 MHz, i.e. give the bandwidth of 22 MHz a significant overlap larger van 75 % exists between neighbouring channels. Thus, in order to limit the mutual distortions at least four channels should remain unused, and usually, only a subset of these channels is used. In Europe, these are mainly the channels {1, 6, 12} (center frequencies 2.412, 2.437 and 2.462 MHz) or {1, 6, 12} (2.412, 2.437 and 2.467 MHz). In the 5 GHz bands, the separation between center frequencies of realistic channels in the grid is larger with a minimum of 20 MHz.

The regulation on the radiated power differs in many countries. In the 2.4 GHz band, in Germany a maximum transmit power of 20 dBm EIRP complies with the regulation (US 25 dBm), in the 5 GHz range it is between 15 dBm and 30 dBm in Germany (US 30 dBm), without DFS and TPC that limit is 23 dBm.

2.4.3.2.2 Spectral analysis

The spectral analysis of the WiFi systems is contained in the previous spectral analyses above, i.e. WiFi in the 2.4 GHz range as found in Fig. 6 on the WISMIT/Goniometer system suffers additionally from interference from Bluetooth and ZigBee. As displayed in Fig. 10, only the LPR system has potential coexistence issues with WiFi in the 5 GHz ISM and U-NII bands. The distortion of the WiFi systems themselves is relatively weak due to the relatively strong transmit signal levels. An example for the "high channels" in the 5 GHz range is depicted in Fig. 18. However, the displayed channel 171 and all the other channels of this range are not usable without a notification of the authorities except for the USA.

The coexistence of WLAN in the 2.4 GHz band is discussed in Subsection 2.4.2.5 on WLAN RTLS.

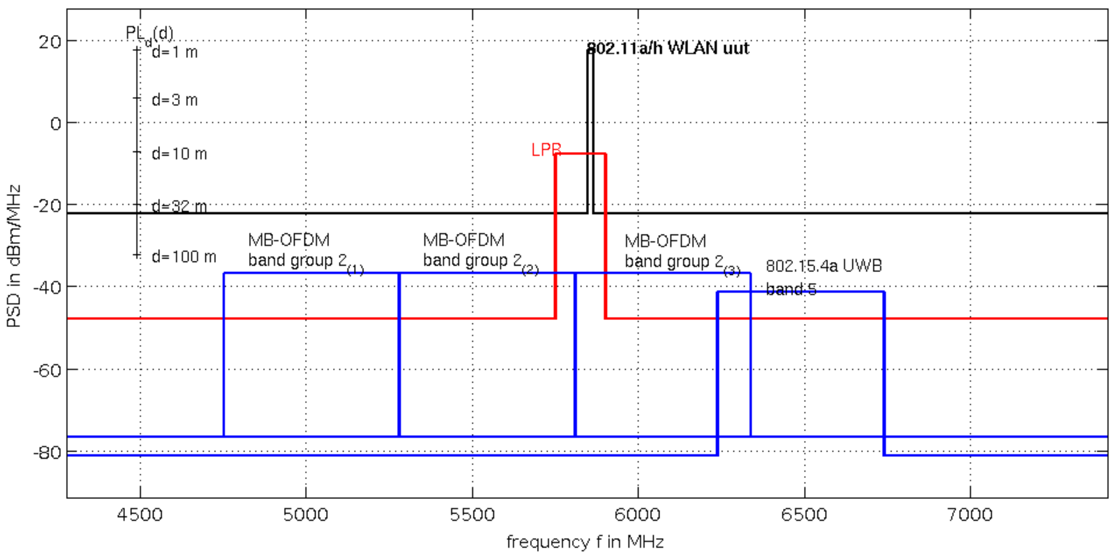

Fig. 18: Spectral analysis for the WiFi channel 171 at relatively high carrier frequency.

2.4.3.2.3 Interference Power analysis

The corresponding interference power for the example of WLAN channel 171 can be investigated in Fig. 19. It is visible that a nearby LPR system may have the potential to distort WiFi signals in the ISM band at 5.8 GHz. Additionally, the opposite can be said on the MB-OFDM system from *band group 2* [17]: the radiated power of the UWB system (MB-OFDM) is that weak that interference levels are several orders of magnitude below that of WLAN devices.

[17] They may coexist in the USA – in Europe, both the WiFi and the MB-OFDM system are.

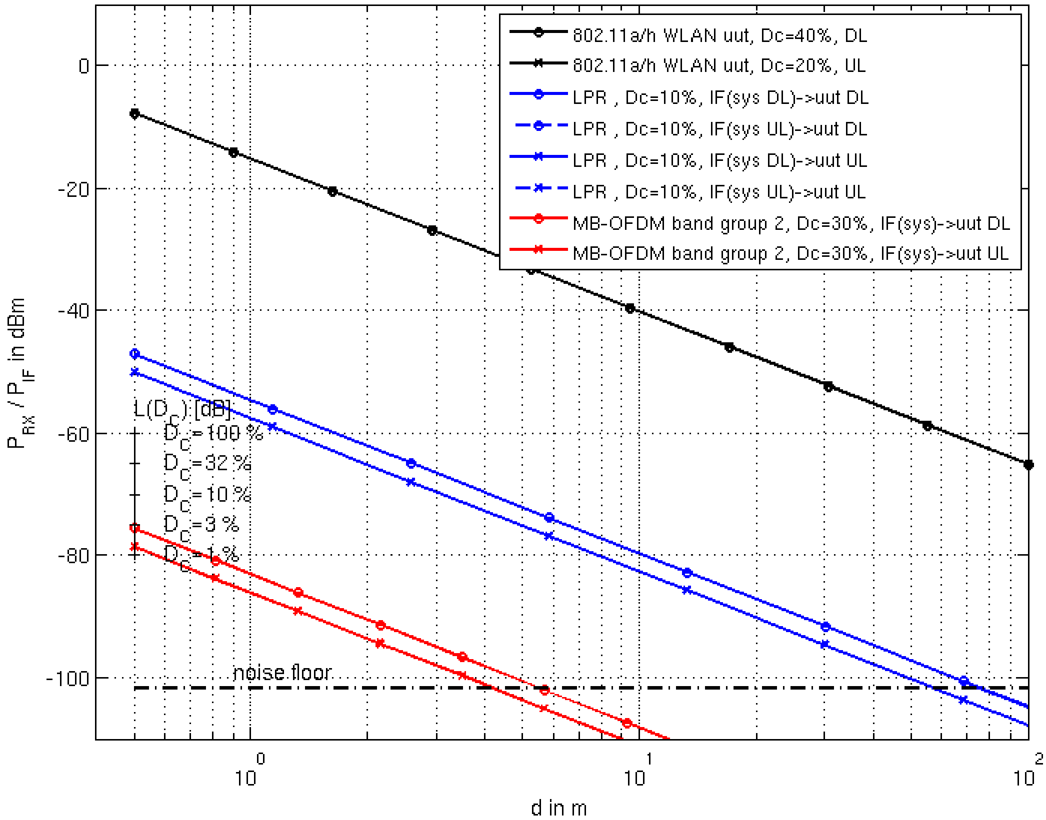

Fig. 19: Interference power vs. the distance for the a 5 GHz WiFi device in channel 7 for indoor NLOS channels.

2.4.3.2.4 Discussion

WiFi systems as they are situated in the unlicensed frequency ranges in the ISM and U-NII bands are affected rather strongly by coexistence issues with all other users residing in the same frequency bands. Thus, for WiFi several coexistence techniques, e.g. LBT, DFS and TPC are applied. Accordingly, if these techniques do not suffice to mitigate detected interference, coexistence with WiFi may be assured by implementing AWMA or PTA based on a combined node for WLAN and the other system in order to temporally coordinate the channel access between the two.

However, the tremendous freedom with regard to available bands at least in the 5 GHz range together with the limited range of WiFi devices in indoor environments may allow for avoiding relevant frequency bands in most of the scenarios.

2.4.3.3 WMAN (WiMAX)

The most commonly known implementation of a wireless metropolitan area network (WMAN) is the implementation of the WiMAX standard IEEE 802.16. The IEEE 802.16d-variant is intended for the wireless broadband access in people's homes (wireless local loop). The WiMAX mobile systems for mobile broadband access are standardized as IEEE 802.16e and its updated version 16j.

2.4.3.3.1 Description

All versions of WiMAX employ OFDM as modulation of choice – respectively OFDMA as multiple access technology. Especially, the mobile implementations are rather similar to the specifications for LTE with similar bandwidths and data rates (see above). For the fixed WiMAX implementation the only frequency band coarsely of interest (for this study) is sometimes in use, that at 3.5 GHz. Sometimes, also carrier frequencies around 2.4 and 2.6 GHz have been discussed. WiMAX basestations are allowed to transmit at a power level of 30 dBm EIRP.

2.4.3.3.2 Discussion

WiMAX at 3.5 GHz may interfere with UWB devices in the lower part of the spectrum envisioned for the US, such that a US version of the UWB RTLS may interfere with WiMAX there. However for Europe, a fast adoption of LTE networks is expected reducing the market for WiMAX based systems and with it the danger of coexistence issues.

2.4.3.4 WPAN

There is also a multiple of wireless personal area network (WPAN) standards to support the data exchange in the personal domain of a user; that may be a room, a flat or the interior of a car. Aiming at the mass market of mobile, battery-powered devices, other main features of WPANs are low cost and low energy consumption. Examples are Bluetooth (802.15.1), Zigbee (802.15.4), low rate DS-UWB (802.15.4a), and WiMedia MB-OFDM (formerly 802.15.3a). While the first three are considered for medium (Bluetooth) to low (ZigBee, 802.15.4a) data rates the last one (MB-OFDM) aims at high rate data transfers. Accordingly, they envision different applications and, thus, have different modulations and access schemes. The intended data transfer ranges from exchanging sporadic sensor data (<10 kByte/s) to streaming of uncoded HiFi audio and video data (>400 Mbit/s). Nevertheless in terms of this work, they are treated together in these paragraphs due to limitation in time and paper space.

2.4.3.4.1 Description

Bluetooth [11] is the most common and successful of the WPAN standards aimed at providing medium data rate services (in the order of Mbit/s). Meanwhile, the standard exists in its fourth revision. Bluetooth devices transmit in the 2.4 GHz ISM band and use frequency hopping between 79 subchannels. This frequency hopping has been extended to be adaptive to the interference or coexistence situation (AFH, see Section 3.1.8.3) since the revision 1.2. The subchannels have an individual bandwidth of 1 MHz (total bandwidth ca. 80 MHz) and the minimum hopping interval (or the time within one band) is approximately 1 ms.

Formerly Bluetooth used GFSK modulation which has been changed to M-PSK (with M up to 8) in newer revisions of the standard (2.0 and higher). The maximum transmit power of a Bluetooth device differs from application and distance to be achieved is maximally 20 dBm EIRP (class 1), but other devices are only allowed with 4 dBm (class 2) and 0 dBm (class 3). These classes determine the range the Bluetooth devices can cover: class 1 → 100 m, class 2 → 10 m, and class 3 → 1m.

Due to the frequency hopping, the diversion between TDD and FDD as the duplex scheme is hard to make. If the complete frequency range of all hopping frequencies is regarded as transmission bandwidth, it must be regarded as TDD. Beneath the frequency hopping, other coexistence techniques with WLAN are standardized like LBT, *alternating wireless medium access* (AWMA) and *packet traffic arbitration* (PTA). The latter two presume the integration of the Bluetooth master with a WLAN node in the same device in order to coordinate both networks and to distribute the time slots for channel accesses between the two. The mechanisms are included in the coexistence part of the WPAN specification in IEEE 802.15.2.

The **ZigBee** standard [16] envisions low data rate (<250 kbit/s) transmissions of low cost devices, e.g. for wireless sensor networks (WSN). ZigBee devices transmitting in one of the 10 bands of 2 MHz bandwidth (and 5 MHz spacing) in the 2.4 GHz band are rather vulnerable against interference due to WLAN, and especially Bluetooth traffic. Therefore it uses direct spread spectrum techniques. The usual power of transmitted signal is around 0 dBm EIRP. The communication is established in a TDD fashion.

Also due to the coexistence issues, the alternate physical layer **IEEE 802.15.4a** [17] has been issued mainly as an UWB implementation based on DSSS. It offers 16 channels determined by their center frequency and bandwidth combination: the bandwidths range from 500 MHz to 1350 MHz with center frequencies from 3.5 GHz to 9.5 GHz. In Europe, only the channels 6, 8 and 9 with 499.2 MHz bandwidth completely lie within the UWB frequency band from 6 to 8.5 GHz. If DAA or LDC (see the section 3.1.5 and 3.1.6) are implemented the channels 1 and 2 with center frequencies 3.5 and 4 GHz may be used.

The maximum transmit power of the standard is 0 dBm. However in Europe, the relatively small bandwidths (for UWB) limit the EIRP to -14.3 dBm. The duplex mode is TDD. The standard is also directly intended in its design phase to support ranging services for locating systems.

Also the **nanoLoc** transmission protocol based on chirp spread spectrum (CSS, see above and Section 3.1.8.2) and as employed by the WISMIT system (Section 2.4.2.1) is proposed to the standardization group as alternate PHY for ZigBee, i.e. also in IEEE 802.15.4a, in 2008.

MB-OFDM (for *multiband OFDM*) has been proposed for the 802.15.3a for high data rate UWB transmissions. The standardization failed due to an irresolvable deadlock situation with the competing DS-UWB (*direct sequence UWB*) proposal. While the DS-UWB consideration quickly faded away, MB-OFDM has been driven forward for some time intended to become PHY for *wireless USB* and Bluetooth 3.0, but these plans have been revoked and they never came into effect. The distribution of devices is still more than sparse, although the sales in the US have been reported. The MB-OFDM standard employs OFDM modulated symbols in three subbands of 528 MHz. They are used alternately to transmit one OFDM symbol according to one of the defined time frequency codes of interval length six. The frequency hopping is employed enabling the simultaneous channel access of multiple piconets. The transmit power is limited to -14.3 dBm. In Europe, the frequency bands between 3.1 and 4.8 GHz[7] with DAA and between 6 and 8.5 GHz[18] are usable with a reasonable radiated power. After similar considerations as for Bluetooth, TDD must be regarded as duplex mode.

In ostensible disregard of the UWB regulation, MB-OFDM employs a PSD level of

$$-41.3 \text{ dBm} + 10 \log_{10}(3) \text{ dB} = -36.5 \text{ dBm}$$

for the OFDM symbols in each subband. However, the signalling is absent from each subband for two thirds of the time. Hence, when observing the average PSD over a sequence of at

[18] With DAA, it is band group 1 with the triples of center frequencies {3.432, 3.960, 4.488} in GHz, and, without DAA, these are the band groups 3 and 6 with the frequency triples {6.600, 7.128, 7.656}, respectively {7.656, 8.184, 8.712} all in GHz.

least six symbols (the interval length), it obeys again the power level -41.3 dBm as intended by the regulating authorities. During the standardisation attempt in terms of IEEE 802.15.3a, this argumentation has been doubted as part of the general controversial, but the FCC approved the reasoning of the supporting Multiband-OFDM Alliance.

2.4.3.4.2 Spectral and Interference Power Analysis

At this point, no individual spectral analysis has been made for the WPAN systems, as they are clearly not part of the objective of the study in terms of the LocON project. Provided the tools developed in here however an analysis is well feasible.

2.4.3.4.3 Discussion

The WPAN systems from their definition and from their consequently chosen radio spectrum have to be robust to interference. Being situated either in the ISM band or employing the UWB paradigm, WPAN systems suffer from a large variety of potential interference causes and themselves cause dangerous interference for the respective other user. However, WPAN devices usually have very limited coverage range, and therefore, the distortions on other systems are often small and concentrated on few spots.

2.4.4 The Microwave Oven

The microwave oven is one of the main reasons for the freely available (or unlicensed use) of the ISM band at 2.45 GHz. In this frequency range electro-magnetic waves achieve to stimulate water molecules and to set them into oscillation realized by the user of the oven as heat. The frequency is the result of a trade-off: it is close enough to the resonance frequency of the water dipole and easy enough to be generated at reasonable power levels. Radiated powers of microwave ovens are usually beyond 500 W, however the electromagnetic shielding prevents the main part of the radiation from leaving the interior of the oven. Thus, the escaping radiation has to comply with the limit of other radiation sources (<10 W/m²).

Obviously, no coexistence mechanisms are built in the microwave oven. In principle the insensitivity to the radiation of the oven must be assured by each manufacturer. However, the radiation level quickly decays and only in the most uncommon circumstances the location of RTLS and microwave ovens coincide. Nevertheless, candidates for suffering from this interfering source are the WISMIT system (i.e. the nanoLoc) and the WLAN RTLS as well as the Ubisense communication channel.

2.4.5 Required System Separation

Tab. 2 presents some advices for the deployment of the localisation and communication systems, where in the upper analyses coexistence issues have been detected. The respective advices on the required separation[19] have been determined graphically in the respective interference power plots from the previous sections. This scheme follows the example of the interference power plot in Fig. 8 and the results have been rounded reasonably.

The SINR value of 0 dB has been chosen because of the statistical nature of the collisions[20], i.e. not all signal bursts suffer from the interference of 0 dB. But some will have an SINR = -20 dB, while during some other bursts interference will be totally absent. In order to judge those

[19] where needed for both, tag and anchor node.

[20] if the duty cycle is smaller than 100 %. This is true for all systems that are considered in the tabular.

distances (for SINR = 0 dB), also those separations required for an SINR = 10 dB are displayed, although, that will provide a much too critical view on the situation. When judging the results the attenuation due to walls and windows should be kept in mind (-10 dB minimally).

The most critical outcomes are again obtained for the WISMIT/Goniometer system, for which a distinct separation of anchor nodes and tags to WiFi (2.4 GHz, indoor) and Bluetooth class 1 devices is definitively needed. For all other systems, we do not expect coexistence issues.

System of Interest (SOI)	provider	covered range	duty cycle of SOI	Radio Interferer (RIF)	duty cycle of RIF	required distance for an SINR =	
						0 dB	10 dB
Wismit / Goniometer (RTT burst is decisive)	Fraunhofer	100 m	30 %	IEEE 802.11b/g	100 %	**> 50 m**	**> 150 m**
					30 %	**> 30 m**	**> 100 m**
				2 x IEEE 802.11b/g channel 1 und 11	30 % each	**> 40 m**	**> 120 m**
				Bluetooth class 2 (4 dBm)	100 %	> 7 m	> 20 m
					30 %	> 3 m	> 10 m
				Bluetooth class 1 (20 dBm)	100 %	**> 40 m**	**> 120 m**
					30 %	**> 20 m**	**> 60 m**
				ZigBee	30 %	> 2 m	> 7 m
LPR	Symeo	400 m	10 %	IEEE 802.11a	100 %	> 0.5 m	> 2 m
					30 %	> 0.1 m	> 1 m
UWB RTLS	Leti	20 m	10 %	MB-OFDM (UWB)	30 %	> 0.1 m	> 1m
				IEEE802.15.4a (UWB)	30 %	> 0.5 m	> 2 m

Tab. 2: Minimum separation for the set of RTLS as used in LocON with respect to identified interferers (values in bold type are critical to be maintained in deployment).

2.4.6 SUMMARY

The localisation systems usually provide a smaller subset of available interference mitigation techniques than communication systems, at least if not based on the infrastructure of an existing network structure for communications. This is mainly reasoned due to the considerably larger attention and market penetration, and with it, designing effort for wireless communication standards if compared with localisation systems usually supported by a single manufacturer. Additionally, these manufacturers are often start-ups and have mostly SME-status (*small or medium sized enterprise*). Therefore, they may not afford as large efforts for coexistence mitigation techniques.

3 MITIGATING INTERFERENCE

Since their spectrums are located in the freely available ISM-bands many systems already foresee interference mitigation techniques that try to limit the impact of this interference from and to other coexisting systems. For other systems like those making use of the UWB approach or of the 5 GHz bands (for both under European legislation) even the regulators had some mitigation techniques in mind. Although most of these techniques have been designed for radio communication systems, they may be – due to similar scenarios and regulation – also employed in many location systems. Additionally, some location systems just make use of the infrastructure provided by available communication systems like the WLAN system from the LocON partner CIT [1] or a similar system from Ekahau [19]. Thereby, these systems inherently apply the interference mitigation techniques comprised in the respective communication standard.

In the following, some of the mitigation techniques with examples from location systems and communication systems are presented and their impact on this research is discussed shortly. Afterwards, proposals for improving the coexistence of the involved systems are concluded.

3.1 HINDERING INTERFERENCE ON MAC AND PHY LAYER

The next paragraphs consider several methods to hinder or to diminish the interference before it can happen. Thus, for hindering they mostly consider the MAC layer. Other methods are also based on processing PHY data. For most of the presented methods, [9] is a good literature advice if not stated otherwise.

3.1.1 ALTERNATING WIRELESS MEDIA ACCESS

If WLAN systems and WPAN systems coexist in the ISM band both can negotiate an alternating media access within a time period T_B, the beacon interval. This static alternating access is indicated according to IEEE802.15.2 by the Bluetooth master collocated with a WiFi node.

Continuing this idea leads to a dynamic *packet traffic arbitration* (PTA) that polls WLAN and Bluetooth device for intended traffic and then confirms the allowed spectrum access. PTA is also part of IEEE802.15.2. However, relatively few WLAN access points or devices have implemented these approaches.

3.1.2 PACKET SIZE VARIATION/REDUCTION

The reduction of the packet size also reduces the probability that this data packet is harmed by a sporadic interferer according to (3) for the temporal analysis of packet collisions. Now considering an automatic repeat request (ARQ) scheme like applied in all modern communication standards, only a shorter packet has to be repeated [2]. Hence, the channel load and the duty cycle are further reduced reducing the total probability of collisions. However, the potential gain is limited by the quasi-constant overhead per packet in data headers and training data. An extreme implementation of these considerations is an impulse radio UWB system with low duty cycle (LDC) as discussed below (see Subsection 3.1.6).

3.1.3 LISTEN BEFORE TALK (LBT)

The simplest method of mitigating or hindering interference is achieved by scanning the radio channel, respectively, the part of the spectrum the transmitter intends to use, before the transmission is started. If another ongoing channel use is detected the attempt to access the channel is discontinued and delayed until the end of the ongoing transmission. The detection of the channel use can adopt one of two different main variants:

- Firstly, only the signal power in the transmission band is measured. This method has a relatively low sensitivity due to an SNR loss introduced by a non-linear (squaring) device. However, it is possible to detect interfering devices of multiple standards–even such standards unknown do the measuring device and of multiple bandwidths.
- The second variant detects dedicated signals from other devices. Since it is in most cases infeasible to integrate different receivers or run them simultaneously on the same platform most systems employing this variant do only detect transmissions according to their own physical layer implementation.

If pure LBT is employed by the respective systems it is nevertheless highly probable that packet collisions occur frequently in case that

a) the overall channel utilization is large (~100%),

b) the distances, i.e. also the propagation delay, of the signal are large relative to the packet lengths because, considering large propagation delays, it is more probable that a transmission will be started although another signal packet already travels through the air.

Examples:

- Bluetooth (IEEE 802.15.1[11]).
- the nanoLoc chipset has the option to choose one of both modes.
- the LPR system by Symeo.

3.1.4 CARRIER SENSE MULTIPLE ACCESS (CSMA)

Carrier sense multiple access (CSMA) is an extension or another flavour of the above LBT approach as such used to reduce the intra-system interference, i.e. the interference between different users within the same network and – however, not necessarily – the same cell competing for the same access medium like a radio channel. Like for LBT, the signal strength is measured before transmission. Additionally, all participants of the network continue the measurements during the data transmission. Two different main realizations exist as CSMA schemes that are signalized by extending the abbreviation. CSMA implementations are arbitrating for the channel access non-deterministically.

3.1.4.1 CSMA/CD (collision detection)

System employing CSMA-CD scan the channel during transmissions and send a jam signal if a collision is detected indicating to all users that the current transmissions are erroneous and must be terminated by the transmitters and discarded by the receivers. Afterwards, the competing transmitters wait for a (pseudo-) random time interval before restarting the transmission in order to prevent from a repeated packet collision. The basic realization dates back to the ALOHA system [21] by the University of Hawaii used to interconnect the university departments on different islands and was adopted by bus-based systems like Ethernet.

Examples:

- The ALOHA system introduced this scheme. Its slotted variant extends the scheme to only allow transmissions in distinct slots.
- Ethernet (IEEE 802.3).

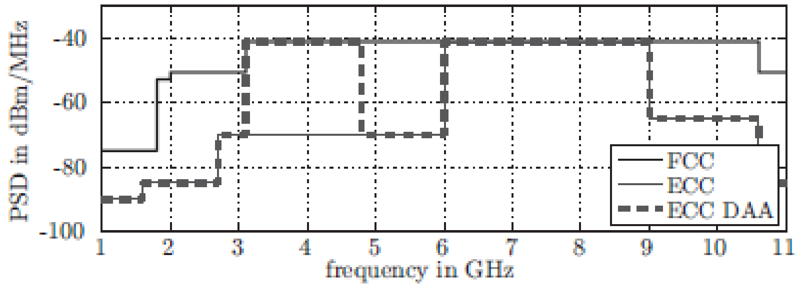

Fig. 20: ECC and FCC spectrum regulation [10] for UWB systems.

3.1.4.2 CSMA/CA (collision avoidance)

The same method as after a detected collision is used by each user willing to transmit after the regular termination of a transmission. Each user waits for a random time interval before transmitting if no other user has begun to transmit during that time span. Dedicated time slots exist e.g. for random access.

Examples: WLAN systems according to IEEE 802.11 in all variants (a/b/g/h/n, [11]) and with it in all WLAN localisation systems like those by CIT or Ekahau make use of CSMA/CD and CSMA/CA.

3.1.5 Detect and Avoid (DAA)

The detect and avoid (DAA) technique has been proposed for UWB systems and has found entry into the European [6],[7] (but also the Japanese) regulation for that kind of systems in certain frequency bands (3.1 – 3.4GHz, 3.4 – 4.2 GHz, and 8.5 – 9 GHz) in order to protect primary spectral users.

For DAA schemes, the channel is also scanned in a large part of the spectrum, and spectral areas already in use by primary users are avoided by the upcoming UWB transmission. In return those UWB systems are allowed for utilizing the medium at a power spectral density (PDS) level of -41.3 dBm/MHz EIRP like visualized in Fig. 20. Consequently, DAA achieves to avoids to distort this primary user, but also avoids that the own transmission is falsified by the other channel access. To the author no direct commercial implementation of DAA is known.

Examples: UWB regulation in Europe and Japan

3.1.6 Low Duty Cycle (LDC)

Another restriction for UWB systems in the bands between 3.4 and 4.8 GHz is introduced by the regulating authorities in Europe [6] similar to DAA. For low duty cycle (LDC) systems, the time ratio between active channel accesses and mute periods of the transmitter must be in the order of 5 percent in order to have the right to exploit the full power spectral density level of -41.3 dBm/MHz EIRP, otherwise severely lower limits are valid (see Fig. 20). According to [5], a system is regarded as being LDC if

a) The maximum continuously active time period is 5 ms.
b) The mean time between active intervals is larger than 38 ms.
c) The relative active time period in *one second* must not exceed 5%.
d) The relative active time period in *one hour* must not exceed 0.5%.

The idea behind LDC is that a system that makes a very rare use of the channel will hardly distort another existing system in the long run because the probability of collisions is tiny or even negligible (probably in the order of or smaller than 5%/s). The converse conclusion does not necessarily hold, the probability of a packet collision in case of the active LDC system, depends strongly on the duty cycle of the primary user that may be large like the related probability of a distorted UWB signal.

Examples:

- UWB regulation in Europe and Japan.
- the UWB system by CEA-LETI can be regarded as an LDC system.

3.1.7 Dynamic Frequency Selection (DFS) and Transmission Power Control (TPC)

European regulation requires for unlicensed devices operating in the U-NII bands (between 5.15 and 5.825 GHz) to implement dynamic frequency selection (DFS) and transmission power control (TPC) [9]. This has concluded e.g. in the IEEE 802.11h standard as an update and extension of IEEE 802.11a in order to make it applicable to Europe.

3.1.7.1 DFS

Devices that are based on DFS need to monitor the channels intended to be used for 60 seconds prior to transmission in order to insure that it is unoccupied by a radar signal in that part of the spectrum. The regulation defines a threshold of -62 dBm for detecting the interference in devices with maximum power of 200 mW EIRP. Otherwise, this threshold becomes -64 dBm. If a channel occupation is detected during transmission the device has to cease the data transfer and must switch to another channel within 200 ms.

DFS allows reducing both the interference to other primary users and the interference from the primary users to the regarded DFS device.

Examples: IEEE 802.11a/h WLAN devices.

3.1.7.2 TPC

U-NII band devices with a maximum radiated power of 500 dBm EIRP or higher require a built-in TPC ability for some parts of the U-NII band. TPC implements a feedback loop from the receiver of the data indicating the received power level via an received signal strength indicator (RSSI) and adapt the transmit power accordingly, such that it can provide the demanded service quality. Consequently, the mean employed power level may be orders of magnitude below the maximum power level, and thus, the potential to distort other uses is significantly reduced.

Examples:

- IEEE 802.11h.
- Bluetooth (IEEE 802.15.1).
- WISMIT/Goniometer (nanoLoc)

3.1.8 Spread Spectrum

Spread spectrum is a possibility to mitigate several interference effects, such as multipath interference, multi-user interference, but also radio interference from alien (in the sense of unlike or heterogeneous) sources. Realizations of spread spectrum systems differ notably, and thus they cannot be unified easily. Usually, they provide to the user a spreading or, since it is achieved in the inner receiver, processing gain with respect to the SNR. Consequently employing spread spectrum in principle, communication below the noise floor is feasible. Spread spectrum techniques now do not make any difference between the noise and the interference. In consequence, the spreading gain also applies as factor for the reduction of the resulting power of the radio interference. In the following paragraphs, some spread spectrum techniques are introduced with a discussion of their impact on the interference.

3.1.8.1 Direct Sequence Spread Spectrum

In time domain, the data signals with an interval length of T are spread by multiplying them with a spreading sequence of an S-times higher rate that consists of S so called chips. Those can be regarded as sub-symbols of the resulting spread sequence that has an S times higher symbol rate (and bandwidth) than the original data symbol sequence. This is depicted in the Fig. 22. The dispreading in the receiver is achieved by decorrelation with the respective spreading sequence used to spread in the transmitter.

In frequency domain, the effect of spreading and dispreading becomes more obvious and understandable. Thus, the sketch in Fig. 21 displays how dispreading mitigates narrowband interference with a narrowband spectrum of an interferer depicted in green and a spread spectrum signal represented by the blue lines in a baseband representation.

The signal spectrum of bandwidth B as displayed on the top is spread with an increased rate spreading sequence in time domain of length S, called spreading gain. The related signal spectrum is then S-times as wide as the original one but maintains the same overall power.

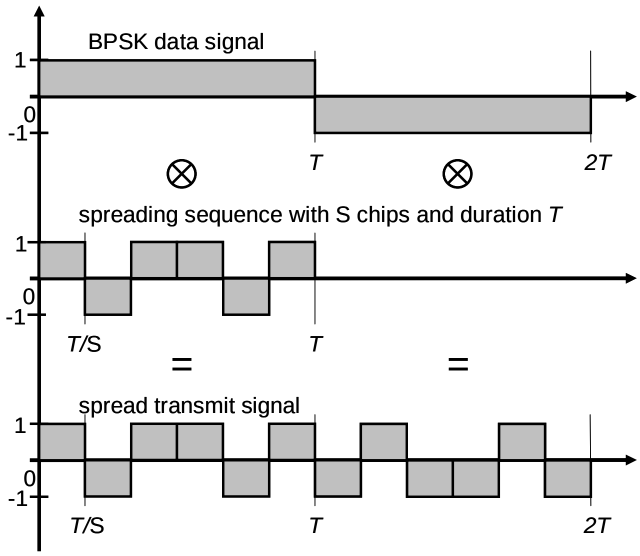

Fig. 21: Principle of spreading in DSSS.

After dispreading, the received signal with inherent rate reduction by the factor S, the interference signal is spread itself reducing its relative power level by the factor $1/S$ in the frequency range of interest i.e. the transmission band between $-B/2$ and $B/2$.

CDMA systems are a subtype of these spread spectrum signals that divides multiple users by their respective (pseudo-) orthogonal spreading codes. This kind of systems is (co-channel) interference limited, i.e. the noise effect is usually weaker than the distortion of the mutual distortion of the user signals due to imperfect orthogonality of the received spread signals. Spreading sequences can be pseudo-random signals or other orthogonal sequences designed to meet the requirements of the spreading-despreading process like Gold codes or Walsh sequences.

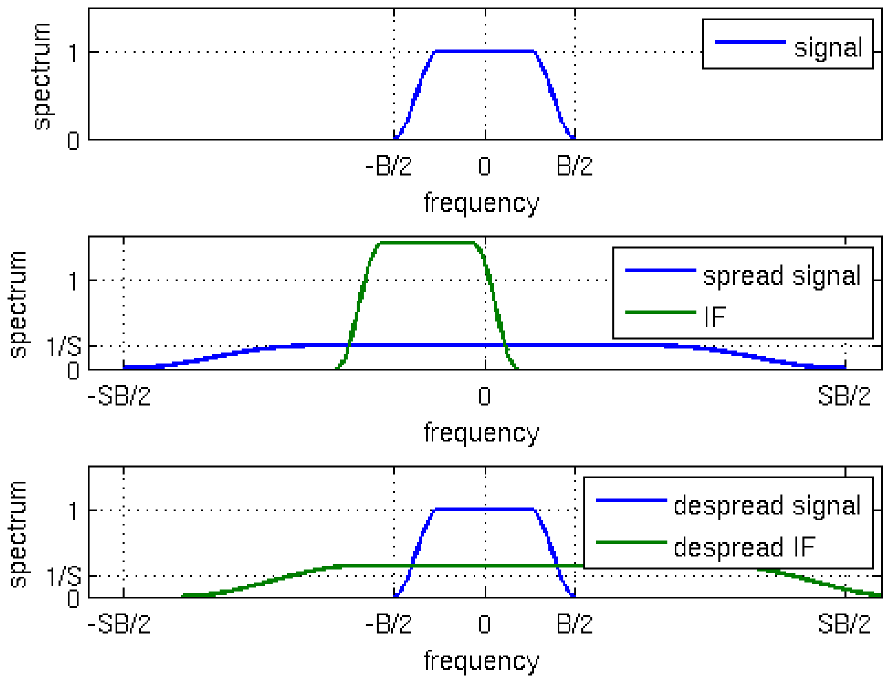

Fig. 22: The effect of a narrowband interferer on a spread spectrum system with the spreading factor S before and after dispreading, e.g. according to [6].

3.1.8.2 Chirp Spread Spectrum

Another subtype of spread spectrum techniques employs chirp signals, i.e. signals with linearly growing or decreasing frequency, to transmit data. An example for a chirp signalling strategy is an upchirp for a data bit One or a downchirp for a Zero. These chirp signals are very robust against frequency selective distortions like multipath or narrowband interference due to their concentration of instantaneous signal energy in time and frequency, while at the same time they exploit a high degree of time-frequency diversity. Chirp spread spectrum signals are often also called frequency modulated continuous wave (FMCW) describing the continuously varying carrier frequency of the chirp signal. In Fig. 23, an example for an FMCW burst transmission is depicted, where it is obvious that only a small part of the chirp is distorted by conventional narrowband signals.

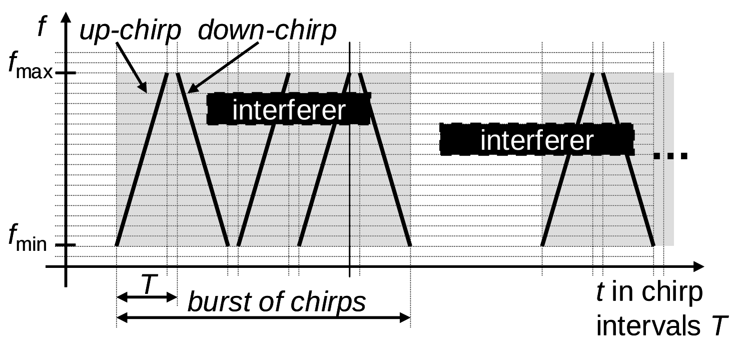

Fig. 23: Chirp spread spectrum (FMCW) with interferer signals.

3.1.8.3 Frequency Hopping Spread Spectrum (FHSS) and Adaptive Frequency Hopping (AFH)

Frequency hopping may be an effective method to reduce the number of collisions of coexisting narrowband systems mutually, but also to more wideband non-hopping systems. If the carrier frequency of a narrowband system changes very often between a large number of possible frequency bands like e.g. in Bluetooth with 79 frequency bands of 1 MHz bandwidth, then collisions with other static frequency systems are relatively unlikely like indicated by Fig. 24. Thus, the mean effective interference power is low (cf. Section 2.1.3.2 and Fig. 24), and assuming a sufficient amount of redundancy due to interleaving and coding, all data can probably be recovered despite the sporadic interference.

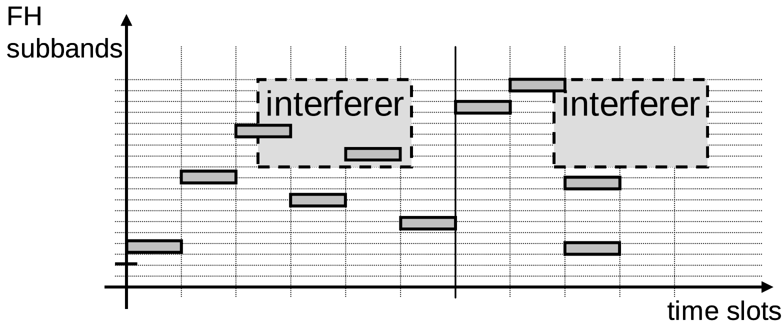

Fig. 24: Frequency Hopping in time domain with interferer.

A means to even improve this insensitivity to coexistence is adapting the employed hopping sequence in order to avoid spectral ranges instantaneously employed by other services. At least for Bluetooth, this scheme is called adaptive frequency hopping (AFH). The excision of the WLAN bands from the hopping is displayed schematically in Fig. 25. There, the other coexisting services can be detected either by referring to the above LBT mechanism before the transmissions or by an analysis of the bit and/or packet error rates from the packets received via the previously utilized frequency bands. If, there, a large bit error rate is detected, it is likely that harmful channel conditions can be found in the respective frequency band. At this point, it is uninteresting, however, why the channel conditions are that unpleasant: beneath interference also strong multipath fading may be the source for such distortions.

FHSS and AFH help both devices – the frequency hopping device and the static frequency device – to cope with their mutual interference if the total bandwidth of the set of frequency bands used for hopping is significantly larger than that of the wideband static frequency user. A counter example for the benefit results from observing the coexistence of Bluetooth and of WisMIT platform from Fraunhofer based on the nanoLoc. The latter employs a bandwidth of 80 MHz in the 2.4 GHz ISM band comprising all 79 bands for frequency hopping of Bluetooth. Then, the ranging with the nanoLoc platform is distorted irrespective the actual carrier like indicated in Fig. 25. However, a frequency selective signal collection of the chirp signal would be able to mitigate that effect by rejecting frequency bands currently distorted by Bluetooth transmissions. But, this method is not implemented due to the analogue pulse compression of the nanoLoc receiver.

Examples:

- The GSM standard describes frequency hopping within the 200 kHz bands of a GSM network, but this option is not implemented or used in practice.
- Bluetooth is the most known example for frequency hopping spread spectrum. From its revision 1.2 on, the standard specifies an AFH scheme.
- MB-OFDM uses time-frequency codes to switch between the three subbands contained in each band group. However, some of the time-frequency codes make the system reside within a single band.

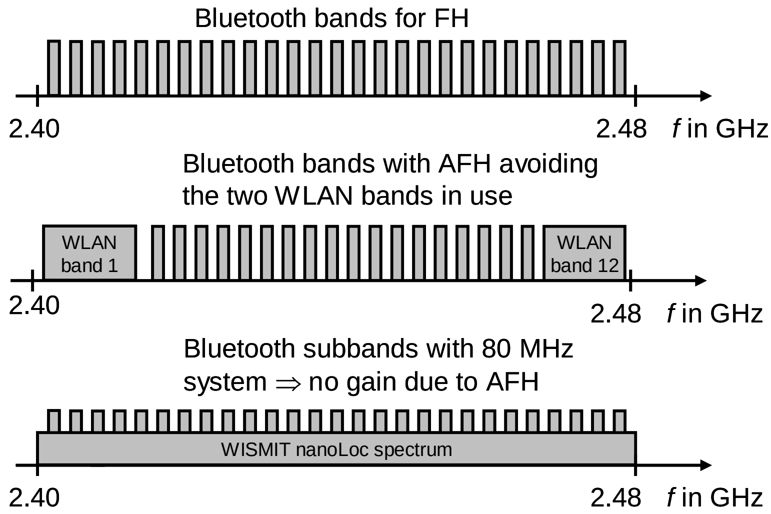

Fig. 25: Coexistence and frequency hopping.

3.2 Interference Suppression on the PHY Layer

The question how the user can react on the detection of interference in the received signal remains an active research topic, and the answer strongly depends on the regarded systems – SOI and interferer. Most works just consider communication systems, but many techniques can be instantly applied on location systems if it possible to intervene into the analogue or the digital baseband processing. The presented references should serve as a starting point, but do by far not cover the full range of approaches important for that field of research.

3.2.1 Active Interference Handling for Single Carrier Systems

With respect to the post-processing, the flexibility of single carrier systems is reduced significantly if compared to multi-carrier system. They allow for a frequency domain processing by nature. Any kind of Interference can be regarded as a frequency selective distortion, which limits the use of single carrier processing solely in time domain. Even the detection of that interference will be easier in frequency domain.

However, in principle it is desirable to have the interference of coexisting systems suppressed

a) before the *analog to digital converter* (ADC) in order to be able to reduce the amount of used bits. Considering the costs of the ADC and of the processing units, this becomes more and more interesting, the larger the sampling rate is.

b) It is interesting to have the interference suppressed before data conversion into frequency domain. Otherwise given a limited word width, a *discrete Fourier transform* (DFT) processor spreads the interference into all frequency bins.

3.2.1.1 Analogue Notch Filtering

Some antennas are already designed to notch out the interference, when this interference is very costly in terms of performance or processing effort or when the interference is that frequent that it can be assumed permanent [22]. This already relieves the *low noise amplifier* (LNA) in the receiver from the burden to amplify the interference reducing the required dynamic range. The same can be achieved with a permanent analog band rejection filter in the receiver chain [23].

[24] introduces an implementation of a tuneable notch filter that is driven by the digital part of the receiver, where the interference is detected and its parameter are estimated in a *least mean square* (LMS) fashion. The work is demonstrated as a hardware realisation.

However note an important drawback of *notch filters*: they increase the length of the channel impulse response making a larger temporal signal dispersion due to strong multipath even more severe. Additionally, notch filters alter the signal shape which has to be kept in mind when designing the signal detection algorithms. An advantage arises when implementing also adaptive transmit signal shaping because then the distortions of the coexisting system is also reduced.

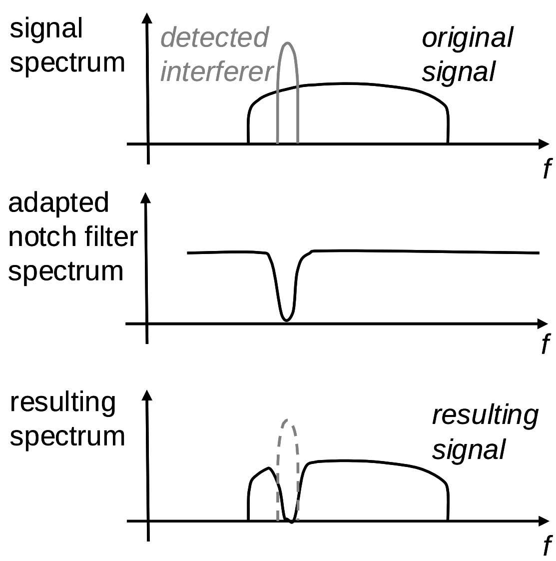

Fig. 26: Notch filter for interference suppression in the RX or the TX.

3.2.1.2 Digital Notch Filtering

In [25], the digital notch filter suppressing a detected interferer is approached for spread spectrum communication, i.e. in this context DSSS (CDMA). The author considers an LMS and a Fourier space realisation. But there are further filter design methods that may be more suitable for this application. For frequency hopping spread spectrum, [26] presents a signal pre-whitening filter approach that works in absence of knowledge of the desired signal. It adapts the employed FIR filter based on the least-squares algorithm.

Especially for UWB systems operating at high sampling rates, a digital notch filter is a tough job due to the involved processing. Thus, it is reasonable to think about *infinite impulse response* (IIR) filters [27] that are decisively less computationally complex. But, if adaptive filtering is considered a careful adaptation of the filter coefficients becomes even more important due to stability reasons.

3.2.1.3 Discarding strong samples

Impulse radios as one realisation of UWB systems (and the most common one for locating applications) may appear to narrowband systems as sporadic impulses given a low duty cycle. A well known method to reduce such noise is median filtering additionally extreme value theory [28] can be used to suppress or discard such error events.

3.2.2 Active Interference Handling in Frequency Domain/for OFDM

Coded OFDM has the great advantage that it can simply discard subcarriers suffering from narrowband interference. Given coding rate that is small enough and a sufficiently high SNR, then, the signal can still be decoded error free. OFDM techniques may be also employed on frequency hopping and FMCW systems given a frequency domain analysis of the respective signals. However, the implementation effort will rise decisively. Ideas for handling interference are discussed in the following.

3.2.2.1 Notch filtering with Interference Information

Shi et al. discuss in [32] the topic of OFDM in the presence of narrowband interference with the focus on ADC performance in conjunction with an analogue notch filter. Another discussed aspect is subcarrier nulling in the transmitter. The work assumes already partial interference knowledge when analysing the impact on the BER, but does neither take the interference detection nor the channel estimation into account—a perfect, i.e. error free, synchronisation is assumed.

3.2.2.2 Notch Filtering before DFT

In [31], adaptive filtering in time domain before the DFT is applied. A normalized least-mean-square (NLMS) notch filter is trained in the mute periods before and after the signal frame at a high SNR, and then suppresses the interference before the DFT. This approach can be extended by adding erasures at the position of notched out carriers.

3.2.2.3 Estimating, and eliminating interference signals after the DFT

In [30], narrowband interference is combated by estimating it in frequency domain from distinct measurement tones, and then, by cancelling the extrapolated interference on the other subcarriers comprising user data and training data. These measurement tones are usually null tones. In the context of digital subscriber line (DSL) systems, they can be placed arbitrarily by the transmitter after a measurement phase. The key contribution of [30] is the respective estimation and extrapolation matrices and their performance evaluation.

3.2.2.4 Interference detection and elimination through Erasures

In the text [10], an interference detection based on the burst preamble is introduces learning the position of the interferers and suppressing it early in the receiver chain before it may distorts e.g. the channel estimation.

3.3 DISCUSSION OF CHAPTER 3

In this chapter, the interference mitigating techniques have been described that may help to resolve a coexistence issue, once it is detected and when it cannot be solved by reducing transmit powers or just increasing the spatial separation between the victim device and the interferer. The latter methods, situated in the PHY layer are however part of the system design, i.e. have to enter consideration at rather early stage because many transceivers have parts that are not easily reconfigured[21]. The MAC layer is usually implemented in software and therefore preferable for improving the coexistence characteristics of systems late in the design cycle.

However, most of the introduced techniques have a deep impact on the system design. Hence, they may have benefits with respect to the interference robustness, but may cause other unwanted effects like a data rate reduction, an increase or a jitter of the delays or too hard hardware constraints. Thus a careful preliminary evaluation and simulation must be kicked off by the analysis results.

[21] This concerns mainly (partial) hardware implementations.

4 SPECTRUM USAGE AT FARO AIRPORT

The spectrum usage at Faro Airport will be measured when deploying the systems for the final demonstration at the site. The communication networks for inside the buildings is a WiFi according to the IEEE 802.11g standard with the implementation of the IEEE 802.11b standard as compatibility and fallback solution in the 2.4 GHz band. For the outside, WLAN communication employs the 5 GHz band, i.e. following the specification IEEE 802.11a (and its coexistence extension IEEE 802.11h). The actual bands in use are not publically available due to security reasons and must, thus, not be published in this public deliverable. The same is also in principle true for the actual spectrum usage and the airport band plan specifications.

5 Measuring the Physical Coexistence of Localisation Systems

In this section, the measurements of the signal spectra are executed. They are chosen in order to indicate the coexistence of localization and communication systems. First the measurement setup is described and discussed. And afterwards a detailed discussion of the measurements follows and the results are set into relation with the previously defined theoretical analysis.

5.1 Measurement Procedure

The measurements are performed with a spectrum analyzer i.e. the spectrum is analysed for the existence of resource conflicts:

- The direct output of the radio systems should be measured with a broadband antenna and a spectrum analyzer. Therefore, a representative channel use must be assured of the radio systems representing tag and infrastructure nodes. This will mainly serve as an affirmation of the output spectrum and of the computations of the channel loss vs. the distance.
- Additionally, the spectra in the existence of an interferer are recorded in order to be able to compare the signal integrity in these cases. Therefore, the distance of the interferer and of the SOI is always approximately the same in order to enable a fair judgement.
- The duty cycles of the radio systems are analysed shortly based on the average measured signal power and the maximum power levels.
- The envisioned configuration of the test scenario is introduced in the following paragraphs and depicted below in Fig. 27 providing an insight into the test equipment and in the performed test procedure.

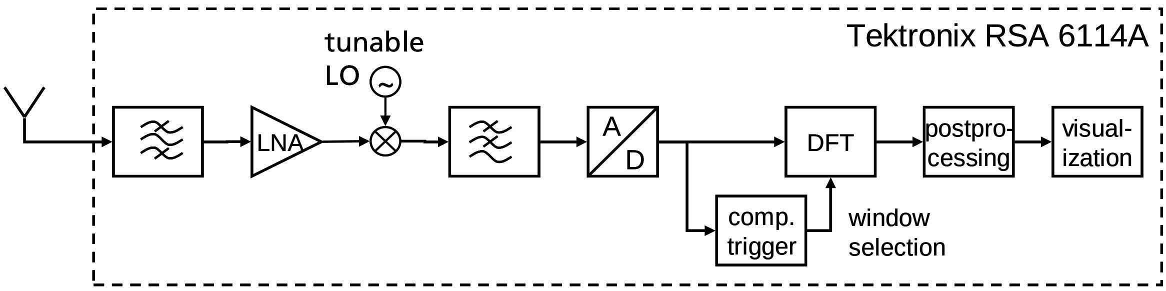

Fig. 27: Measurement setup.

5.2 MEASUREMENT EQUIPMENT

A schematic of the test setup is displayed in Fig. 27. The components therein are described in the following in more detail.

5.2.1.1 The Antenna

The measurements have been performed with the help of a (directed) horn antenna with flat broadband spectrum over the frequency range from 2 to 8 GHz developed at Fraunhofer IIS. In that range, the antenna gain rises slowly from 4 to 7 dB with growing frequencies. The variation in the antenna gain is caused by the increased directivity, i.e. the narrower main lobe at higher frequencies. This is due to the relatively larger antenna area related to the wave length of the electromagnetic waves.

5.2.1.2 The Spectrum Analyzer

In order to analyse the signals, the real-time spectrum analyzer (RSA) *RSA6114A* from Tektronix [33] has been used as it allows for a large selection of signal triggers. The principle of the RSA [34] distinguishes decisively from that of conventional spectrum analyzers, where the device sweeps through the spectrum of the measured signal employing a mixer with variable frequency and a narrowband lowpass filter. The RSA also employs mixer for converting the frequency range of interest to the complex baseband domain, i.e. the analog signal exists as I/Q-components[22]. However in case of the RSA the frequency is fixed for one measurement period. Afterwards, the signal is filtered by a lowpass of 110 MHz bandwidth and sampled at a maximum rate of 110 MSamples/s. Afterwards, the device performs a DFT on the samples allowing for a spectral analysis. That way, the RSA is capable of recording 60,000 spectra per second. The total frequency range covered by the RSA reaches from 9 kHz to 14 GHz. Another speciality of this spectrum analyzer is the option not only to trigger on the power of the signal, but also based on a dedicated spectral mask.

Important options in the visualisation are the following options:

- The *maximum hold* spectrum records the maximum signal strength that has been detected at each frequency.
- The *average* shows the average signal strength of the last 1000 (this value ischosen by the user) spectra.
- The instantaneous spectrum resulting from the DFT of the incoming I/Q-samples.
- DPX (Digital Phosphor Technology) [34] emulates a luminescence effect based on the calculated instantaneous signal spectra. Therein, recently and frequently measured signal strengths are indicated by a more intense colour.

5.2.1.3 Other equipment

As other equipment a Foundry Networks AP200 WLAN access point is used to support the WLAN traffic of a HP NC 8230 notebook employing the internal WLAN functionality. The devices have been connected via the channel 1. Additionally, a 5 GHz WLAN connection via a CISCO access point via channel 64 at 5.320 GHz has been recorded and a mobile phone Nokia 6233 has been used to generate Bluetooth traffic.

[22] The "I" therein indicates the in-phase component and "Q" the quadrature-phase component. In signal processing theory both are usually presented as complex numbers with the *I-component* being represented by the real valued part, and the *Q-component* by the imaginary part of the complex value.

5.3 SIGNAL MEASUREMENTS

5.3.1 WISMIT/GONIOMETER SYSTEM

The spectrum (or more likely the spectra) of the signal transmitted by the WISMIT tag can be recognized excellently on the screen shot from the spectrum analyzer. The maximum hold function effectively displays the envelope of the chip spectrum that has effectively less than 60 MHz bandwidth if the 3 dB-bandwidth definition is employed. Also the average spectrum shows the realistic part of the spectrum very well.

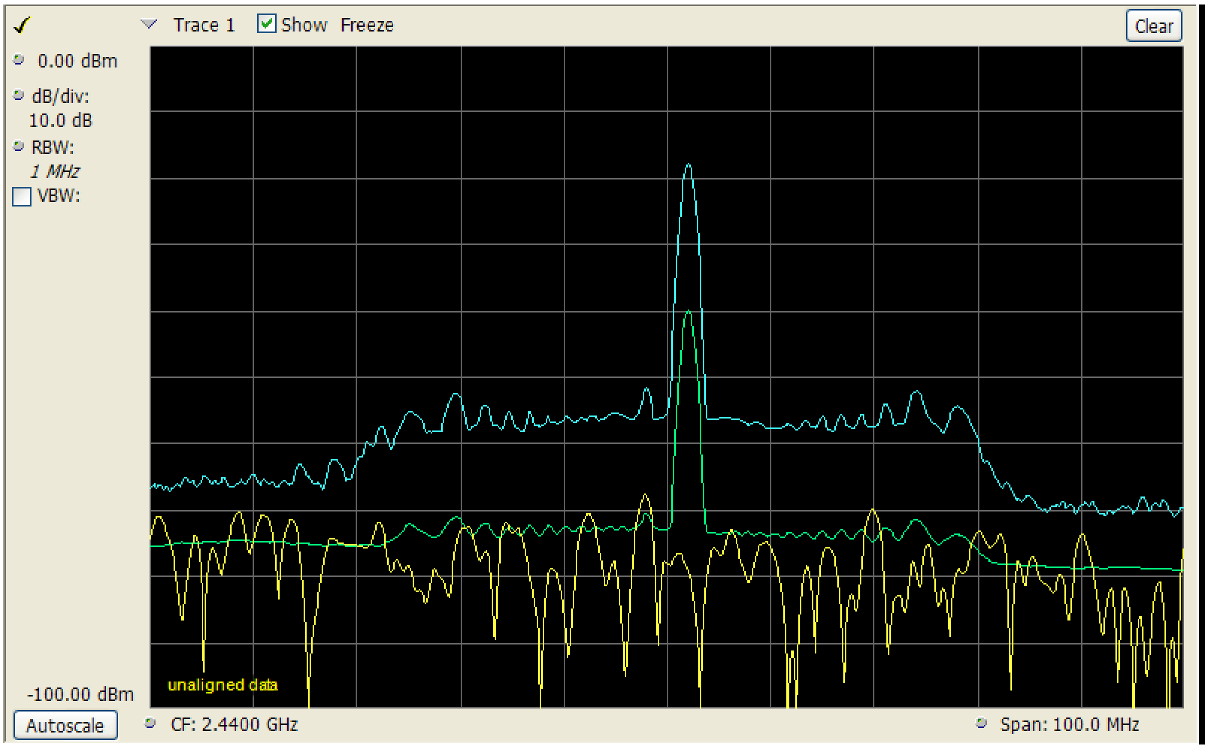

Fig. 28: Spectrum of the WISMIT chirp for RTT measurements together with the carrier signal for DoA measurements at 2.442 GHz (cyan: maximum hold, green: average, and yellow: instantaneous signal spectrum).

Note that all measurements in this subsection are based on a span of 100 MHz, i.e. measurements of 100 MHz bandwidth.

From the comparison between average and maximum the approximate duty cycle can be concluded. Since there are approximately 15 dB between maximum and average power levels, the duty cycle of the tag can be estimated to

$$D_C = \frac{T_{active}}{T_{total}} = \frac{T_{active} E_s}{T_{total} E_s} = \frac{E_s / T_{total}}{E_s / T_{active}} = \frac{P_{average}}{P_{peak}} \approx 10^{-15} \approx 3\,\% \qquad (9)$$

for one tag communicating with 4 active nodes. Therein E_s is the signal energy of in one time interval T_{total} from which T_{active} is the time, where signals are transmitted. The measurements do not comprise the radiated power of the nodes because they have been much farther from the measuring antenna, and additionally because the nodes have not been in the direction of this directed antenna.

For the DoA burst the difference between average and peak is even larger (>23 dB) indicating a separate duty cycle of D_C < 0.5 %, which becomes evident if considering that only one DoA burst for the employed nodes is transmitted, while 16 RTT signal transmissions are needed.[23]

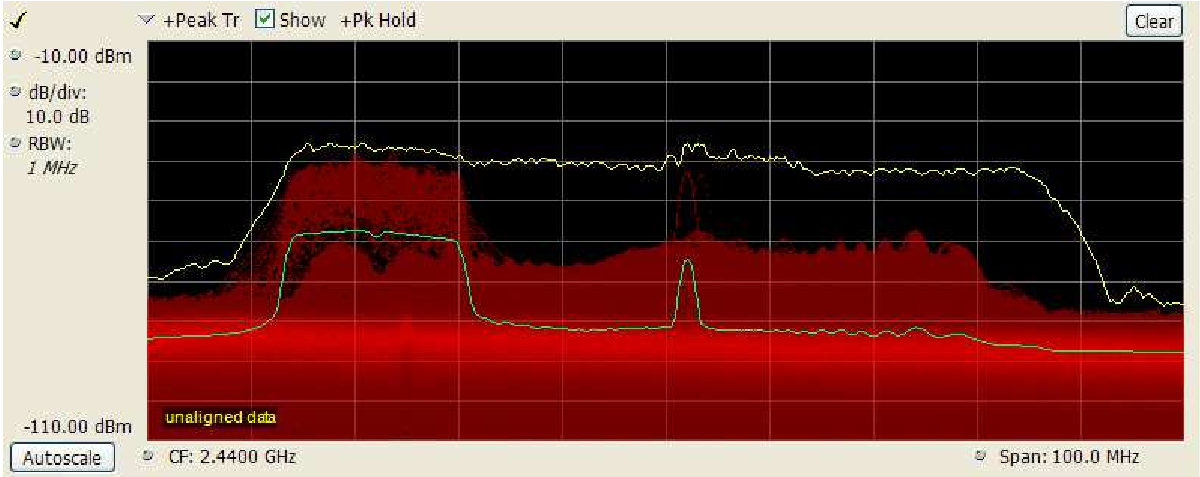

Fig. 29: DPX spectrum of the WISMIT signals (chirp and carrier) at center frequency of 2.442 GHz together with WiFi signal IEEE 802.11g signal in channel 1 around 2.412 GHz. (yellow: maximum hold, green: average).

In Fig. 29 and Fig. 30, the spectra of the WISMIT in the presence of an interferer are presented. In the case of Fig. 29, this is an active WiFi device performing a large data upload and, for the creation of Fig. 30, a Bluetooth device[24] has been searching for possible devices to connect to. In order to stress the dynamics in the distortion, the DPX mode of the spectrum analyzer has been utilized.

The results for the WiFi upload (Fig. 29) show conspicuously that the totally radiated power of the WISMIT is increased. However, the level of the power spectral density is approximately as high as that of the interference. The average power of the DoA burst is decreased, indicating that the initiation of the DoA burst has failed several times.

If investigating the Bluetooth interference in Fig. 30, almost all Bluetooth subcarriers manifest themselves in the diagram. DoA bursts cannot be detected any more at all. This clarifies the connectivity problems the WISMIT device and the anchor nodes encounter, when trying to establish a communication in the presence of a strong Bluetooth transmission.

A manual test of the locating performance of the WISMIT/Goniometer system in the presence of a WLAN download with IEEE 802.11g on channel 1 in the same room also supported the above observations; almost all packets were lost such that no position information could be obtained despite of the spreading gain 19 dB.

[23] Dual way ranging based on RTT requires 4 transmissions per distance estimate.

[24] The Bluetooth device has been a mobile phone (Nokia 6233).

Fig. 30: DPX spectrum of the WISMIT signals at center frequency of 2.442 GHz together with Bluetooth signals in several bands (max. hold: yellow, average: green).

5.3.1.1 LPR

For the LPR system, Fig. 31 depicts the envelope of the signal spectrum with a display spanning 110 MHz. Easily the employed bandwidth of 100 MHz can be identified, i.e. in the test lab only five transponders have been deployed. If compared to the WISMIT/Goniometer system and to the noise floor, the decisively higher signal level is remarkable.

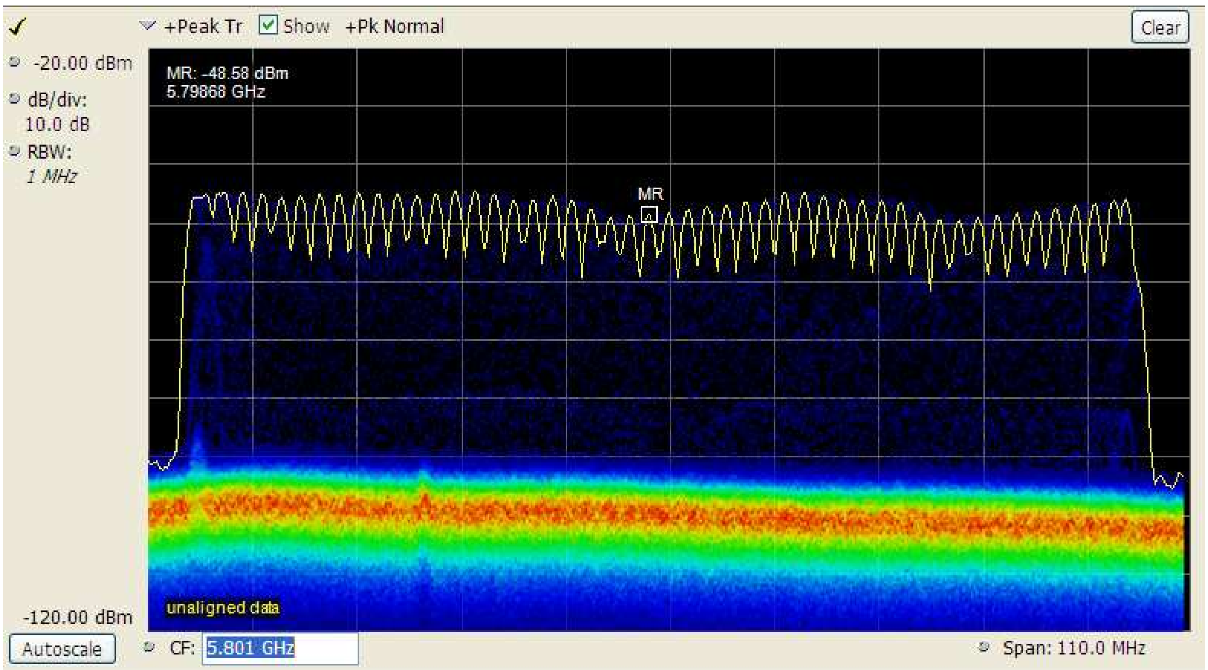

Fig. 31: DPX spectrum of the LPR signal at center frequency of 5.8 GHz (max. hold: yellow).

The Signalling channel with its two used FSK signals can be verified excellently in Fig. 32, where this channel has been measured at a span of 5 MHz. The bandwidth of the channel is approximately 200 kHz and the duty cycle can be estimated according to (6) as 1.5 % from a peak to average ratio of ca. 18 dB. The estimated duty cycle D_C is much lower than that given in the specification in [1].

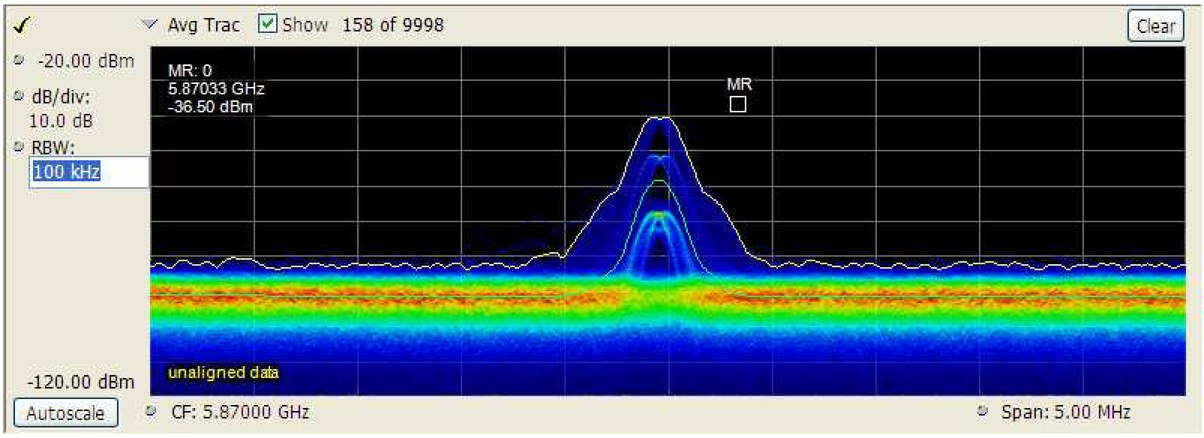

Fig. 32: The FSK signaling channel of the LPR system (max. hold: yellow and average: cyan).

WiFi traffic colliding with the spectrum of the LPR system could not be provided because the WLAN equipment has not been capable of the channels beyond channel 64 at 5.32 GHz (see Fig. 33). The channels 151 to 171 that may lead to signal collisions are not used in Europe. Thus, the equipment is not imported and sold there. However, that also indicates that WLAN traffic as a source of interference on the LPR system is irrelevant in Europe. Remembering, the huge spreading gain of 300 Thousand also if deployed in the US, the impact of the WiFi interference in the 5.8 GHz band may well be neglected.

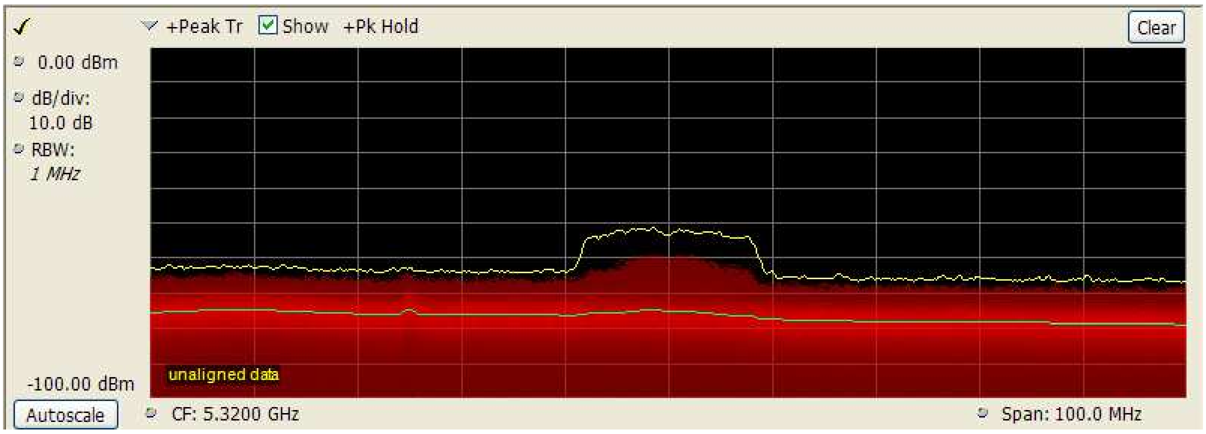

Fig. 33: IEEE 801.11a in channel 64 (max. hold: yellow, average: cyan).

5.3.1.2 UWB-LETI

For the UWB system by LETI no measurements of the spectrum could be performed employing the described hardware setup, mainly due to two setbacks: firstly due to a missing trigger for the short UWB pulses (the pulses are too weak to trigger the spectrum analyzer themselves) and secondly due to insufficient bandwidth resolution of the RSA. Furthermore, the signal level and the overall power of the UWB system is that weak that it could not be visualised by the RSA in contrast to the existing noise floor, neither in the average nor in the peak power display.

Thus, we present here some measurement by Leti in Fig. 34. It is realised from time-domain sampling of the output signal and computing the spectrum with Matlab. Additionally masks by FCC, IEEE, and ETSI have been plotted for comparison reasons. The expected spectrum usage in the range between 4.2 GHz and 4.8 GHz is well visible.

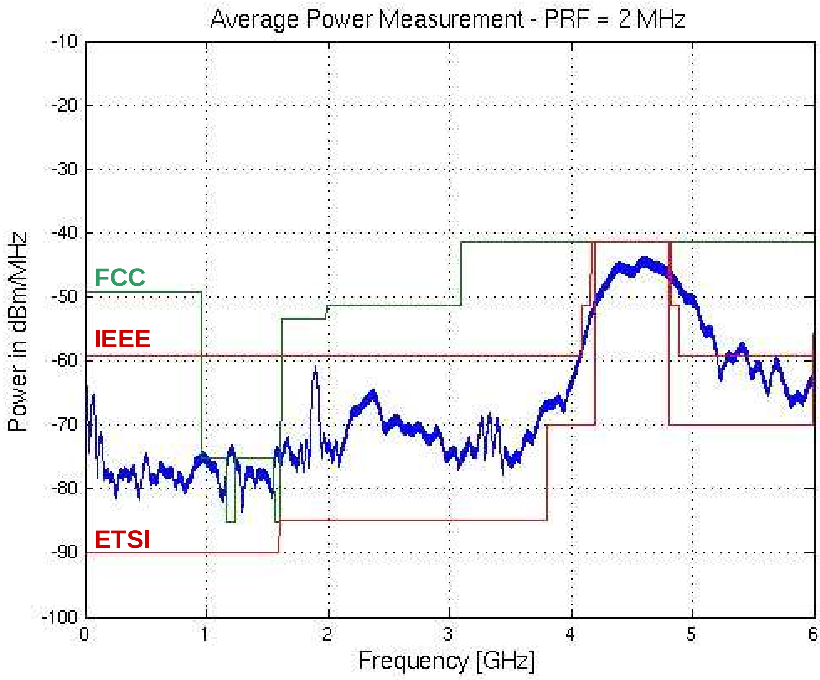

Fig. 34: Spectrum of signal bursts of the UWB system by Leti.

5.3.1.3 WLAN/WiFi and Bluetooth

In Fig. 35 showing coexisting Bluetooth and WLAN traffic in the 2.4 GHz ISM band, a speciality of WLAN is visible: since many IEEE 802.11g devices (it is the same device as in Fig. 29) are downward compatible, devices can switch to the IEEE 802.11b mode if the distortions are to strong. Fig. 29 obviously displays an OFDM spectrum. It is nearly rectangular, which is typical for OFDM, and even the unmodulated DC carrier can be concluded from the ditch in the center of the signal spectrum. In contrast Fig. 35, shows an IEEE 802.11 b spectrum that has the shape of a cosine half wave. The latter b-standard is an spread spectrum standard – it uses direct sequence spread spectrum – and therefore the protection against interference is much higher due to the processing gain.

Nevertheless, according to the above argumentation it can be concluded that Bluetooth interference is much more severe for the WLAN traffic than the interference from the chirp signals of the nanoLoc chip in the WISMIT device.

In order to complete the discussion, the used Bluetooth device seems not to make use of the AFH feature. However, this may only be the case for the short search for devices that initiated the traffic.

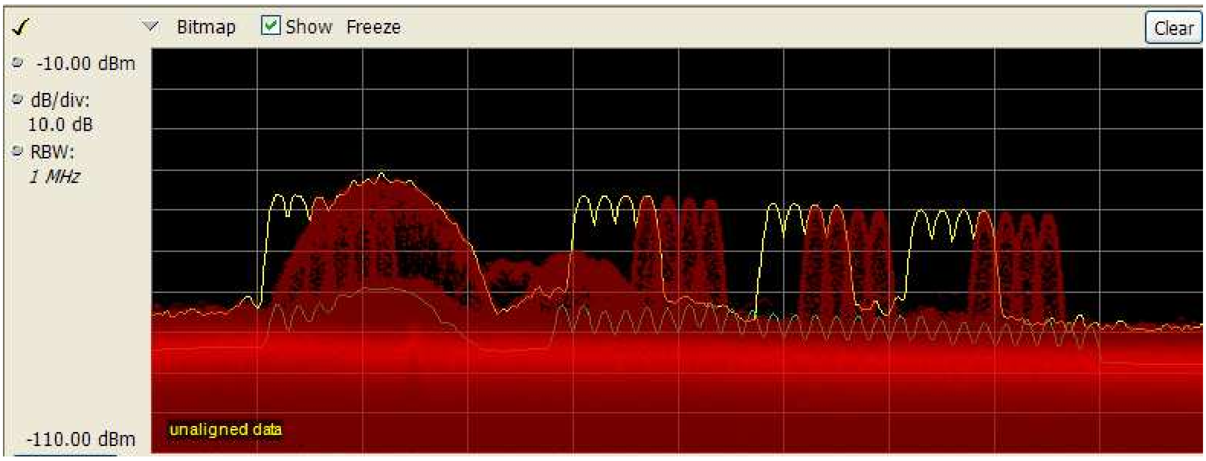

Fig. 35: Spectral coexistence of Bluetooth and WiFi in the 2.4 GHz range (max. hold: yellow, average: cyan).

5.4 DISCUSSION

As extracted from the theoretical analysis, the WISMIT/Goniometer system has been identified as the main victim (or the main source if changing the point of view) for coexistence issues. However, the measurements indicated that as source for interference the chirp signal of the WISMIT is negligible. A coordination of the WLAN with the WISMIT/Goniometer system seems to be a reasonable and required approach for the application of the system in indoor environments with WiFi infrastructure. The other systems seem to offer less coexistence problems with existing hardware, even though this is only true for the UWB system by LETI due to the lacking pervasion of other UWB devices in the market.

6 SUMMARY AND CONCLUSION

In this text and in the underlying research work a methodology for the analysis of coexistence of radio systems is been developed. According to this methodology, a software tool for the analysis has been designed, and the analysis has been exemplarily performed for the set of location systems as used for the LocON project. Following, several interference mitigation techniques are introduced that may help to reduce the vulnerability to interference and to improve the coexistence with other radio users. Afterwards the theoretic results are backed up by measurements of the spectra.

6.1 COEXISTENCE TOOL

After some further development and refinement the implemented software tool may offer the potential to be used in other related contexts in system evaluation, system design, or system deployment. The existing tool may serve as a basis and a feasibility study for such a redeveloped and then commercialized tool.

In the following the analyses of the real-time locating systems (RTLS) are shortly resumed and if needed short advices are introduced.

6.2 WISMIT/GONIOMETER (FRAUNHOFER IIS)

The WISMIT/Goniometer system shows severe coexistence issues with WLAN and Bluetooth. If the PHY could be altered it is advisable to increase the spreading gain e.g. by increasing the chirp duration (effectively the LPR system is similar with a tremendously higher gain). Regarding to the MAC layer, a coordination with WLAN traffic will make the system much more robust with respect to that distortion.

6.3 LPR (SYMEO)

The Symeo device seems to be rather invulnerable against interference. Additionally, potential interferers are scarce in the employed 5.8 GHz ISM band.

6.4 UWB RTLS (CEA-LETI)

The low duty cycle and the low range of UWB are the most helpful features for UWB RTLS as a whole and the device by CEA-Leti especially if considering coexisting systems. With a larger market penetration of other UWB devices more issues may arise. However, the spreading gain is variable and may be increase in strong interference scenarios.

6.5 WLAN RTLS (CIT)

WLAN RTLS are based on existing infrastructure and make use of their implemented coexistence techniques. Thus, the equipment should always be up to date in order to provide the best protection against and for other users of the ISM and U-NII bands.

6.6 GPS

GPS does not suffer from interference of the introduce devices and standards. The greatest danger for navigation with GPS are intentional jammers and the US military that still has the possibility reduce the precision of GPS systems. Additional dangers may still come from other users in the L- band. However, the implementation of the Galileo system has shown that the US government is always willing to create pressure on institutions that may provide danger for the integrity of GPS signals.

7 REFERENCES:

[1] A. Casaca, M. Weyn, M. Faßbinder, M. Klepal, N. Daniele, P. Gulden, T. Silva, and T. Denis. "Deliverable 1.2: LocON Platform Requirements", available on www.locon.org, Tech. Rep., Dec. 2008.

[2] L. Angrisani, M. Bertocco, D. Fortin, and A. Sona. „Experimental Study of Coexistence Issues between IEEE 802.11b and IEEE802.15.4 Wireless Networs" IEEE Transactions on Instrumentation and Measurement, No. 8, Vol. 57, Aug. 2008.

[3] IEEE SCC41 P1900.2 Group. "IEEE P1900.2™/D2.0, Draft Recommended Practice for Interference and Coexistence Analysis", IEEE P1900.2, Draft Standard Proposal, Jan. 2006.

[4] A. Molisch, K. Balakrishnan, Chia-Cin Chong, S. Emami, A. Fort, J. Karedal, J. Kunisch, H. Schantz, E. Schuster, and K. Siwiak. "IEEE 802.15.4a channel modell – final report", IEEE 802.15 WPAN Low Rate Alternative PHY Task Group 4a (TG4a), Tech. Rep., Nov. 2004.

[5] Electronic Communications Committee. "ECC Decision of 1 December 2006 on the harmonized conditions for devices using Ultra-Wideband (UWB) technology with low duty cycle (LDC) in the frequency band 3.4-4.8 GHz", (ECC/DEC/(06)12), Dec. 2006.

[6] The Commission of European Communities. "Commision Decision on allowing the use of the radio spectrum for equipment using ultra-wideband technology in a harmonized manner in the Community, L 55/ 33", Official Journal of the European Union, Feb. 2007.

[7] Electronic Communications Committee. "ECC Report 120 (June 2008) on Technical requirements for UWB DAA (Detect And Avoid) devices to ensure the protection of Radiolocation in the bands 3.1 -- 3.4 GHz and 8.5 -- 9 GHz and BWA terminals in the band 3.4 -- 4.2 GHz", Kristiansand, June 2008.

[8] "nanoLOC TRX, High Performance RF Transceiver with, Location Awareness and Robust Wireless Communication", data sheet, www.nanotron.de, Nov. 2009.

[9] R. Morrow. "Wireless Network Coexistence", McGraw-Hill, New York, USA, 2004.

[10] N. Hadaschik. "Analysis ofWideband OFDM in the Presence of Narrowband Interference", Dissertation RWTH Aachen, Shaker Verlag, Aachen, Germany, 2009.

[11] Bluetooth SIG. "Specification of the Bluetooth Systems, Master Table of Contents & Compliance Requirements, v2.1 + EDR", Dec. 2009.

[12] IEEE-SA Standards Board. "Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications, High-speed Physical Layer in the 5 GHz Band IEEE, IEEE 802.11a", IEEE Std 802.11a-1999(R2003), June 2003.

[13] IEEE-SA Standards Board. "Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: Higher-Speed Physical Layer Extension in the 2.4 GHz Band IEEE, IEEE 802.11b", IEEE Std 802.11b-1999 (R2003), June 2003.

[14] IEEE-SA Standards Board. "Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications, Amendment 4: Further Higher Data Rate Extension in the 2.4 GHz Band, IEEE 802.11g", IEEE Std 802.11g-2003, June 2003.

[15] IEEE-SA Standards Board. "Part 11: Wireless LAN Medium Access Control (MAC) & Physical Layer specifications Enhancements for Higher Throughput, IEEE 802.11n", IEEE Std 802.11n-2009, Sep. 2009.

[16] IEEE-SA Standards Board. "Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs)", IEEE Std 802.15.4-2003, Oct. 2003.

[17] IEEE-SA Standards Board. "Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs), Amendment 1: Add Alternate PHYs, IEEE 802.15.4a", IEEE Std 802.15.4a™-2007, August 2007.

[18] WiMedia Alliance. "WiMedia PHY layer technical specification V1.1", Published on www.wimedia.org, June 2005.

[19] www.ekahau.com.

[20] www.ubisense.net.

[21] N. Abramson. "The ALOHA system – another alternative for computer communications." in AFIPS Proc. of the Fall Joint Computer Conf., vol. 37, pp. 281-285, Montvale, USA, 1970.

[22] H. Schantz, G. Wolenec, and E. Myszka. "Frequency notched UWB antennas", Proc. of IEEE Conf. on Ultra wideband Systems and Techniques (UWBST 2003), Reston, USA, Nov. 2003.

[23] G. Cusmai, M. Brandolini, P. Rossi, and F. Svelto. "A 0.18-μm CMOS Selective Receiver Front-End for UWB Applications," IEEE J. Solid-State Circuits, 41(8): 1764–1771, Aug. 2006.

[24] T. Fisher, B. Kelleci, Kai Shi, A. Karsilayan, and E. Serpedin. "An Analog Approach to Suppressing In-Band Narrow-Band Interference in UWB Receivers", IEEE Transactions on Circuit and Systems I: Regular Papers, 54(5):941-950, May 2007.

[25] L. Milstein. "Interference rejection techniques in spread spectrum communications," Proceedings of the IEEE, 76(6): 25–33, Jun. 1988.

[26] R. Iltis, J. Ritchey, and L. Milstein. "Interference rejection in FFH systems using least squares estimation techniques," IEEE Trans. Commun., 38(12): 2174–2183, Dec. 1990.

[27] Jun Won Choi, and Nam Ik Cho. "Suppression of narrow-band interference in DS-Spread spectrum systems using adaptive IIR Notch filter", ACM Signal Processing, 82(2), Dec. 2002.

[28] S. Kalyani, V. Raj, and K. Giridhar. "Narrowband interference mitigation in turbo-coded OFDM systems," Proc. of IEEE Intl. Conf. on Communications (ICC 2007), June 2007.

[29] T. Li, W. H. Mow, V. K. N. Lau, M. Siu, R. S. Cheng, and R. D. Murch. "Robust joint interference detection and decoding for OFDM-based cognitive radio systems with unknown interference." IEEE Journal on Selected Areas in Communications, 25(3):566–575, Apr. 2007.

[30] F. Sjöberg, R. Nilsson, P. Börjesson, P. Ödling, B. Wiese, and J. Bingham. "Digital RFI Suppression in DMT-Based VDSL Systems." IEEE Transactions on Circuit and Systems I: Fundamental Theory and Applications, 51(11):2300–2312, Nov. 2004.

[31] A. Coulson. "Narrowband interference in pilot-assisted OFDM systems", Transactions on Wireless Communications, (5)9:2277-2287, Nov. 2004.

[32] K. Shi, Y. Zhou, B. Kelleci, T. Fischer, E. Serpedin, and A. Karsilayan. "Impacts of narrowband interference on OFDM-UWB receivers: analysis and mitigation." IEEE Transactions on Antennas and Propagation, 55(3):1118–1128, Mar. 2007.

[33] Tektronix, "Spectrum Analyzers, RSA6000 Series Data Sheet", data sheet, www.tektronix.com, Sep. 2009.

[34] Tektronix, "Fundamentals of Real-Time Spectrum Analysis", primer, www.tektronix.com/rsa, Sep. 2009.

8 ANNEX

8.1 ACRONYM LIST

3G	third generation of cellular wireless standard
3GPP	3G partnership project
4G	fourth generation of cellular wireless standard
ADC	automatic data capture or analog-to-digital converter
AFH	adaptive frequency hopping
ARQ	automated repeat request
AWGN	additive white Gaussian noise
AWMA	alternating wireless media access
BER	bit error rate
BFSK	binary frequency shift keying
BPSK	binary phase shift keying
CDMA	code division multiple access
CDMA-2000/450	3G mobile phone standard mainly in the US operating in the 2000 MHz respectivley the 450 MHz band
CEPT	European Conference of Postal and Telecommunications Administrations
CSMA	carrier sense multpile access
CSMA/CD	CSMA with collision detection
CSMA/CA	CSMA with collision avoidance
CSS	chirp spread spectrum
DAA	detect and avoid, technique foreseen for UWB. A secondary transmission system scans the channel and avoids frequency bands in use.
dBm	power level in decibel compared to 1 mW
DFS	dynamic frequency selection
DFT	discrete Fourier transform
DoA	direction of arrival (sometimes also AoA, i.e. angle of arrival)
DSL	digital subscriber line
DSP	digital signal processor (sometimes also: digital signal processing)
DSSS	direct sequence spread spectrum
ECC	Electronic Communications Committee (part of CEPT)
EIRP	equivalent isotropically radiated power
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Committee (of the US)
FDD	frequency division duplex
FDMA	frequency division multiple access
FER	frame error rate

FH	frequency hopping
FIR	finite impulse response (filter)
FMCW	frequency modulated continuous-wave
FSK	frequency shift keying
GFSK	Gaussian filtered frequency shift keying
GMSK	Gaussian minimum shift keying
GNSS	global navigation satellite system
GSM	Global System for Mobile Communications (mobile phone standard of the second generation, formerly: Groupe Spécial Mobile)
GPS	global positioning system (one implementation of GNSS)
IEEE	Institute of Electrical and Electronics Engineers
IEEE 802.11	standard group concerned with WLAN systems
IEEE 802.15	standard group concerned with WPAN systems
IIR	infinite impulse response (filter with recursive definition)
ISM	industry, scientific, medical (frequency band)
LDC	low duty cycle, technique foreseen for UWB. The secondary system has a low activity rate over time. Therefore, the distortion of a primary user is improbable.
LNA	low noise amplifier
LOS	line-of-sight
MAC	media access control (network layer)
MB-OFDM	multiband-OFDM (UWB standard)
NLOS	non line of sight
OFDM	orthogonal frequency division multiplex(-ing)
OFDMA	orthogonal frequency division multiple access
PHY	physical (network layer)
PSK	phase shift keying
RF	radio frequency
RFID	radio frequency identification
RSS(I)	received signal strength (indicator)
RTLS	real-time locating system
RTT	round trip time
RX	receiver
SME	small or medium sized enterprise
SINR (SNIR)	signal-to-noise-and-interference ratio
SNR	signal-to-noise ratio
SOI	system of interest
TDMA	time division multiple access
TDOA	time difference of arrival
TOA	time (delay) of arrival

TPC	transmit power control
TX	transmitter
UMTS	Universal Mobile Telecommunications System (mobile phone standard of the third generation)
UUT	unit under test
UWB	ultra-wideband
UWB-IR	ultra-wideband impulse radio
WiFi	equiv. WLAN
WiMAX	Worldwide Interoperability for Microwave Access (WMAN standard)
WLAN	wireless local area network
WLAN	wireless metropolitan area network
WP	work package
WPAN	wireless personal area network
WSN	wireless sensor network
ZigBee	WPAN standard for WSN (IEEE 802.15.4)

8.2 LOCATION SYSTEM DATA BASE

The following part represents the entries in the user data base for the location systems as prepared for the prepared coexistence evaluation tool. It is an abstract from the data base.

```
System (1),
name : WiSmIt_Goniometer,
manufacturer : IIS,
info : The RTLS working in the 2.4 GHz
range determines the posistion based
on two algorithms DOA and RTT the
wideband (80 MHz) RTT measurements are
based on the nanoLoc chipset by
Nanotron the DOA calculation needs a
narrowband (2 MHz) signal
modulation : chirp, unmodulated,
channel access : tdma, csma,
spectrum bandwidth [MHz] : 80.0000,
2.0000,
carrier frequency [GHz] : 2.4390,
2.4400, 2.4410, 2.4420, 2.4430,
2.4440,
localisation method : rtt, doa,
duty cycle in percent : 30.00,
radiated power [dBm] : 0.00,
range [m] : 100.0,
communication : bidirectional,
interface : ethernet,usb,
domain : indoor, outdoor,
```

```
System (2),
name : LPR,
manufacturer : Symeo,
info : the LPR system working at 5 GHz
uses RTT and TDOA techniques to
determine the position nodes
communicate wirelessly with the node
that determines its own position
(coupling with GPS possible)
modulation : chirp, uwb,
channel access : cdma, tdma, csma,
spectrum bandwidth [MHz] : 150.0000,
carrier frequency [GHz] : 5.8000,
localisation method : tdoa, rtt,
duty cycle in percent : 10.00,
radiated power [dBm] : 14.00,
range [m] : 400.0,
communication : bidirectional,
interface : wifi,
domain : outdoor,
```

```
System (3),
name : UWB RTLS,
manufacturer : CEA-LETI,
info : UWB system between 4.2 and 4.8
GHz(UWB indoor)
modulation : dbpsk, n-ppm,
channel access : cdma, tdma, uwb,
spectrum bandwidth [MHz] : 600.0000,
carrier frequency [GHz] : 4.5000,
localisation method : tdoa, toa,
duty cycle in percent : 10.00,
radiated power [dBm] : -13.50,
range [m] : 20.0,
communication : bidirectional,
interface : ethernet,
domain : indoor,
```

```
System (4),
name : WiFi RTLS,
manufacturer : CIT,
info : WLAN based system (2.4 GHz or 5
GHz a/b/g/h/n) that uses mainly RSSI
for channel allocation see info of
WLAN systems
modulation : ofdm, cdma,
channel access : cdma, tdma, csma,
spectrum bandwidth [MHz] : 22.0000,
16.6000,
carrier frequency [GHz] : 2.4120,
2.4170, 2.4220, 2.4270, 2.4320,
2.4370, 2.4420, 2.4470, 2.4520,
2.4570, 2.4620, 2.4670, 2.4720,
2.4840, 5.2000, 5.2200, 5.2400,
5.2600, 5.2800, 5.3000, 5.3200,
5.5000, 5.5200, 5.5400, 5.5600,
5.5800, 5.6000, 5.6200, 5.6400,
5.6600, 5.6800, 5.7000, 5.7350,
5.7550, 5.7750,
localisation method : tdoa, toa,
duty cycle in percent : 30.00,
radiated power [dBm] : 20.00,
range [m] : 200.0,
communication : bidirectional,
interface : wifi,
domain : indoor,
```

```
System (6),
name : GPS/EGNOS,
manufacturer : INOV/Symeo,
info : satellite navigation (NavStar)
modulation : dsss, rrc,
channel access : cdma,
spectrum bandwidth [MHz] : 1.0000,
10.2000,
carrier frequency [GHz] : 1.5750,
1.2280,
localisation method : tdoa,
duty cycle in percent : 100.00,
radiated power [dBm] : -10.00,
range [m] : 3000000.0,
communication : unidirectional,
interface : wifi,ethernet,
domain : outdoor,
```
