IEEE P802.15

Wireless Personal Area Networks

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Title	**CSEM FM-UWB Proposal**
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Re:	This is in response to the TG6 Call for Proposals (CFP), IEEE P802.15-08-0811-03-0006.
Abstract	[The CSEM Frequency-Modulation Ultra Wide-band (FM-UWB) technology is described and the detailed in response to the BAN technical requirements document. Specifically, this proposal is submitted with respect to Low Data Rate (LDR) medical BAN.]
Purpose	Submitted as the candidate proposal for TG6-PHY-MAC
Notice	
Release	

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1 Introduction

This document contains the technical description of a Physical Layer and Medium Access Control Layer (PHY-MAC) proposal to IEEE TG6, Body Area Networks (BAN), targeting non-invasive, wearable, Low Data Rate (LDR), medical BAN applications. It is submitted in response to the TG6 Call for Proposals [IEEE1].

The proposed PHY is Frequency Modulation UltraWideBand (FM-UWB) [GER1] and the proposed MAC is the High Availability Wireless sensor Medium Access Control protocol (WiseMAC-HA) [CSEM1, ROUS].

1.1 LDR medical BAN applications

Figure 1 provides an illustration of a typical future medical BAN operating scenario. In this scenario, miniature, wearable, sensors communicate over short range wireless links to a portable device(s), such as a handset, PDA or watch. This device serves as a gateway to wide area networks (WAN) for the purposes of supporting end-to-end services.

Typical medical and health applications employing non-invasive, wearable medical BAN solutions may include:

- EEG Electroencephalography
- ECG Electrocardiogram
- EMG Electromyography (muscular)
- Blood pressure
- Blood SpO_2
- Blood pH
- Respiration
- Posture (human position)
- Vital signals monitoring
- Temperature (wearable thermometer)
- Respiratory monitor
- Wearable heart rate monitor
- Wearable blood pressure monitor
- Wearable glucose sensor
- Muscle tension sensing and stimulation
- Wearable weighing scale
- Fall detection
- Sports training aids

Many other health and medical applications may also be possible and wearable LDR BANs are not limited to health and medical applications. However, LDR health and medical applications are the focus of this proposal.

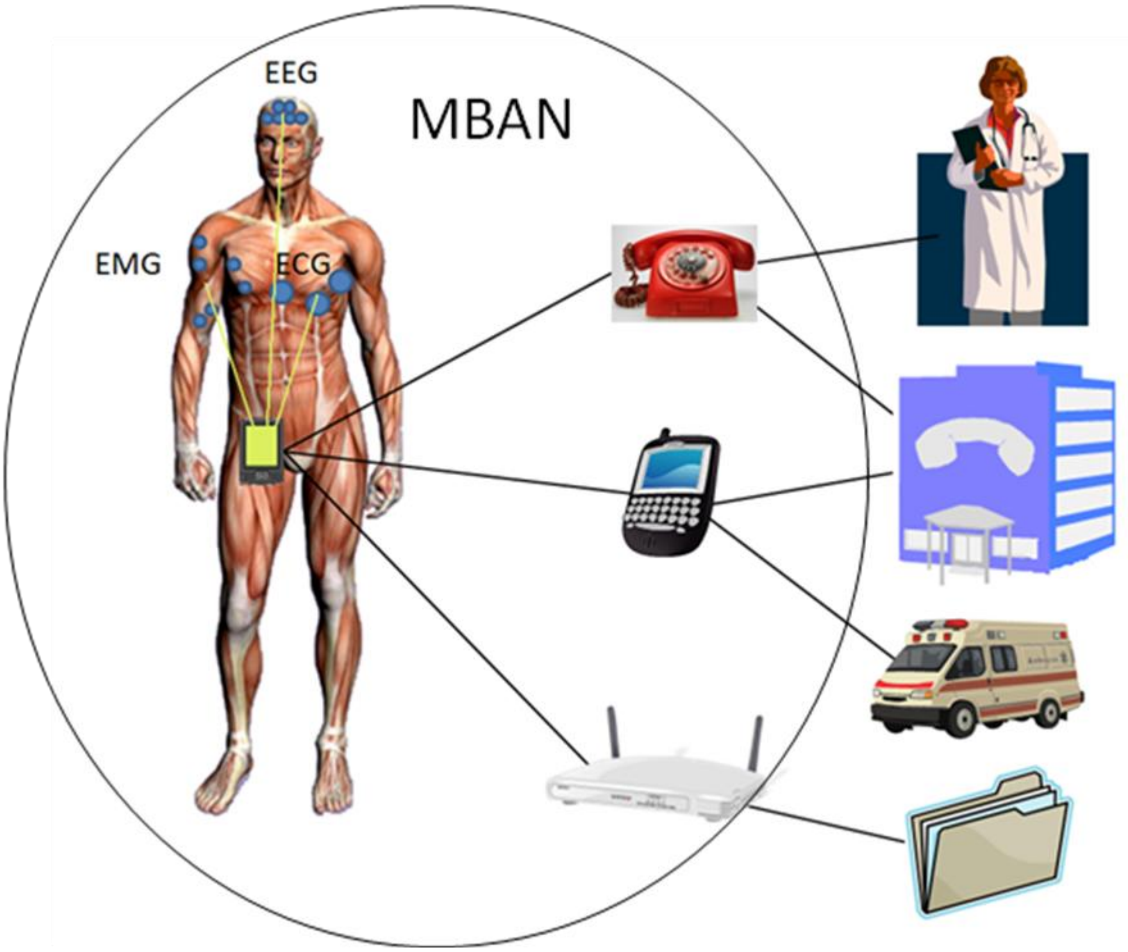


Figure 1 Medical BAN use scenario

1.2 Requirements for wearable BAN applications

The requirements for LDR medical BAN applications include [IEEE2-IEEE5]:

- long autonomy (μW-mW, possible operation via energy scavenging)
- high robustness, high reliability
- low cost
- small size
- good coexistence and the potential for unlicensed worldwide operation
- and high scalability.

A summary of key technical requirements for wearable BAN applications is provided by Table 1 [IEEE3, IEEE4]. As will be described in the sections that follow, the proposed FM-UWB PHY-MAC solution meets or exceeds the requirements for wearable Medical BAN applications.

Table 1: Summary of key technical requirements for wearable BAN

Parameter	**Wearable BAN Requirements**
Coexistence and robustness	Good (low interference to other systems, high tolerance to interference)
Data Rates	10 kbps to 10 Mbps (LDR medical / MDR commercial)
Insertion/de-insertion	< 3 seconds
Network topology	Star (mandatory), mesh (optional)
Power consumption	Low, autonomy > 1 year (e.g. with 1% duty cycle, MAC sleep modes, 500 mAh battery)
QoS (Medical BAN)	PER < 10%, delay < 125 ms
Reliability	Robust to multipath interference > 99% link success/availability
SAR regulations	< 1.6 mW (US) / < 20 mW (EU)
Scalability	High, up to 256 devices
Transmission range	≥ 3m

2 The proposed solution

The proposed PHY-MAC solution targets wearable Medical BAN. It combines Frequency Modulation UltraWideBand (FM-UWB) radio with Wireless sensor Medium Access Control High Availability (WiseMAC-HA).

2.1 The radio

FM-UWB was first identified as a promising technology for low power, low data rate (LDR), yet robust medical telemonitoring applications in 2001. It has been developed from the start specifically to support LDR wearable Medical BAN applications.

A first Proof-of-Concept (PoC) demonstrator was developed in the IST URSAFE (2002-2004) project [URSA]. This demonstrator was implemented using Commercial-off-the-Shelf (COTS components and operated at 1.25 GHz.

FM-UWB was studied in detail in the IST MAGNET project (2004-2005) and selected as the LDR air interface. In the follow-on to MAGNET, the IST MAGNET Beyond (2006-2008) project [MAGB], first generation IC building blocks were designed and manufactured for the purpose of implementing an advanced prototype. This allowed for the validation of the power consumption and confirmation of the robustness of FM-UWB to interference and multipath and also for demonstrating the radio with a medical application.

Additionally, during the course of MAGNET Beyond, CSEM also initiated efforts to standardize FM-UWB for medical BAN applications with the IEEE, ETSI and ECMA

Today, a working FM-UWB prototype exits. This prototype operates in the 7.25 to 8.5 GHz band and meets worldwide regulatory limits for UWB radiated power.

7.25 GHz to 8.5 GHz band well suited for international operation and mobility

2.2 The MAC

The WiseMAC-HA protocol provides advantages in terms of ultra low power consumption, robustness to interference and scalability with respect to network size. The protocol is traffic limited. As such, it is scalable and can support potentially large numbers of wearable devices. WiseMAC-HA is ultra low power for all nodes as there is no need for synchronizing.

WiseMAC-HA’s “fairness” allows for coexistence and simultaneous operation of independent networks. The protocol implements “detect and avoid” (DAA) to deal with interferers

WiseMAC-HA is flexible. It supports both star and meshed network topologies and offers low latency connectivity. It supports throughput and latency vs. energy tradeoffs, the ability to decide on mode changes and the ability to accommodate other operating modes.

2.3 The competitive edge

The major advantages of low complexity FM-UWB technology are:

- Ultra low power consumption
- Robustness to interference and multipath
- Good coexistence
- Simple low cost design
- Fast acquisition for nomadic users
- High scalability.

The major advantages of WiseMAC-HA are:

- Ultra Low Power
- Robustness to Interference
- Scalability with network size
- Flexibility (star and mesh topologies)
- Low latency

The proposed solution combines the advantages of the FM-UWB PHY with the WiseMAC-HA protocol. FM-UWB is a very promising technology for short range wireless communication [AWTE]. It was developed specifically to support LDR Medical BAN applications and together with the scalable, ultra low power WiseMAC-HA protocol, it fully satisfies the requirements for wearable, LDR Medical BAN [IEEE2- IEEE5].

Descriptions, technical details and performance of the FM-UWB radio and WiseMAC-HA protocol are provided in the sections that follow.

3 FM-UWB PHY

FM-UWB exploits high modulation index analog FM to obtain an ultra-wide signal. Frequency modulation has the unique property that the RF bandwidth B_{RF} is not only related to the bandwidth f_m of the modulating signal, but also to the modulation index β that can be chosen freely. This yields either a bandwidth efficient narrow-band FM signal ($\beta < 1$) or a (ultra) wideband signal ($\beta >> 1$) that can occupy any required bandwidth.

FM-UWB constitutes an analog implementation of a spread-spectrum system. This constant-envelope approach, where peak power equals average power, yields a flat spectrum with steep spectral roll-off. Instantaneous de-spreading in the receiver makes that the FM-UWB radio behaves like a narrowband FSK radio from a synchronization and detection point-of-view. FM-UWB technology combines low complexity with robustness against interference and multipath. The following sub-sections present the FM-UWB system and its properties.

3.1 System characteristics

Table 2 presents the FM-UWB radio characteristics. The proposed solution is designed to operate in the 7.25 – 8.5 GHz band. This band is suited for international operation and mobility.

Table 2: FM-UWB system characteristics.

Parameter	Value
RF center frequency	6.4 – 8.7 GHz
RF bandwidth	500 MHz
RF output power	-15 dBm
Subcarrier frequency	1.0, 1.25, 1.50, 1.75 MHz
Subcarrier modulation	FSK, $\beta = 1$
Raw bit rate	< 250 kbps
Receiver sensitivity	<-85 dBm[1]
TX, RX switching time	< 100 µs
RX synchronization time	< 500 µs

1. At BER ≤ 10^{-6}

3.2 Transmitter

Figure 2 shows the block diagram of the FM-UWB transmitter. Low modulation index digital FSK is followed by high modulation index analog FM, creating a constant-envelope UWB signal [GER1]. The transmitter consists of a 1-2 MHz subcarrier oscillator generating a triangular signal that is FSK modulated by the transmit data. This subcarrier signal m(t) modulates the RF VCO, yielding a constant-envelope UWB signal with a flat power spectral density and steep spectral roll-off.

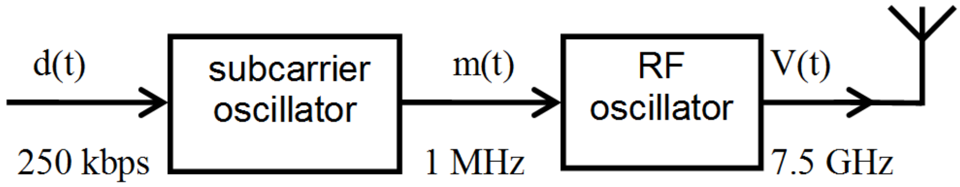


Figure 2 FM-UWB transmitter block diagram.

Low complexity transmitter

Figure 3 shows the data, the subcarrier and the UWB signal in the time domain for a data transition at t = 0 and subcarrier frequency of 1 MHz; the center frequency of the UWB signal V(t) is not to scale for the sake of clarity.

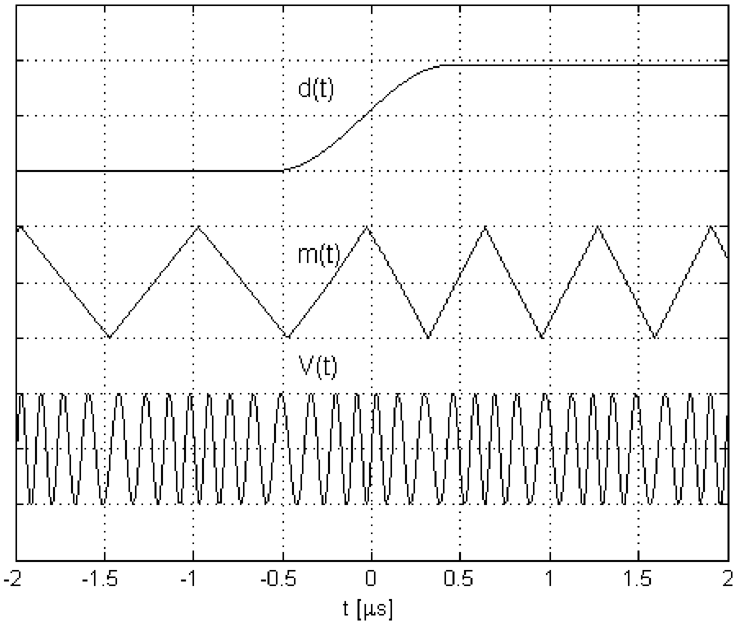


Figure 3: Time domain view of data d(t), subcarrier m(t) and UWB signal V(t).

Figure 4 shows an example of the power spectral density (PSD) of an ideal FM-UWB signal. The signal is compliant with the relevant regulatory limits [IEEE6-IEEE7]. The signal power is –15 dBm (112 mV_{pp} in a 50 Ω load). The subcarrier frequency is 1 MHz and the deviation Δf is 250 MHz, yielding a modulation index β of 250. The –10 dB bandwidth equals 500 MHz.

The power spectral density of a wideband FM signal is determined by and has the shape of the probability density function (PDF) of the modulating signal m(t) [TAUB]. The use of a triangular subcarrier waveform, which is characterized by a uniform PDF, results in a flat RF spectrum. From an implementation point of view the triangular waveform is straightforward to generate using either analog or digital circuit techniques.

The roll-off and noise floor of the FM-UWB signal in a practical circuit realization will be determined by the RF oscillator phase noise and noise floor.

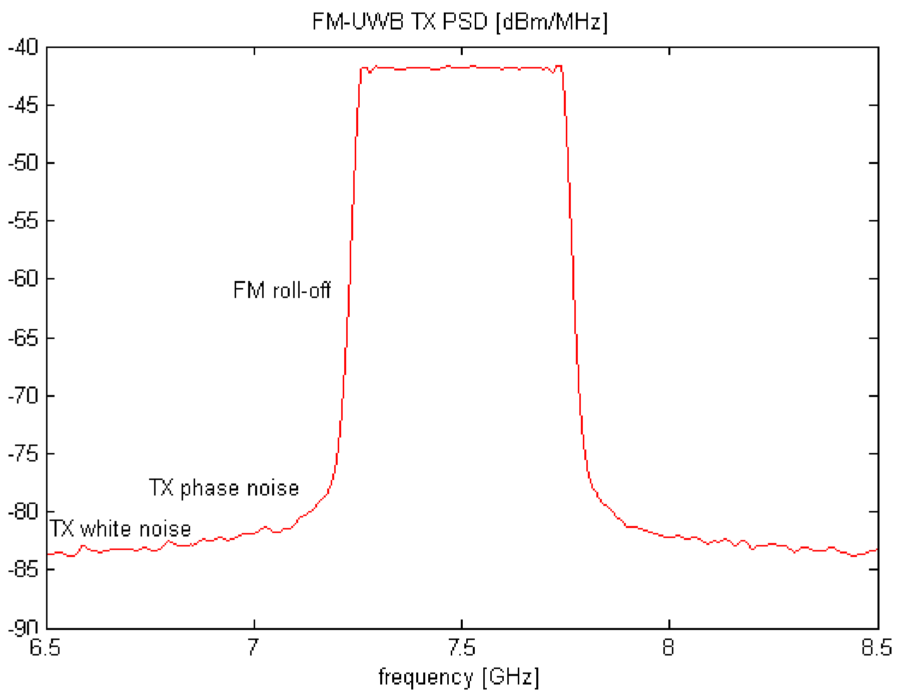


Figure 4: Spectral density of real-life FM-UWB signal

obtained with f_{SUB}= 1 MHz and β = 250.

Compliant with international regulatory limits for UWB. Rapid rolloff, low PSD, and low radiated power for good coexistence, less than 50 μW radiated power meets SAR.

3.2.1 Transmitter implementation aspects

Direct Digital Synthesis (DDS) techniques are advantageously used in the subcarrier generation [NILS]. The DDS approach offers both precision and flexibility. Subcarrier frequency and subcarrier frequency deviation can be easily modified. Table 3 presents the DDS characteristics.

Table 3: DDS characteristics

Parameter	Value
Clock frequency	24 MHz
Phase resolution	16 bits
Amplitude resolution	10 bits
Output frequency	1 – 2 MHz
Frequency resolution	366 Hz
Digital data pre-filtering	Gaussian, BT = 0.7

5 shows the block diagram of the DDS used in the transmitter. The raw data d(t) may be encoded (typically Manchester encoding) before it enters the DDS. Digital pre-filtering of the data reduces the sidelobe level of the FSK signal. Pre-filtering is performed with 8 samples per bit and easy-to-implement coefficients [NILS].

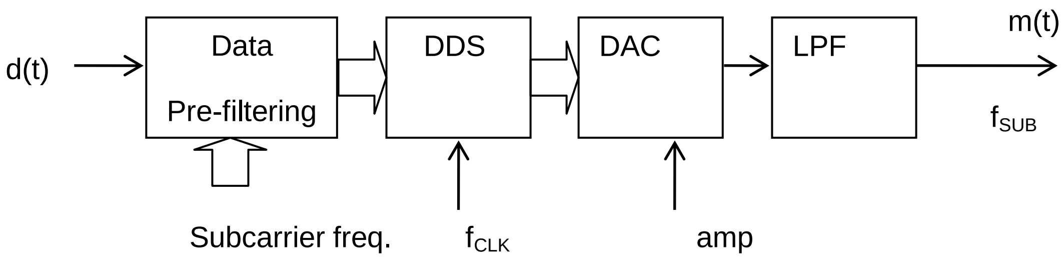


Figure 5: Transmitter DDS block diagram.

Generation of a triangular wave does not need a look-up table as would be required for the generation of a sine wave, reducing the complexity and memory requirements of the circuit. A bank of XOR circuits takes care of the sawtooth-to-triangle conversion [NILS]. The DDS digital output word is converted into a triangular signal in a DAC. The DAC output signal is next low-pass filtered in a 2nd order analog low-pass filter with cut-off frequency of 10 MHz to attenuate the aliasing components. Figure 6 shows the spectrum of a 1 MHz FSK subcarrier signal with deviation Δf_{SUB} = 50 kHz.

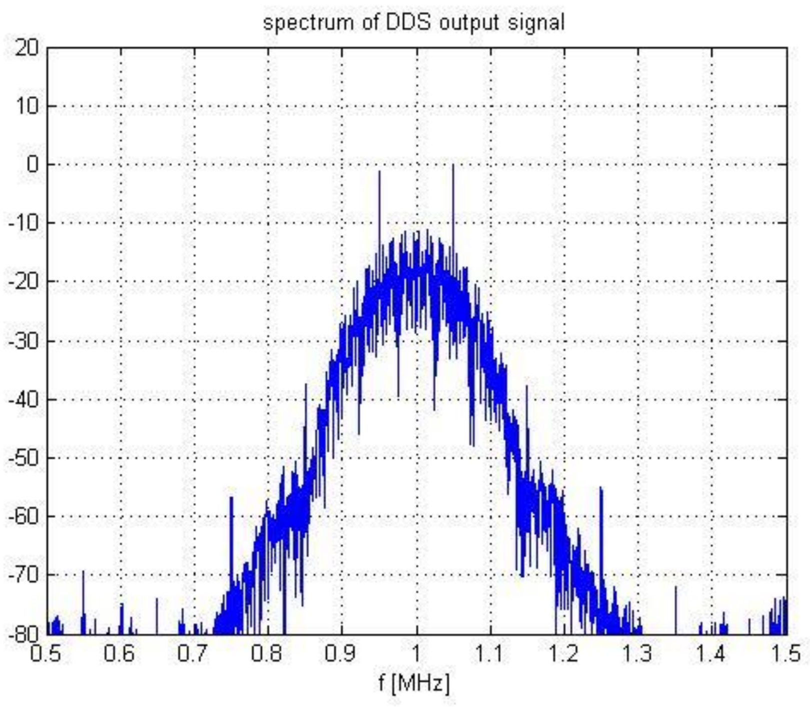


Figure 6: Spectrum of digitally generated subcarrier signal m(t).

The filtered DDS signal is passed on to the RF VCO. By using a multiplying DAC the amplitude of the subcarrier signal and as a result the RF deviation of the FM-UWB output signal can be adjusted. Table 4 shows the subcarrier frequencies for a 4-user 100 kbps FM-UWB system.

Table 4: Subcarrier frequencies for the case of a 4-user 100 kbps system

Subcarrier	Subcarrier frequency
1	1.00 MHz
2	1.25 MHz
3	1.50 MHz
4	1.75 MHz

3.3 RF-UWB signal generation

The subcarrier signal m(t) modulates the RF oscillator, that implements the analog spreading and yields a constant-envelope UWB signal with a flat power spectral density and steep spectral roll-off at its output.

The RF signal is generated by a free-running RF VCO that is regularly calibrated by a PLL frequency synthesizer. This frequency synthesizer ensures the correct center frequency of the UWB signal. As the PLL doesn't operate continuously, it will not really impact transmitter power consumption. Frequency modulation of the RF VCO with the subcarrier signal occurs in open loop mode and the frequency synthesizer switched off.

Figure 7 shows the block diagram of the RF signal generation. The phase noise of the RF oscillator in the sub-carrier bandwidth (at offset f_{SUB} from the carrier) needs to be taken into account. The demodulated phase noise (random frequency variations) from a strong FM-UWB interferer may lower the subcarrier SNR of a weak wanted FM-UWB signal up to the point where the probability of error of the demodulated sub-carrier becomes unacceptable. A typical phase noise requirement for this oscillator is -80dBc/Hz at 1MHz offset from the carrier, motivated by the possibility to cope with a 20dB stronger FM-UWB interferer at the same center frequency [GER7].

The VCO output signal is the FM-UWB signal which is fed to the output amplifier OA providing the appropriate RF output level. The VCO output signal is also fed into a fixed ratio prescaler (P = 256) that reduces the high VCO output frequency (6-9 GHz) to a lower frequency (23-35 MHz) compatible with the programmable divider hardware. The RF center frequency is directly related to the division number N of the programmable divider by

$$f_{RF} = NPf_{REF} \qquad (1)$$

With a reference frequency f_{REF} = 250 kHz, the center frequency of the UWB signal will have a resolution of 64 MHz. Table 5 and Table 6 show two possible options for the RF center frequencies.

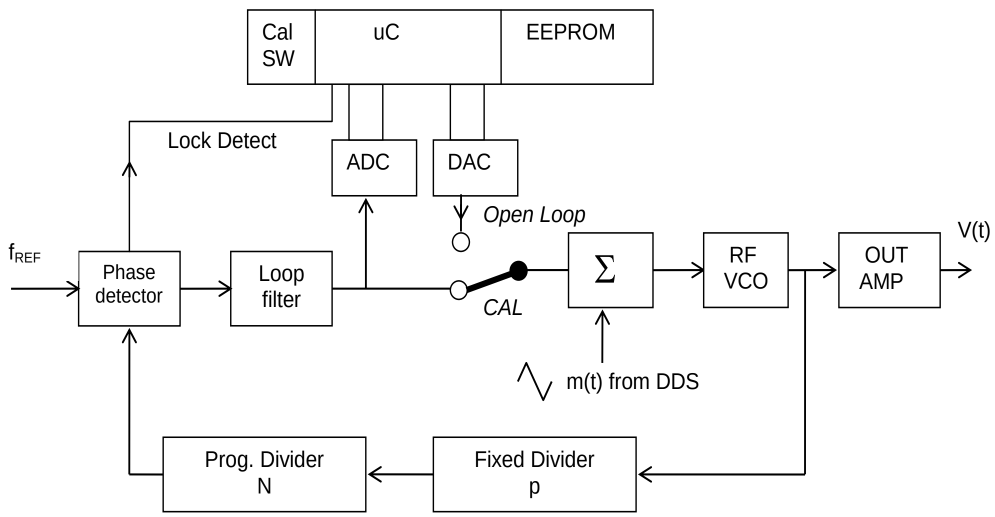


Figure 7: Block diagram of RF signal generation

Table 5: Transmitter RF center frequencies with 576 MHz channel spacing

Channel	N_{RF}	RF center frequency
H_1	100	6400 MHz
H_2	109	6976 MHz
H_3	118	7552 MHz
H_4	127	8128 MHz
H_5	136	8704 MHz

Table 6: Transmitter RF center frequencies with 512 MHz channel spacing (MBOA compatible)

Channel	N_{RF}	RF center frequency
H_1	101	6464 MHz
H_2	109	6976 MHz
H_3	117	7488 MHz
H_4	125	8000 MHz
H5	133	8512 MHz

3.3.1 Tx calibration

The TX VCO is used in open loop mode. Due to IC process variations, it is necessary to measure the TX VCO curve and memorize it. A complete calibration procedure is required the very first time the transmitter is turned on, i.e., at the end of the manufacturing process. Referring to Figure 7, the calibration procedure could be implemented as follows. With the switch in the CAL position, the PLL is powered up and for the required transmit channel three measurements are made for the following frequencies:

- f_c – 256 MHz
- f_c
- f_c +256 MHz

These three frequencies correspond to the channel center frequency and the channel edges. For each of these frequencies, the PLL is allowed to settle to its final frequency (indicated by the Lock Detect signal generated by the PLL phase detector) and next the VCO corresponding to that frequency is measured by the ADC and stored in the micro-controller memory. During calibration the DDS signal is not added to the VCO input signal.

After calibration, the switch is moved to the Open Loop position and a DC voltage corresponding to the required center frequency is imposed by the DAC. The DDS voltage is added to this DC value to yield the FM-UWB signal. The required DDS signal amplitude is derived from the two measurements at the channel edge.

3.4 Receiver architecture

The receiver demodulates the FM-UWB signal without frequency translation (i.e., no mixing). Figure 8 shows the receiver block diagram. The low complexity receiver comprises a LNA, a wideband FM demodulator, and low-frequency subcarrier filtering, amplification and demodulation circuitry.

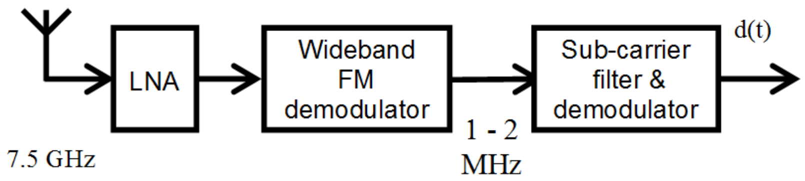


Figure 8: FM-UWB receiver block diagram.

Ultra low complexity UWB receiver

The absence of carrier synchronization allows for rapid synchronization as required in ad-hoc networks. Due to the instantaneous de-spreading in the wideband FM demodulator, the system behaves like a narrowband FSK system where synchronization is limited by the bit synchronization time.

The FM-UWB radio targets bit rates up to 250 kbps at a distance of 3 meters under free-space propagation conditions using transmit and receive antennas with 0dBi gain. The received signal power P_{RX} is then given by Friis' transmission equation

$$P_{RX}(\text{dBm}) = P_{TX}(\text{dBm}) - 20\log_{10}\frac{4\pi d}{\lambda}, \qquad (2)$$

where λ is the free-space wavelength (i.e., 4 cm at 7.45 GHz) and d is the separation between transmitter and receiver. For 3 m range and a 500 MHz wide the FM-UWB signal limited to -41.3 dBm/MHz (in accordance with the FCC), transmit power P_{TX} is equal to -15 dBm and the resulting received signal power predicted from (2) of -74 dBm. Assuming a 50 Ω antenna, 500 MHz bandwidth and a receiver noise figure (NF) equal to 5 dB, the equivalent noise power at the receiver input is -82 dBm. The minimum required SNR to obtain an error rate of $1x10^{-6}$ at 250 kbps is -7dB (see Figure 9) [GER1], corresponding to a signal of -89 dBm. This yields a margin of 15 dB which more than compensates for implementation losses (4 dB) and frequency selective multipath (3 dB).

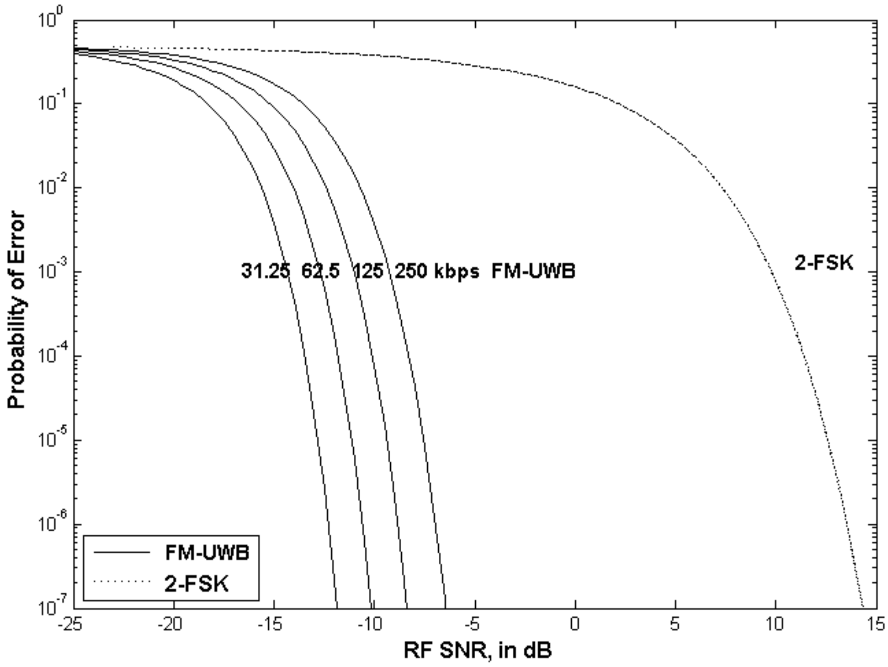


Figure 9: Probability of error for a narrowband FSK and a 500 MHz bandwidth FM-UWB system for various data rates.

Interference from other FM-UWB users also needs to be addressed. Assuming that the worst-case interference scenario is another user 50 cm away, the interference level is -58 dBm at the receiver. This requires an input-referred third-order intercept point (IIP_3) better than -41 dBm in order to avoid blocking of the desired signal, which is easily attainable.

The key receiver building block is the wideband FM demodulator not preceded by any hard-limiting device. As a result, the FM capture effect doesn't occur. This allows for the simultaneous demodulation (de-spreading) of multiple FM-UWB input signals at the same center frequency with different subcarrier frequencies. The demodulator can be advantageously implemented as a delay line demodulator, where the group delay of an all-pass filter or band-pass filter implements the time delay [DONG, GER2].

The receiver processing gain is equal to the ratio of RF and subcarrier bandwidth

$$G_{PdB} = 10\log_{10}\left(\frac{B_{RF}}{B_{SUB}}\right) = 10\log_{10}\left(\frac{2\Delta f_{RF}}{(\beta_{SUB}+1)R}\right) \qquad (3)$$

In a 250 kbps LDR system with a RF bandwidth of 500 MHz a processing gain of 30 dB is obtained. As a result a 250 kbps FM-UWB system can tolerate a 17 dB stronger FM-UWB interferer before the probability of error degrades to $1x10^{-6}$ [GER3].

3.4.1 Synchronization

In the absence of carrier or pulse synchronization, acquisition reduces to bit synchronization, which can be very rapid i.e., possible in less than 500 µs according to measurements made on a 62.5 kbps FM-UWB system, as shown in Figure 10. In a 250 kbps system, synchronization would be 4 times faster. Transmission starts at the rising edge of the TX_ENABLE signal. On the receiver side, the raw data RXD is available almost instantaneously, whereas the bit synchronizer circuit determines the overall receiver synchronization time. From a synchronization and detection point of view, the FM-UWB system behaves like a narrowband FSK system.

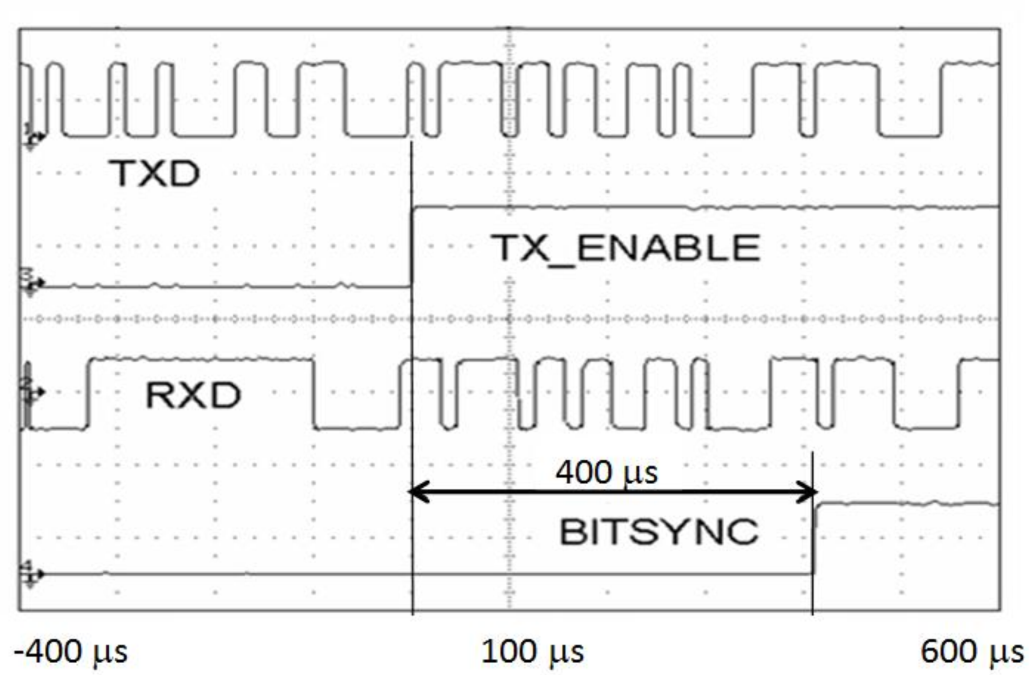


Figure 10: Measured FM-UWB Receiver synchronization time.

Ultra low radio sync time suitable for mobile and near real-time applications

3.4.2 Receiver implementation aspects

This section addresses implementation of the wideband FM demodulator and the subcarrier processing (SCP).

3.4.2.1 Wideband FM demodulator

The key receiver building block is the wideband FM delay line demodulator as shown in Figure 11. Its operating principle is FM-to-PM conversion in the delay line followed by a phase detector implemented by a multiplier [KOUW].

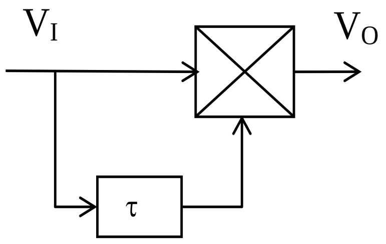


Figure 11: Delay line FM demodulator.

The relation between the input frequency and the demodulator output voltage for the delay line demodulator as shown in Figure 11 is given by

$$V_{FMDEMOD}(f) = \frac{A_1^2}{2}\cos\left(N\frac{\pi}{2}\frac{f}{f_C}\right) \qquad (4)$$

and shown in Figure 12. The delay time τ is chosen equal to an odd multiple of a quarter period (T) for the carrier frequency f_c of the FM-UWB signal

$$\tau = N\frac{T}{4} = \frac{N}{4f_c} \qquad \text{with } N = 1, 3, 5, \ldots, \qquad (5)$$

When the delay is implemented by an ideal lossless delay line, the phase shift at the center frequency $\varphi(f_C)$ equals

$$\varphi = \omega_C \tau = 2\pi f_C N\frac{T}{4} = N\frac{\pi}{2} \qquad (6)$$

When the delay is implemented as the group delay of a filter, $\varphi(f_C)$ doesn't necessarily meet (6), Additional phase shifting circuitry may be required to operate in the middle of the demodulator curve. The delay time τ will determine the slope of $\varphi(f)$ and also the useful range of the demodulator. The demodulator sensitivity is proportional to N. The useful RF bandwidth B_{DEMOD} of the FM demodulator is inversely proportional to N and given by

$$B_{DEMOD} = \frac{2}{N} f_c . \qquad (7)$$

The useful bandwidth is defined as the maximum frequency range over which the static demodulator transfer function is monotonic.

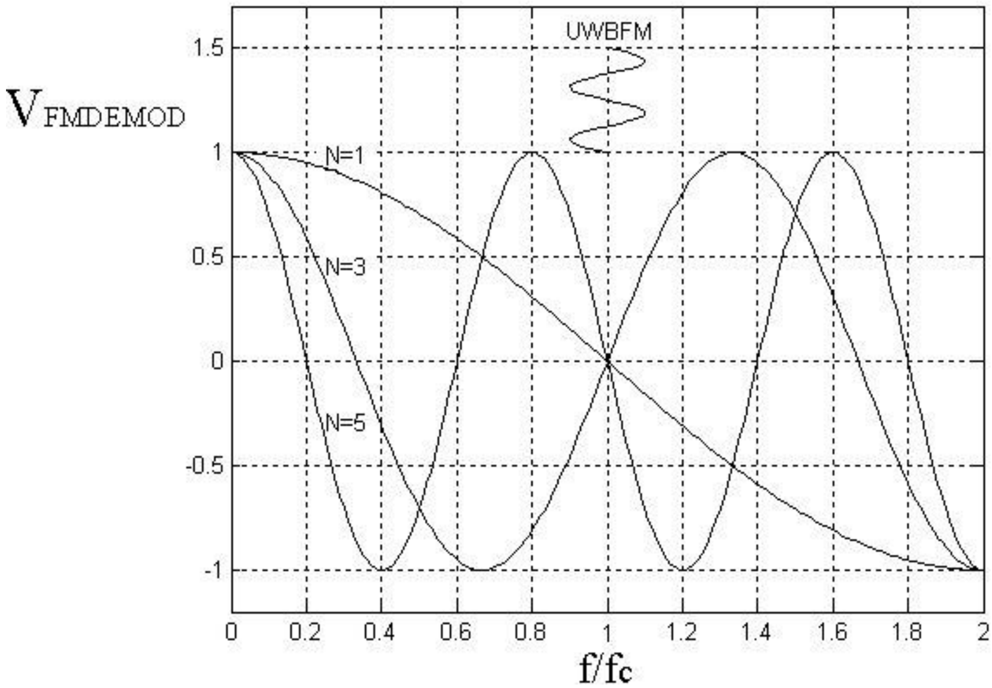


Figure 12: Relation between normalized delay line demodulator input frequency and normalized output voltage for various values of N.

Various implementations of this demodulator have been realized and reported in [GER2] and [DONG]. The latter publication describes a FM-UWB receiver front-end operating at 7.5 GHz with LNA and wideband FM demodulator. The sensitivity of this front-end is -85 dBm. Additional information concerning this front-end can be found in the chapter on the "Proof of Concept and Target Solution".

3.4.2.2 Subcarrier processing (SCP)

The expanded dynamic range of the subcarrier signal due to the quadratic transfer function of the delay line demodulator requires steep filtering. Band-pass filters at the subcarrier frequency do not provide sufficient filtering. A direct-conversion architecture with baseband low-pass filters and a baseband FSK demodulator alleviates the filter requirements.

Figure 13 shows this architecture. Two double balanced mixers driven by the two quadrature subcarrier LO signals LOI and LOQ. These LO signals are generated by a DDS and are triangular resulting in additional attenuation of input signal components at odd multiples of the LO frequency.

The low-pass filters after the mixers have a cut-off frequency f_{LP} equal to half the subcarrier bandwidth.

$$f_{LP} = \frac{B_{SUB}}{2} = \frac{R}{2}\left(\beta_{SUB} + 1\right) \qquad (8)$$

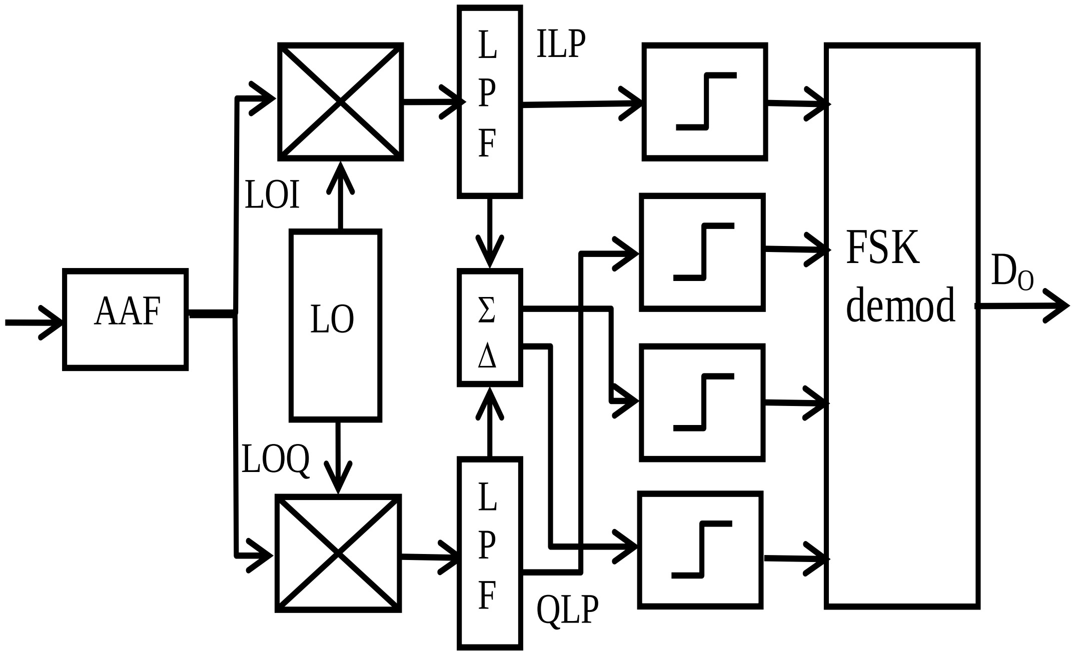


Figure 13: Receiver subcarrier processing.

For low subcarrier modulation index values β_{SUB} = 1, it is necessary to lower the jitter of the demodulated signal. This can be done by having a digital demodulator acting upon more than 2 hard limited versions of multiple phase of the complex baseband signal. Additional phase are created directly after the analog low-pass filters as shown in Figure 13. The digital FSK demodulator determines on each transition of the 4 hard-limited signals, whether the baseband subcarrier signal represents a positive frequency (logical 1) or a negative frequency (logical 0).

The receiver DDS is shown in Figure 14 and is very similar to the transmit DDS except for the following two points: no data filtering or FSK modulation required and Quadrature outputs ϕ_I and ϕ_Q. The TX and RX DDS are combined together.

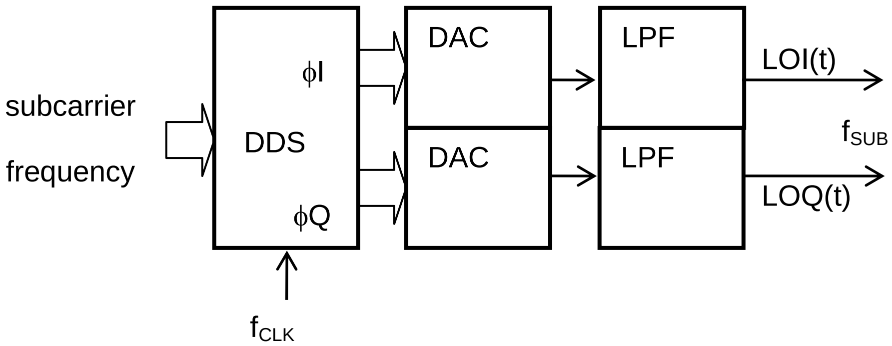


Figure 14: Receiver DDS architecture

3.5 Antennas

Antennas can also be used for interference mitigation since they can be designed to have notches in their frequency response. In [KIM] a bowtie UWB antenna covering the 3 – 10 GHz range with a frequency notch at 5.2 GHz is presented. At that frequency, its gain drops by 10 dB. Figure 15 shows the antenna measures 30 x 22 mm and is realized on a low-cost FR-4 substrate. The measured antenna gain is about 1.5 dBi at 7.5 GHz.

Many different UWB antennas with one or several notches have been published in literature since the first appearance of this antenna in 2006. Due to the fact that there is no pulse to distort, FM-UWB is not sensitive to antenna design and may be used with most of these and other antenna designs without adverse impact on the performance.

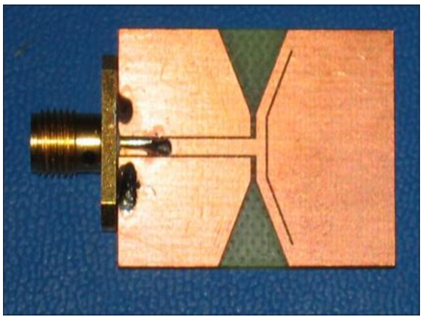


Figure 15: Bowtie antenna

FM-UWB is tolerant to antenna transfer function. Antennas may be small. Size and gain depend on link margin tradeoff.

3.6 Radio performance

In this section system performance issues are examined. A reference link budget analysis is presented. Performance in fading, coexistence and interference resistance are examined.

3.6.1 Link budget

A link analysis is provided in Table 7, from which it can be seen that the link is closed for a data rate of 250 kbps and distance between the transmitter and receiver of 3 m. BFSK modulation is considered in this example.

A link margin of 6 dB was considered and a margin of 6 dB was also taken for implementation losses. The figure of 20 dB for the required SNR is based on the results of [GER1] and considers a BER of less than 10^{-3} with BFSK modulation in a fading channel.

Reliable communication requires sufficiently high receiver sensitivity. The transmission power P_{TX} is fixed by the spectral mask (-41.3 dBm/MHz) and bandwidth of the UWB signal. For a RF bandwidth B_{RF} = 500 MHz, maximum transmission power P_{TX} = -14.3 dBm.

Table 7: Example FM-UWB link analysis (CM 4 Channel)

Parameter	Symbol	Value	Units	Comments
Tx bandwidth	B_{RF}	500	MHz	Nominal UWB signal bandwidth
Tx power	P_{TX}	-14.3	dBm	< 40 μW (max power limit)
Tx antenna gain	G_{TX}	0.0	dBi	
EIRP (peak)	EIRP	-14.3	dBm	Peak EIRP
Center frequency	f_C	7.5	GHz	High band operation (7.25-8.5 GHz)
Distance	D	3.0	m	3 meters required for BAN
Free space path loss	Lp	-59.5	dB	
Rx antenna gain	G_{RX}	0.0	dBi	
Rx power	P_{RX}	-73.8	dBm	
Noise Figure	NF	5.0	dB	Equivalent system noise: 627 K
Noise power density	N0	-169.0	dBm/Hz	
Noise power	N	-82.0	dBm	500 MHz RF bandwidth
Data rate	R	250	kbps	High end for wearable Medical BAN
Subcarrier SNR	SNR_{SC}	13.4	dB	Required subcarrier SNR, BFSK, BER ≤ 10^{-6}
RF SNR	SNR_{RF}	-7.0	dB	Required RF SNR, SNR conversion [EURASIP]
Implementation losses	Li	4.0	dB	Miscellaneous losses + interference
Link margin	M	3.0	dB	Multipath fading, CM3 / CM4 channels
Remaining margin	Mrem	8.2	dB	Positive margin remaining indicates link closed

The LDR system targets short range indoor communication under line of sight (LOS) conditions. Figure 16 shows the received power for operation at 7.5 GHz as function of the distance for a path loss exponent n = 2 and antenna gain of 0 dBi. Measurements of commercially available small UWB antennas show that antenna gain values of 0 dBi are realistic.

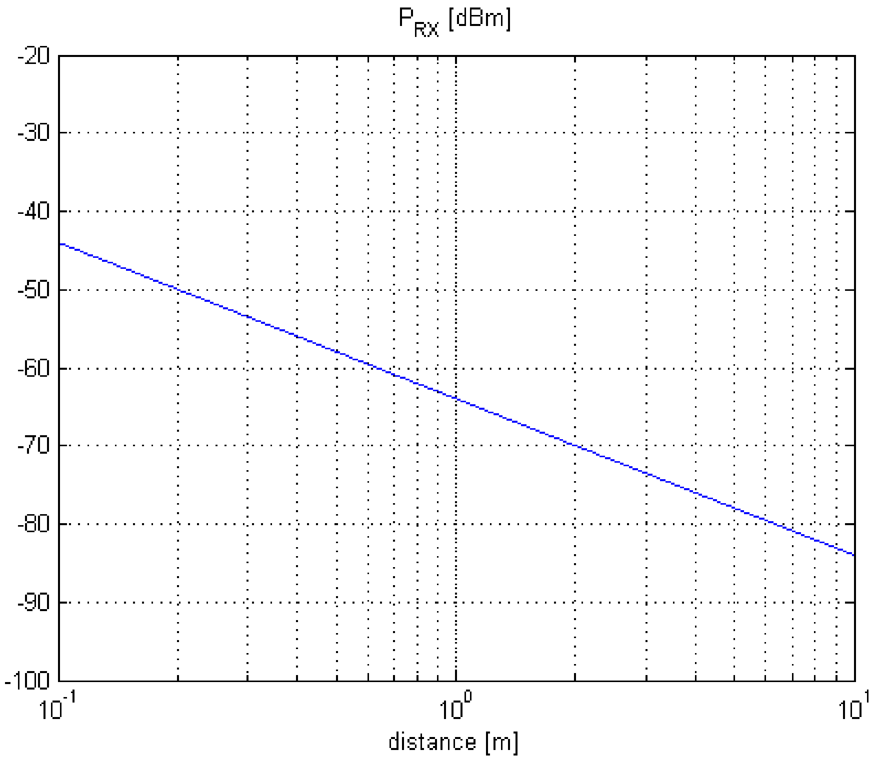


Figure 16: Received power as a function of distance at 7.5 GHz.

3.6.2 Frequency-selective fading channel

BAN communication is subject to frequency-selective fading. Body surface-body-surface communication is modeled by the CM3 channel. Body surface to external device communication is modeled by the CM4 channel. Both models are provided in [IEEE8].

FM-UWB signals are robust to frequency-selective multipath [GER4]. Figure 17 shows MATLAB simulation results of the RF fading level, i.e., the (equivalent) receiver input power for 8000 realizations of the IEEE CM3 BAN channel and 4000 realizations of the IEEE CM4 channel (i.e., with Body Direction = 1, which yields worst case results).

From Figure 17, a fading level of 0 dB corresponds to the case of no fading i.e. relative to the mean signal level. The mean and median values of the fading distribution, as seen at the output of the FM-UWB demodulator, were both found to equal 0 dB meaning that 50% of the time we expect a performance improvement and 50% of the time a degradation. This is clearly illustrated by the histograms in Figure 17.

Figure 18 shows the Cumulative Density Function (CDF) of the fading level for the FM-UWB signal. It can be seen that 99% of the time the fading level is above -2.8 dB for the CM3 channel and above -1.7 dB for the CM4 channel. This means that 2.8 dB of fading margin is required to achieve 99% availability in the CM3 channel and only 1.7 dB of fading margin is required in CM4. This compares favorably to a narrowband radio which requires 20 dB higher received power for 99 % availability (i.e., based on a Rayleigh fading channel).

The reason for the improvement is the diversity gain provided by the ultrawideband transmit signal over the frequency selective multipath fading channel as defined in CM3 and CM4. Importantly, in the case of the FM-UWB, this is achieved without additional receiver complexity given "narrowband" signal detection in the subcarrier.

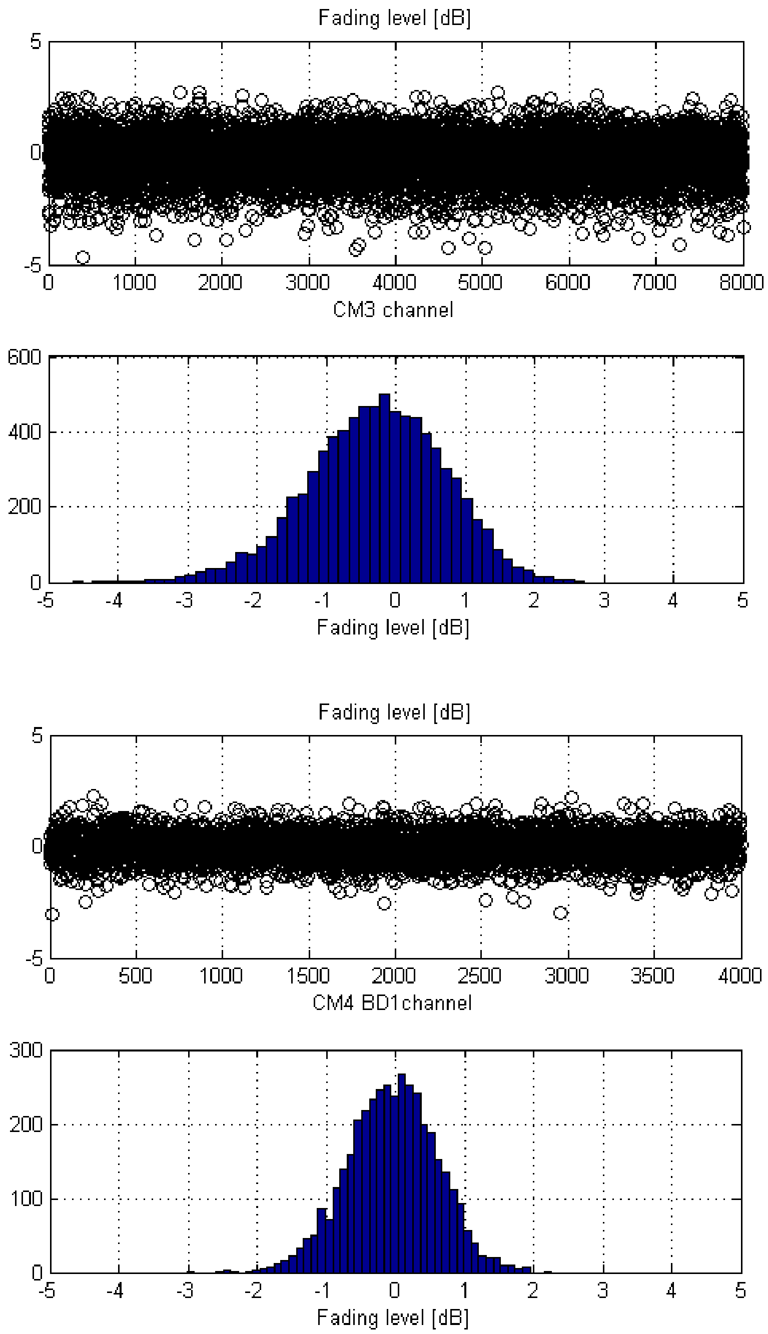
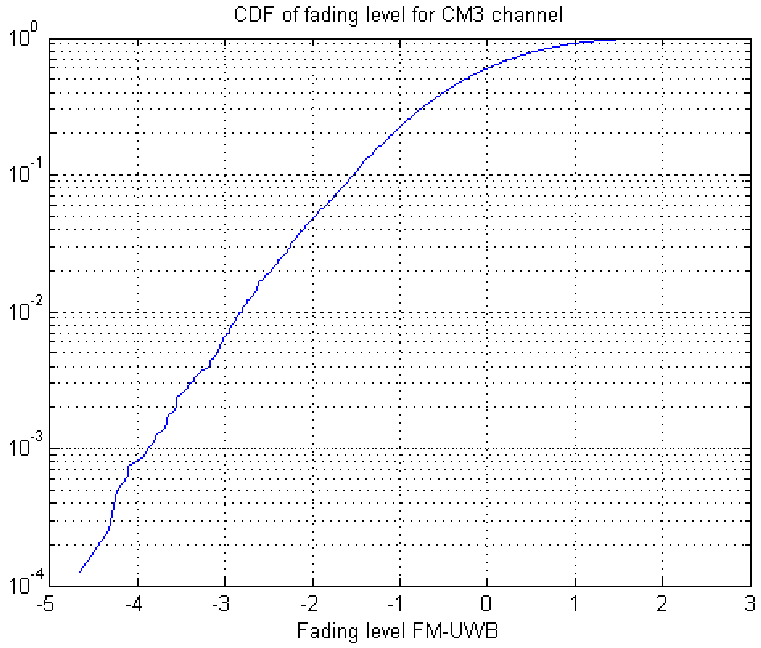


Figure 17: Fading level in CM3 and CM4 BD1 channel.



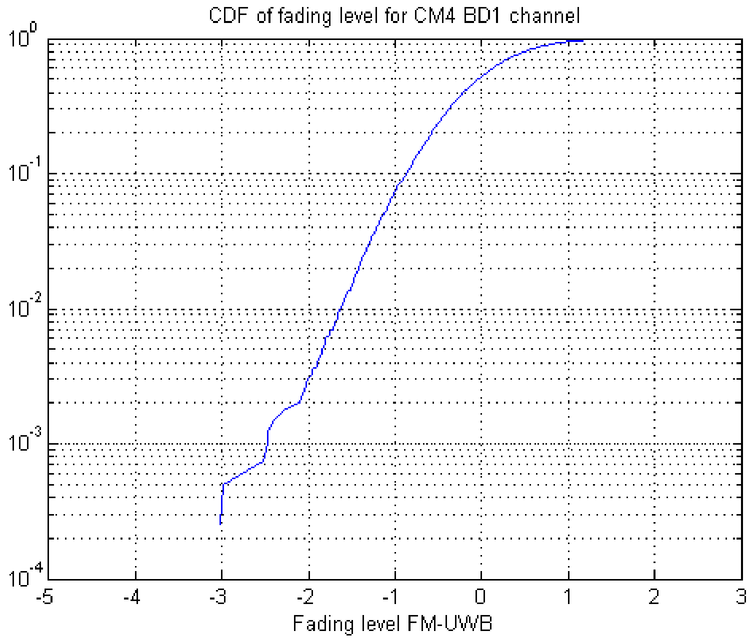


Figure 18: CDF of fading level in CM3 and CM4 BD1 channel

Wideband signal robust to multipath fading combined with a low complexity receiver. 99% availability in CM3 and CM4 channels requiring < 3 dB margin

3.7 Coexistence and interference resistance

Low complexity FM-UWB offers good coexistence and robustness to interference. A discussion follows.

3.7.1 Coexistence

The low radiated power of UWB signal combined with the steep spectral roll-off of the FM-UWB realization provides good coexistence with existing radio systems, typically WLAN systems operating between 5 and 6 GHz. Figure 19 shows the spectrum of the transmitter output signal as observed on a spectrum analyzer. The noise floor observed is originating from the spectrum analyzer.

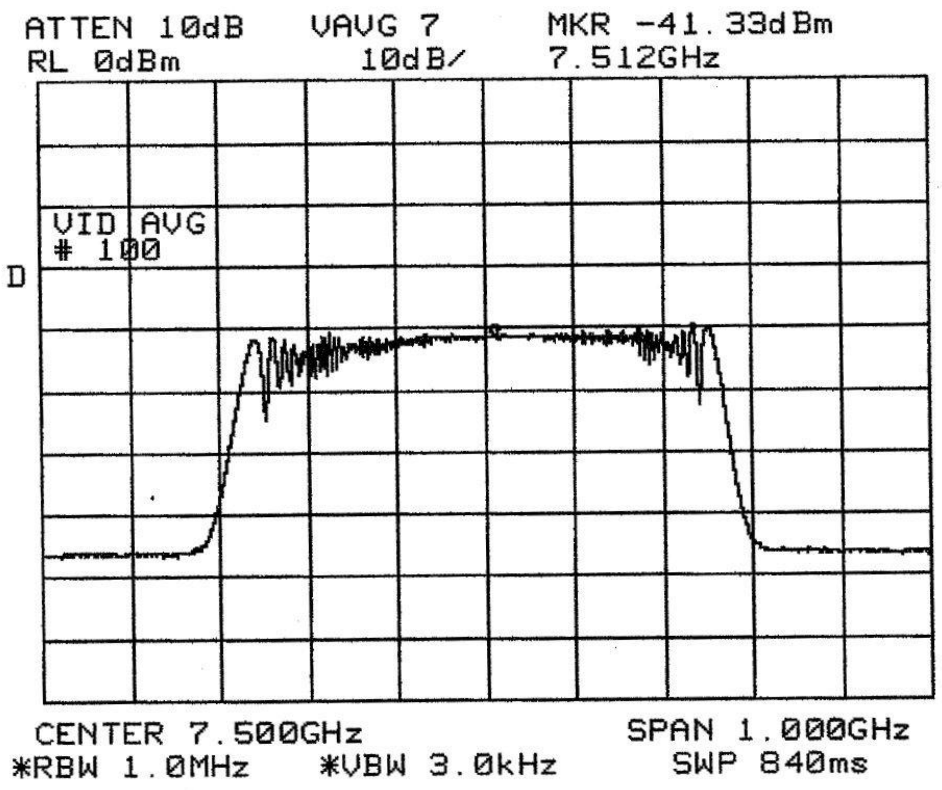


Figure 19: Measured transmitter output signal

Compliance with international regulatory limits for UWB signals is confirmed by measurements and FCC pre-certification for good coexistence worldwide.

3.7.2 Interference resistance

FM-UWB is an analog implementation of a spread-spectrum system. The various subcarrier frequencies can be seen as the analog equivalent of spreading codes. The receiver processing gain is equal to the ratio of RF and subcarrier bandwidth

$$G_{PdB} = 10\log_{10}\left(\frac{B_{RF}}{B_{SUB}}\right) = 10\log_{10}\left(\frac{2\Delta f_{RF}}{(\beta_{SUB}+1)R}\right) \quad (9)$$

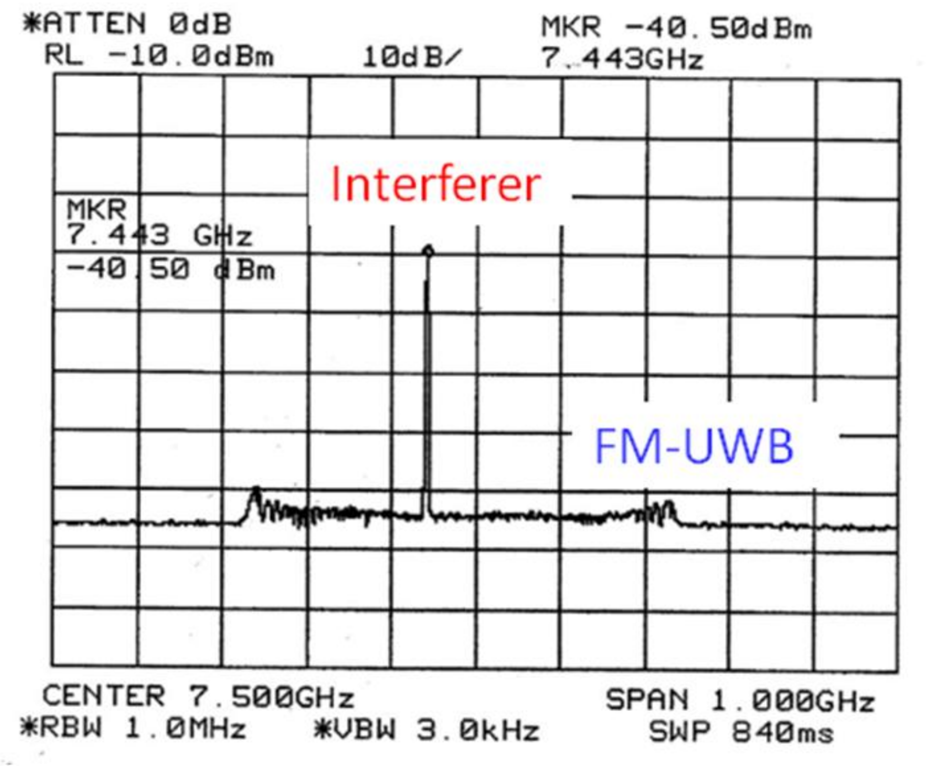


Figure 20: Illustration of FM-UWB in the presence of a strong narrowband interferer

Robust and reliable in the presence of interference

In a 250 kbps LDR system with a RF bandwidth of 500 MHz a processing gain of 30 dB is obtained. As a result a 250 kbps FM-UWB system can tolerate a 17 dB stronger FM-UWB interferer before the probability of error degrades to $1\text{x}10^{-6}$ [GER3].

Interference from in-band UWB users benefits from the receiver processing gain (Figure 20). Simulations indicate that Impulse Radio and MBOFDM interference up to 15 dB stronger than the FM-UWB signal degrades the probability of error to $1\text{x}10^{-6}$.

4 FM-UWB MAC

Medical body area networks can be used to collect periodic measurements performed by several sensor devices. This kind of application generates so called convergecast traffic in which most or all packets are sent to a powerful device able to process data locally, and possibly forward it to a medical overlay network. This is illustrated in Figure 21.

The network thus adopts the form of a single-hop or two-hops star topology. The traffic asymmetry is matched by the resources asymmetry between the sensors and the data collector.

The sensor devices must be small, easy to use, and long battery life is required. In these embedded systems, the power consumption is determined by the sensor power consumption and the use of the radio transceiver.

Solutions close to ideal power consumption have been developed for Ultra Low Power Medium Access Control. This proposal is based on the WiseMAC (Wireless Sensor MAC) protocol [ELHO]. It extends it to operate on multiple channels for increased robustness to interference and it defines a high availability mode to improve WiseMAC adaptivity to variations of traffic intensity and make better use of available energy resources.

This chapter is structured as follows. The Overview provides a description of the operation of the low power and of the high availability modes, the use of multiple channels, the detect-and-avoid mechanism and how to switch between the two modes. Section Network Architecture, Topology and Scalability reviews possible use cases and studies how the proposal meets topology and scalability requirements. Section Power saving modes and power consumption uses analytical power consumption models to evaluate the proposal and to compare it to ideality.

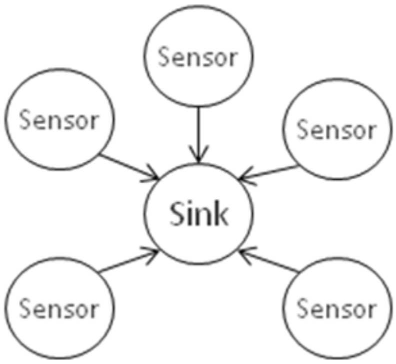


Figure 21: Convergecast traffic in a star topology network.

Star (and mesh) network topology supported

4.1 Overview

Energy waste in wireless communications occurs for the following reasons [ELHO]:

- *Idle listening:* listening to an idle channel to receive possible traffic.
- *Overhearing:* a node receives packets that are destined to other nodes.
- O*veremitting:* the transmission of a message when the destination node is not ready.
- *Collisions:* these occur when a receiver node receives more than one packet at the same time. All packets that cause the collision have to be discarded and retransmission of these packets is required.
- S*ignaling overhead:* the packet headers and the signaling required by the protocol in addition to the transmission of data payloads.

These problems are always due to the radio transceiver spending time in reception or transmission mode while it could be in sleep mode. Two strategies have been proposed in the literature to address these problems:

- *Scheduled access* protocols aim to reduce this waste by scheduling communications appropriately and rely on a network wide time synchronization mechanism. While this kind of approach has been successful in wired networks, the unreliability of the wireless channel makes it difficult to transpose to wireless communications.
- Random access protocols take into account the possibility of packet losses and let nodes compete for channel access.

4.1.1 Low Power Mode

To minimize idle listening, all network nodes spend most of their time in an ultra low power sleep mode. Each node periodically and independently wakes up every time interval *aWakeUpInterval*, performs a clear channel assessment on its channel, and goes back to sleep again if the channel is found idle. If the channel is found busy, the node keeps listening and attempts frame reception. If no frame is received, the node goes back to sleep. If a unicast frame is received and if its destination address matches the node address, an acknowledgement is sent back to the source node, piggybacking timing information on its next wake-up. Figure 22 illustrates the first packet exchange between two nodes.

Node 1 has a packet to send. It immediately starts transmitting a wake-up preamble whose length is equal to the wake-up interval so that all reachable nodes are aware of the incoming packet transmission. The wake-up preamble is followed by the packet itself. Node 2 acknowledges the packet and sends timing information to the source node 1. This timing information will allow node 1 to greatly reduce the wake-up preamble at the next packet exchange.

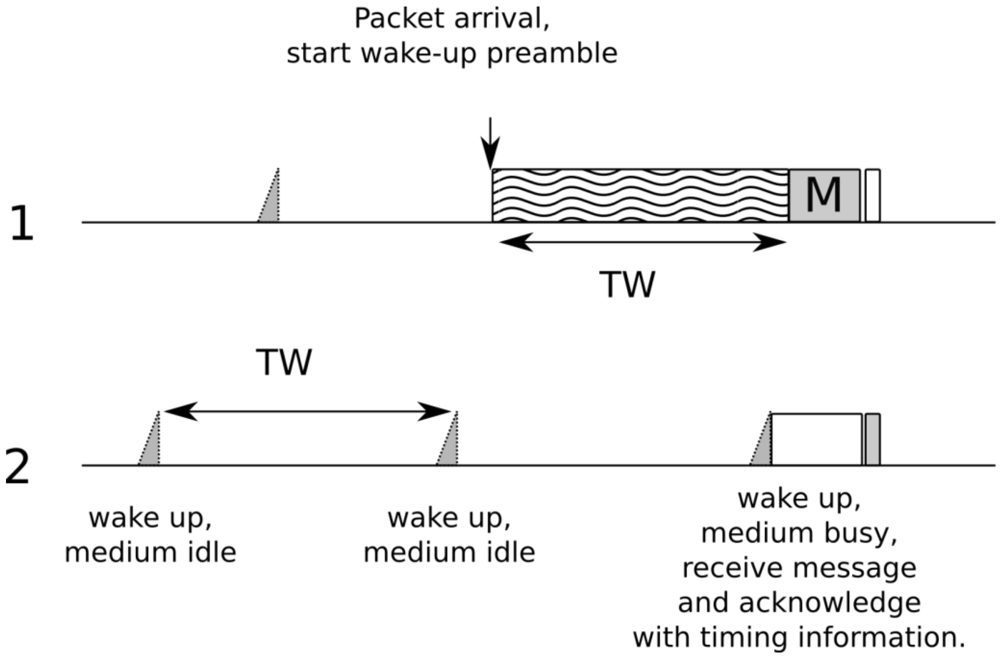


Figure 22: The WiseMAC low power mode uses the Long Preamble Listening mechanism at the first exchange.

Figure 23 shows a second packet exchange between the same two nodes. This time, node 1 does not send immediately its long wake-up preamble. Instead, it computes a minimal size for the preamble, and waits as long as possible before transmitting it. Again, node 2 receives the packet and acknowledges it, including some timing information.

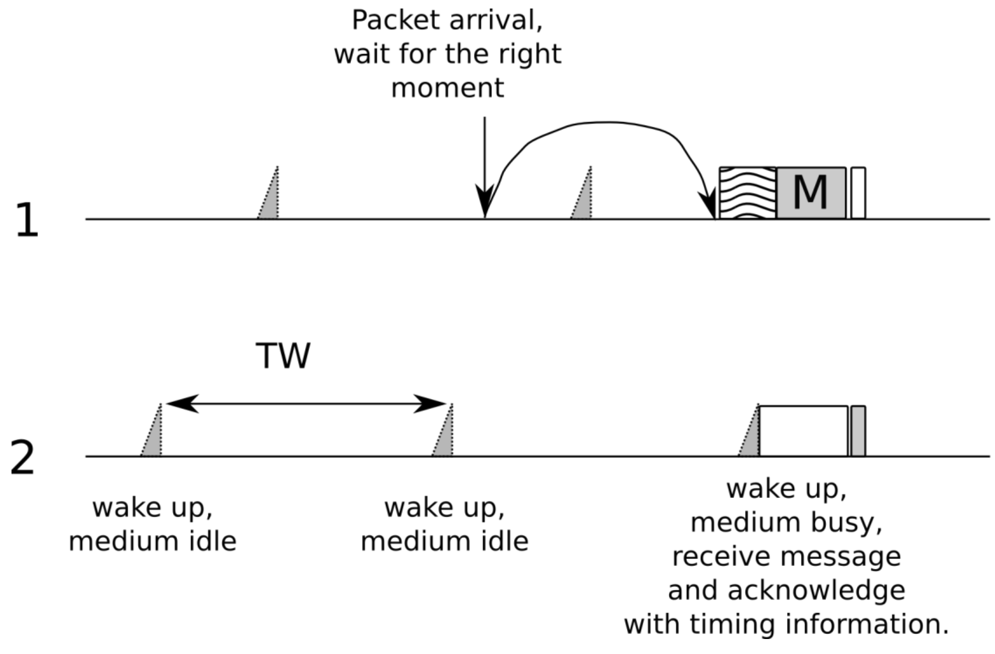


Figure 23: The WiseMAC low power mode saves energy by using a greatly reduced wake-up preamble length after the first packet exchange.

This saves energy at the transmitter since its transmission is shorter. It also saves energy at the destination node as it does not have to listen to a complete wake-up preamble. Additionally, it saves energy at neighbor nodes since they will suffer less from overhearing. Finally, it saves energy by reducing channel usage and thereby collisions. This, at the same time, improves reliability and reduces latency.

Figure 24 shows all these exchanges. Node 1 sends two packets to Node 2, and Node 3 overhears the first packet but not the second one. The timing information is indicated with the notation T*. The duration of the long wake-up preamble, indicated with the notation TW on the figures, is equal to *aWakeUpInterval*.

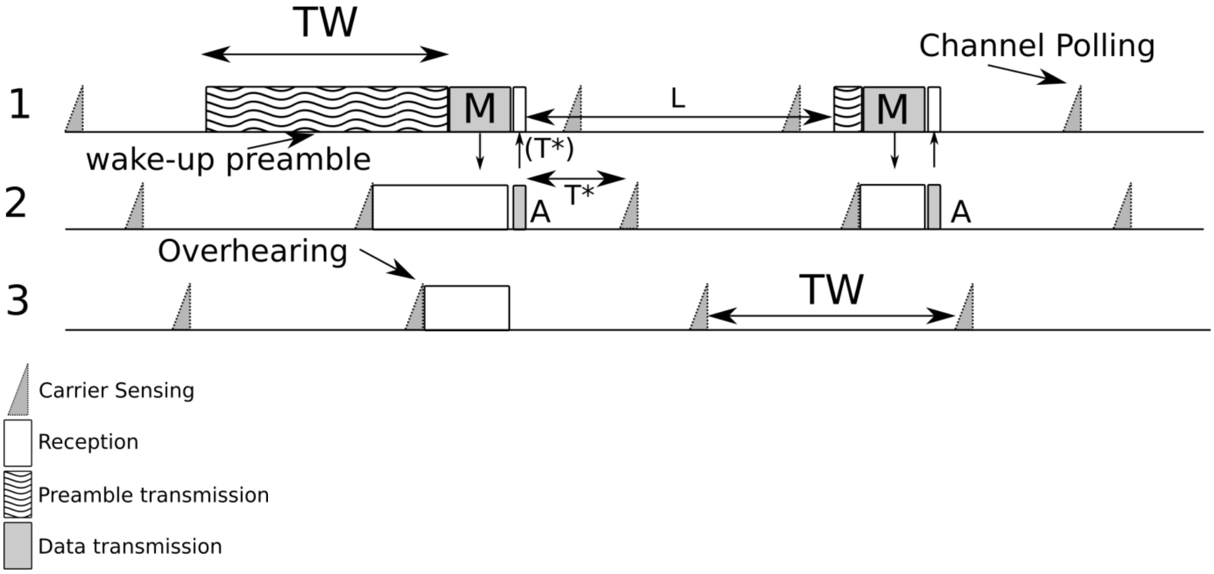


Figure 24: The WiseMAC low power mode for 3 transceivers.

The packet is sent just after the preamble and the source node then switches to reception mode and waits for an acknowledgement message. If it does not receive one, a counter *nbTxAttempts* is incremented and if it is lower than a parameter *MaxTxAttempts* a new transmission attempt will be made. If *nbTxAttempts* is equal to *MaxTxAttempts* the frame is dropped and the upper layer is informed of the transmission failure.

When an acknowledgement message is received, the timing information piggybacked in the message is saved in an associative array with the destination node address as key. This value allows the source node to predict the next wake-up times of the destination node and thus to reduce the length of the wake-up preamble. Due to the imprecision *Theta* of the quartz used, the prediction is not perfect and its precision degrades with time. In practice, the wake-up preamble length is computed with the formula

preambleLength = min(4 *Theta* L, *aWakeUpInterval*) where L is the time interval between the time at which the last acknowledgement was received from the destination node and the time at which the next packet arrives at the MAC layer.

The formula can be explained as follows. If all nodes were using the same absolute time reference, the wake-up preamble would be set to the smallest value detectable by the radio transceiver for all upcoming transmissions.

In practice, all nodes have their own time reference, of given imprecision Theta (in parts per million). This parameter tells us that after a time T, the value given by the time source will be between T(1-Theta) and T(1+Theta). The maximum relative clock drift is 2Theta since one of the time sources can be at the lowest possible frequency and the other at the highest possible frequency. After a time L, the time difference between the two clocks is between -2 Theta L and +2 Theta L. Hence the minimal length of the wake-up preamble at a time L after the last exchange is 4 Theta L. The wake-up preamble length should never exceed *aWakeUpInterval* since this value is large enough to reach all nodes, thus the complete expression is *preambleLength* = min(4 Theta L, *aWakeUpInterval)*.

For broadcast transmissions, a long wake-up preamble is always used. Figure 24 shows the states of three radio transceivers. Transceiver 1 sends two messages to transceiver 2. The first message is sent using a long preamble and the second with a reduced length preamble. Node 3 overhears the first transmission but not the second transmission thanks to the decreased channel use.

4.1.2 High Availability Mode

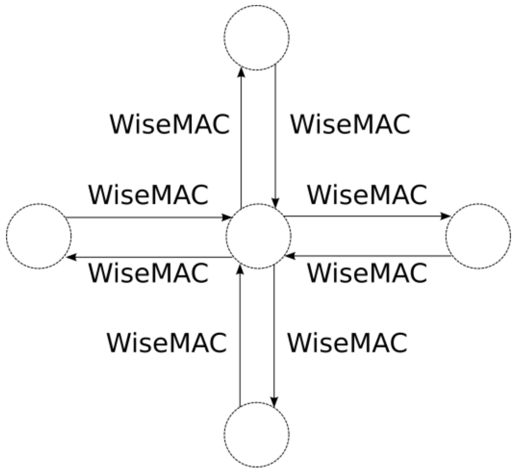
Since some devices can have more energy resources than others, it is tempting to make use of this additional energy to either further reduce the power consumption of energy limited sensors or to use this energy to increase the throughput and decrease the latency of the network.

Also, some low power network applications have two operation modes. The first mode is a low power, low duty-cycle monitoring mode, and the other one is an emergency or alert mode. While in the first case, power consumption is the main issue, in the latter case it does not matter anymore (for instance with fire detection systems) and all the remaining energy should be used to get the best possible performance in terms of latency and throughput. This way, all time-critical data packets reach their destinations as early as possible.

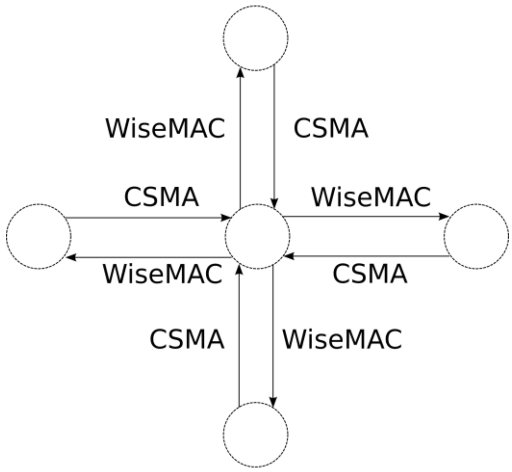
Both cases, heterogeneous networks and dual-mode applications, highlight the need for a high performance mode of the MAC layer. This mode should be interoperable with the low power mode, since in the case of the heterogeneous network these high performance communications should coexist with low power traffic between low powered nodes, and allow asymmetric operations on the same link (low latency in one way and low power in the other). The case of dual-mode applications highlight the requirement that a node should be able to switch between the two modes depending on the application’s current needs and on the state of the battery. Hence, a Carrier Sense Multiple Access (CSMA) mode (possibly the same as IEEE 802.15.4 non beacon enabled mode) is a reasonable choice as it does not impose regular signaling traffic (which would make coexistence of both traffic difficult). It also allows all nodes to switch independently to this mode, by signaling the mode change with a header flag in all data and acknowledgement packets sent by the node. And finally, it greatly decreases latency and substantially increases maximum throughput.

CSMA can be seen as a limit case of WiseMAC in which *aWakeUpInterval* tends to zero. For maximum flexibility and performance, the decision procedure for switching from one node to the other is not specified in this document. The application should take the decision and reconfigure the MAC layer appropriately.

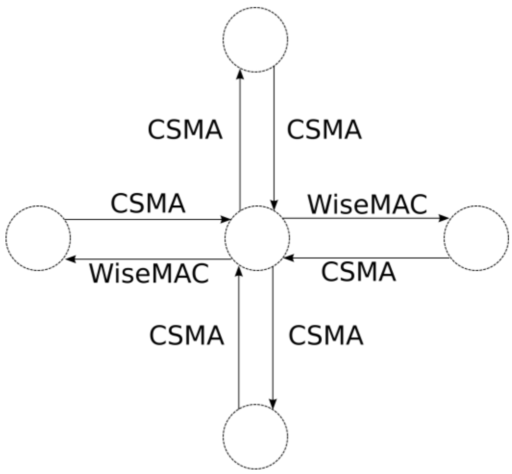
Figure 25 shows three possible configurations for a network of four sensor nodes and one data collector at the center. In Figure 25a, all links use the WiseMAC low power scheme.



a) Low power downlinks and uplinks.



b) Low power downlinks and low latency uplinks.



c) Low power downlinks and mixed low power and low latency uplinks.

Figure 25 : Possible network configurations

In figure 25b, the sink is high powered and thus it is able to keep its radio in reception mode all the time. This allows resource-constrained sensor devices to access the sink in CSMA mode, but the sink access the sensors with WiseMAC since the sensors must save energy.

Figure 25c shows a hybrid configuration in which the sink runs in CSMA mode and some sensors can also be accessed using CSMA. This can be the case for instance when the sink has a lot of traffic to send to a sensor device: all sensors nodes would always access the sink in CSMA, and the sensor would usually be accessed in WiseMAC mode, except when asked by the sink to switch to CSMA mode for high data rate communications. Another usage scenario for this mode is when some sensors are not resource constrained; they can always operate in CSMA mode.

4.1.3 Multiple Channels

In addition to saving energy, a low power MAC protocol must also deliver messages as reliably as possible. Hence, several mechanisms act at different levels to increase reliability. At the lowest layer, error detection and correction techniques are used to guarantee the integrity of the message and correct individual bit errors. When a message is incorrectly received or not received at all, it is not acknowledged and a retransmission procedure is triggered at the source node. When a node has a message to send, it contends for channel access to prevent collisions. If the channel is found busy, the node waits for some time and then retries.

As the traffic increases on a communication channel, it becomes more and more difficult to get access to the medium: the channel will be found busy more often. Collisions will also happen more frequently. These two factors both increase the latency, and the last one also decreases the system's reliability. From an energy viewpoint, an increase of traffic leads to overhearing and collisions, which both increase the power consumption. Therefore, switching to another communication channel is interesting both for performance reasons as latency and reliability will both be improved, and for power consumption reasons as it decreases overhearing and collisions.

A device should select a communication channel on which to perform its periodic carrier sensing at random during its initialization time. When a device has a packet to send, it will send it with a long preamble and wait for an acknowledgement message on each channel. If it does not receive an acknowledgement, it will switch to another channel and send the message with a long preamble again.

The procedure ends when the source node receives an acknowledgement packet or if it has sent the packet on all channels without receiving any acknowledgement. If an acknowledgement packet is received, the channel on which it was received is stored in memory along with the timing information on the next wake-up interval.

Figure 26 illustrates this process with node 1 sending a first packet with a long preamble on channels 1, 2 and 3. It times out for the acknowledgement on the first two channels but receives one on channel 3, along with the timing information on node 2's next channel polling. Node 1 then uses this information to reduce the wake-up preamble to a minimum size for the next packet.

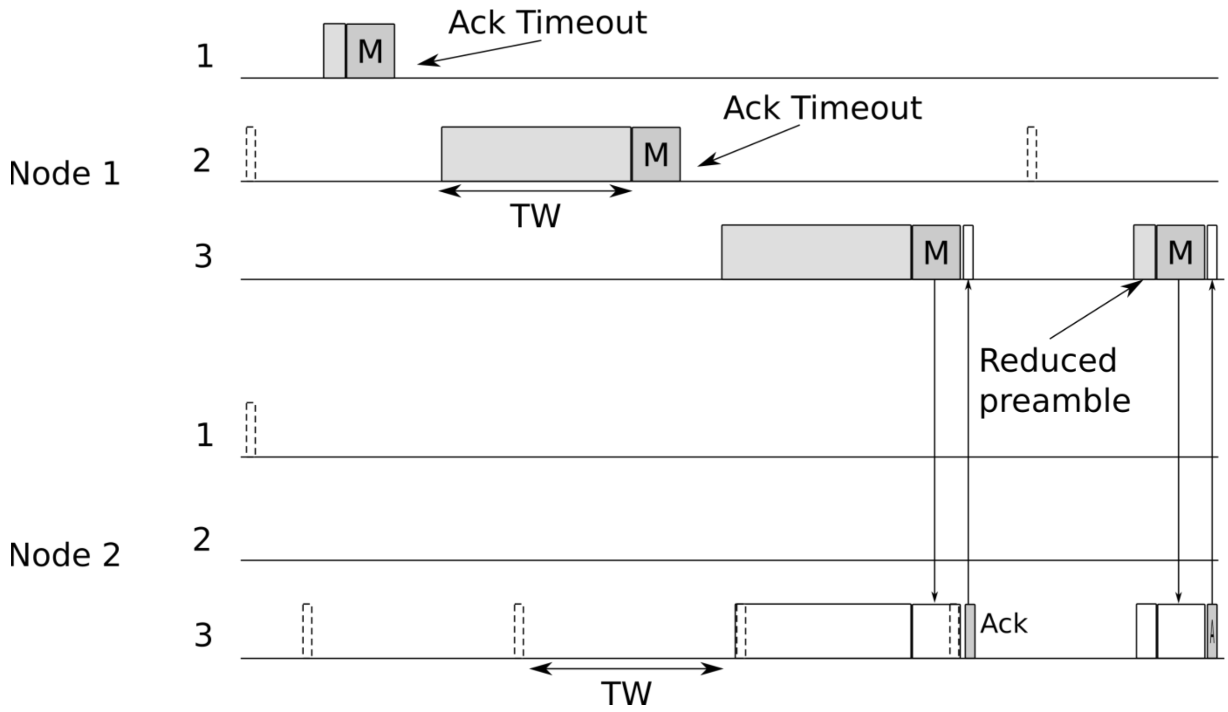


Figure 26: Operation over multiple channels.

4.1.4 Detect-and-Avoid

The operation over multiple channels allows to further increase reliability and lower power consumption. If a device often wakes up to receive invalid frames or to overhear frames, it can switch to another, less used, channel. This solves two problems:

1) it balances channel use on all available channels when traffic increases, reducing overhearing and latency, and increasing fairness,
2) it allows the system to deal with wideband or narrow band interferers, by switching to a communication channel at a different frequency.

When a node switches to another communication channel, the other nodes are not aware of this change. They will continue to address the node on its old channel. However, they will deduce from the lack of an acknowledgement message that the destination node is not receiving the messages anymore. After some retries, up to *maxAckLossesBeforeRediscovery* retransmission attempts on the same communication channel, a rediscovery procedure is initiated. It is the same procedure used when the source node doesn't know the destination node's channel. The message is sent with a long preamble on each channel, until an acknowledgement message is received.

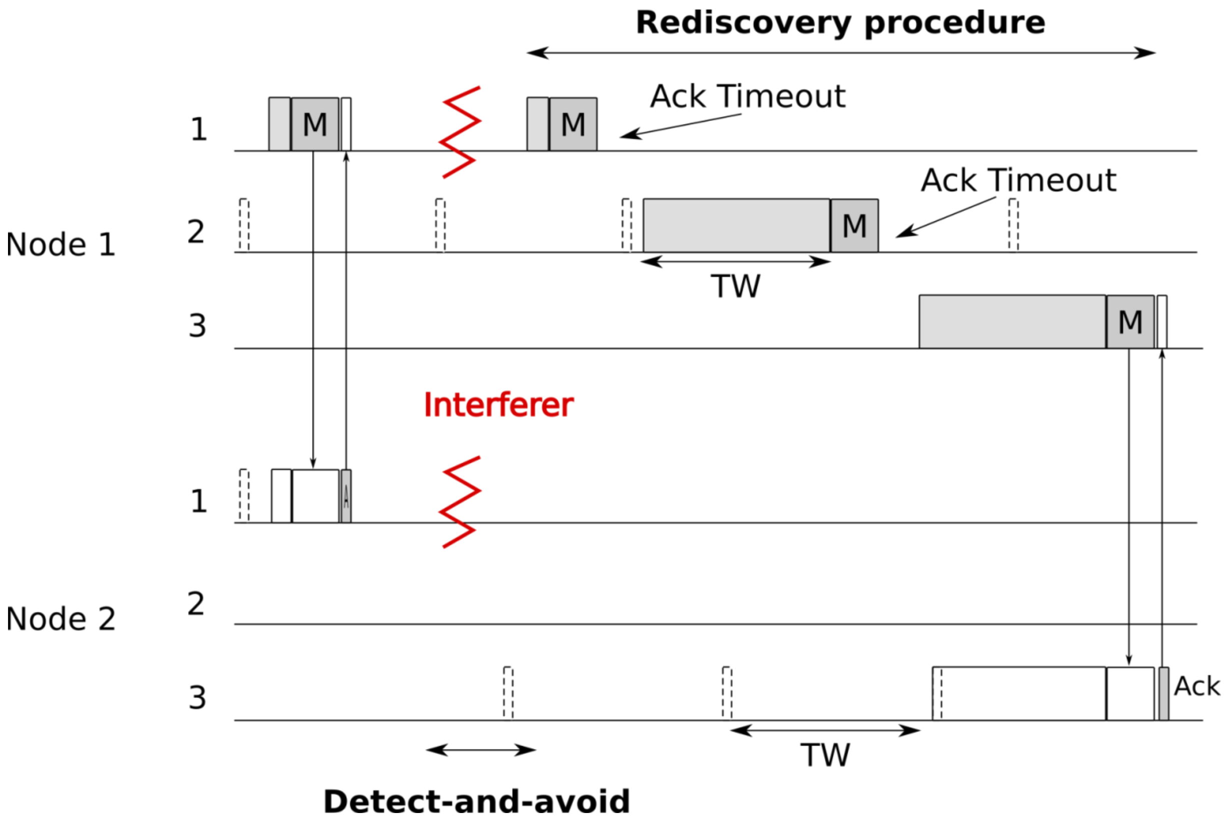


Figure 27: Detection and Avoidance of interferers.

Figure 27 shows node 1 initially sending messages with short preambles to node 2 which is on channel 2. After some time, an interferer appears on channel 1 and node 2 detects it. It switches to channel 3. Node 1 does not receive an acknowledgement message (on this illustration *maxAckLossesBeforeRediscovery* is set to 1 for clarity), and begins sending long preamble packets on each channel. After reaching channel 3, node 1 receives the acknowledgement from node 2 and records the new channel number.

4.2 Network architecture, topology and scalability

Data collection in a star topology network is the main application currently envisioned. However, the solution should avoid introducing single point of failures in the systems since they prevent achieving high levels of reliability.

Due to the low transmission levels authorized by the regulations and required to meet health and safety concerns, multiple hop networks must be supported. In addition, mesh network applications in which all nodes send and receive equally as much data should also be possible.

Networks should scale to e.g. tens of sensor nodes. Multiple independent networks should be able to operate simultaneously as body area networks are by essence mobile, making nodes density hard to predict.

- WiseMAC-HA supports equally well star and mesh topologies, both with low power consumption. This has been demonstrated in real-world deployments lasting several years.
- Scalability is not an issue as the protocol only requires local information exchanges. There is no network wide signalling traffic. Multiple hops communications are supported without any special mechanism (such as synchronization of signalling traffic).

4.3 Power saving modes and power consumption

WiseMAC power consumption can be calculated by starting from a detailed radio model with transition states as shown in Figure 28. This model has three steady states:

- sleep mode (Sleep),
- transmission mode (Tx)
- reception mode (Rx)

as well as four transition states:

- setup Transmission (SetupTx),
- setup Reception (SetupRx),
- switch from transmission to reception (SwitchTxRx)
- switch from reception to transmission (SwitchRxTx).

All transitions to sleep mode are considered instantaneous. The time spent in a transient state is a constant and noted T_State and the energy cost of transiting by this state is noted E_State. The power consumption values in the steady states are noted P_State.

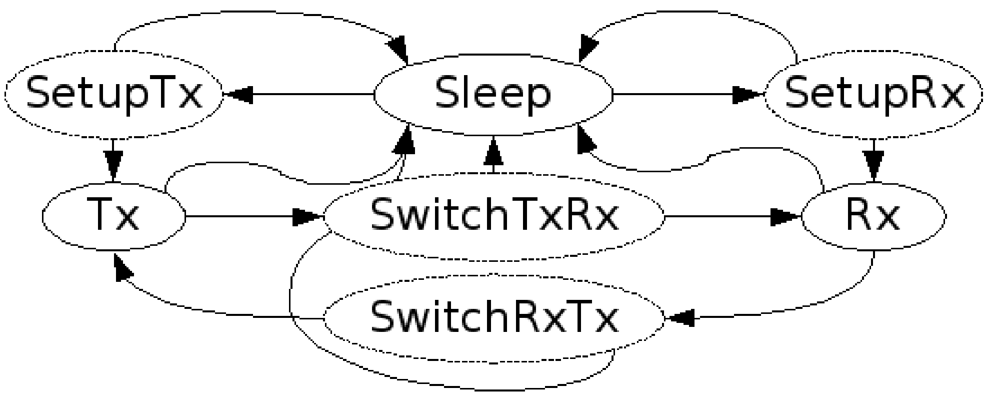


Figure 28: Radio states model.

4.3.1 Store-and-Forward

As illustrated in 31 each node receives and forwards one data packet on average every L seconds and the traffic is distributed according to a Poisson process (of parameter L). This kind of traffic occurs in multi-hop networks.

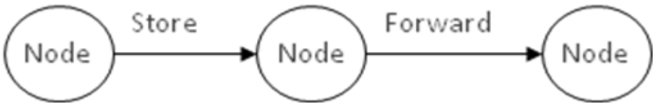


Figure 29: Store-and-Forward configuration.

The probability of receiving k packets during one second is given by:

$$P(X=k)=e^{-\lambda}\frac{\lambda^k}{k!} \tag{10}$$

The power consumption of the ideal protocol, a lower bound on all possible MAC protocols as it considers only the costs of receiving and forwarding packets without overhead, is given by:

$$\overline{P_\lambda^{Opt}}=\frac{1}{L}\left[(P_{TX}+P_{RX})T_M+E_{SetupTx}+E_{SetupRX}+P_Z\left(L-2T_M-T_{SetupRx}-T_{SetupTx}\right)\right] \tag{11}$$

The power consumption of WiseMAC can be computed as follows. During a period *aWakeUpInterval*=T_W, on average a node must perform one clear channel assessment, receive TW/L packets, send TW/L packets, and sleep the rest of the time. The energy cost of these four tasks is given respectively by E_{CCA}, E_{Recept}, E_{Trans} and E_Z.

$$P=\frac{1}{T_W}\left(E_{CCA}+\overline{E_{Recept}}+\overline{E_{Trans}}+\overline{E_Z}\right) \tag{12}$$

$$E_{CCA}=P_{RX}T_{CS}+E_{SetupRx} \tag{13}$$

$$\overline{E_{Recept}}=\frac{T_W}{L}\left[P_{RX}\left(\overline{T_{LP}}+T_M\right)+E_{SetupTx}+P_{TX}T_{Ack}+(N-2)P_{RX}\overline{T_O}\right] \tag{14}$$

$$\overline{E_{Trans}}=\frac{T_W}{L}\left[E_{SetupTx}+P_{TX}\left(\overline{T_{MR}}+\overline{T_{CDC}}+T_M\right)+E_{SwTxRx}+P_{RX}T_{Ack}\right] \tag{15}$$

$$\overline{E_Z}=P_Z\begin{bmatrix}T_W-T_{SetupRx}-T_{CS}-\frac{T_W}{L}\left(T_{LP}+T_M+T_{SetupTx}+\overline{T_{Ack}}+(N-2)\overline{T_O}\right)\\-\frac{T_W}{L}\left(T_{SetupTx}+\overline{T_{MR}}+\overline{T_{CDC}}+T_M+T_{SwTxRx}+T_{Ack}\right)\end{bmatrix} \tag{16}$$

$$\overline{T_{MR}}=\frac{W_R-1}{2}T_{Slot}$$

$$\overline{T_{CDC}} = 2\Theta L\left(1 - e^{\frac{-T_W}{4\Theta L}}\right)$$

Figure 30 compares the power consumption of various MAC protocols as a function of traffic intensity when running on a Texas Instruments CC 2420 radio transceiver. The following assumptions were made with respect to Figure 30:

- 20 nodes
- 50 bytes data packets
- 4 bytes acknowledgement packets
- Quartz precision of 30 ppm
- 250 kbps radio bit rate
- Power consumption in reception mode: 8 mW
- Power consumption in transmission mode: 4 mW
- Power consumption in sleep mode: 60 μW
- WiseMAC wake-up interval TW: 500 ms
- The other MAC protocol parameters are chosen such that they offer an average latency similar to WiseMAC's latency (TW/2, or 250 ms).

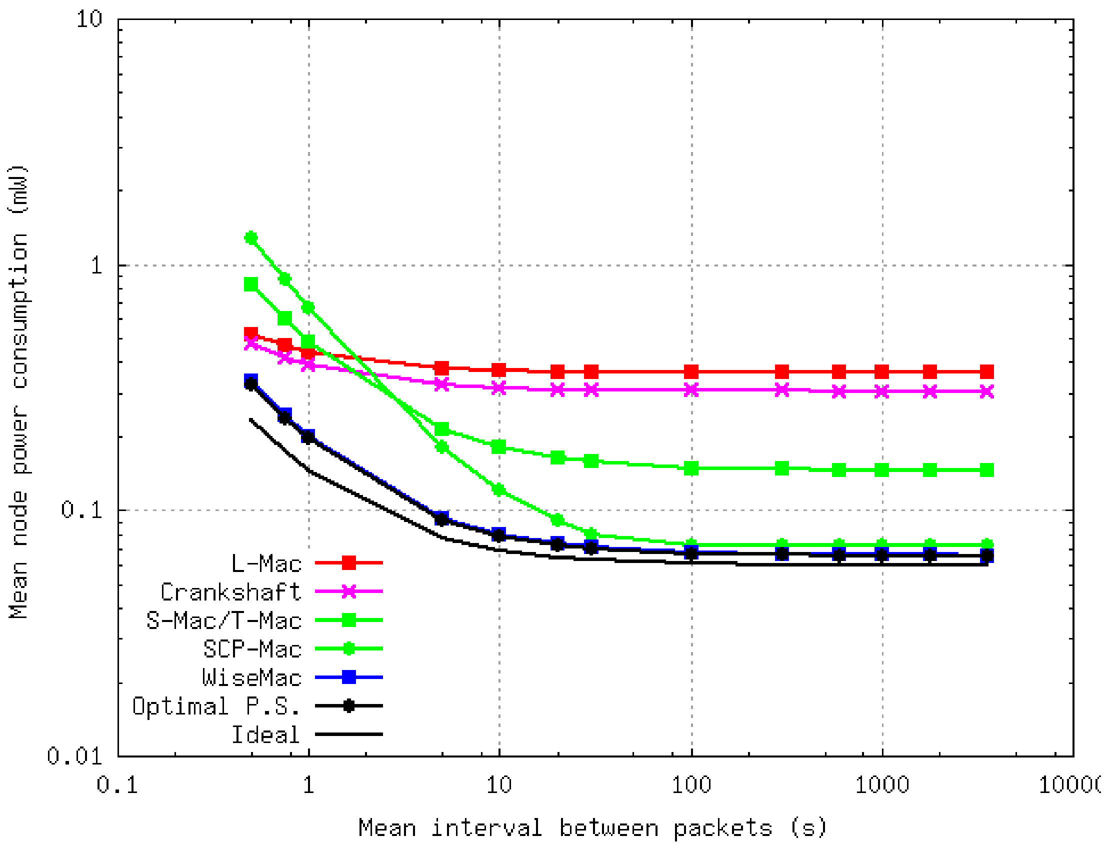


Figure 30: Comparison of power consumptions in a store and forward scenario based upon the FM-UWB radio.

The ideal power consumption is shown in black at the bottom of the figure. L-MAC and CrankShaft, two distributed TDMA protocols, are at the top of the figure. S-MAC, T-MAC and SCP-MAC perform better, but are outperformed by WiseMAC and other preamble sampling-based protocols (such as X-MAC, CSMA-MPS, SyncWUF). This data enables qualitative evaluation of the WiseMAC low power mode of this proposal.

4.3.2 Convergecast Traffic

The models presented in the previous section can be adapted to evaluate sensor and sink power consumption for the case of convergecast traffic and 802.15.4 CSMA, WiseMAC and S-MAC protocols. CSMA power consumption is given by:

$$\overline{P_{CSMA}^{sensor}} = \frac{N}{L}\left(P_{RX}T_{Ack} + E_{SwTxRx} + P_{TX}T_{M}\right) \qquad (17)$$

$$\overline{P_{CSMA}^{\sin k}} = \frac{N}{L}\left(P_{TX}T_{Ack} + E_{SwRxTx} + E_{SwTxRx}\right) + P_{RX}\left[1 - \frac{N}{L}\left(T_{Ack} + T_{SwRxTx} + T_{SwTxRx}\right)\right] \qquad (18)$$

Figure 31 shows the power consumption of a sensor and of the sink as a function of traffic intensity (number of packets emitted by the sensor per second), for CSMA, S-MAC and WiseMAC. A small network of five sensors and one sink is considered, each data packet carries 16 bytes of data, and each acknowledgement packet is 4 bytes long. The radio modeled here is an FM-UWB radio transceiver using 4 mW in transmission mode and 8 mW in reception mode, and all communications occur on the same subcarrier operating at 250 kbps.

The gray areas are zones impossible to reach since they are below the ideal lower bound. The dark gray area (below the gray line) concerns the ideal power consumption of the sensor and the light gray area (below the black line) concerns the sink.

The top red line shows the power consumption at the sink in CSMA mode, which is almost equal to the power consumption in reception mode as the radio transceiver leaves this mode only to send acknowledgement messages. When a sensor accesses a sink in CSMA mode, the sensor's power consumption decreases slightly compared to WiseMAC because of the absence of a wake-up preamble. This is shown by the second red line ("CSMA – sensor").

The two green lines show the sink and sensor power consumption when using S-MAC, and the power consumption in the low power WiseMAC mode is shown in blue.

The sink's power consumption in WiseMAC mode is limited in traffic rate: it stops when the sink receives on average one packet per sleep interval. In reality the sink can continue to operate with higher packet rates but latency will greatly increase: as nodes will often compete for sink access, once a node wins the contention phase it will send all its waiting packets to the sink by making use of the more bit feature of WiseMAC. The results on latency from Figure 32 confirm this point.

1

Figure 31: Sensor and sink power consumption for various protocols in convergecast traffic using the FM-UWB radio.

The switching condition between the two modes (low power WiseMAC mode and High Availability CSMA mode) of the WiseMAC-HA protocol can be derived from this graphic according to the system's required operating life: for instance, a very long operating life on battery excludes any switch to the high speed CSMA mode. The same assumptions were made for Figure 31 as for the case of Figure 30:

4.4 Latency

The average latency is an important system parameter, especially for medical body area networks and other highly reactive systems. The latency that can be obtained in each of the two modes, CSMA and WiseMAC, can be evaluated with a simple queuing model if we ignore buffer size problems and assume instead infinite capacity at each node. With a Poisson arrival distribution, the system can be approximated as an M/D/1/infinity queuing system. The expected delay for such a system is given by:

$$E[Delay] = \frac{1}{\mu} + \frac{\rho}{2\mu(1-\rho)} \tag{19}$$

where $\rho = \frac{\lambda}{\mu}$ is the traffic intensity and $\lambda = N\lambda_s$ is the aggregate packet arrival rate (traffic generation). The service time, i.e., the time to transmit the packet on the channel and receive the acknowledgement, for the CSMA and the WiseMAC mode is given by

$$\mu_{CSMA}^{-1} = T_M + 2T_{SIFS} \tag{20}$$

$$\mu_{WiseMAC}^{-1} = \frac{T_W}{2} \tag{21}$$

Figure 32 shows the average latency for the low power mode WiseMAC and the High Availability mode CSMA. The considered network has a star topology with one sink and a number of sensor devices between 5 and 256. The following assumptions were made:

- Data packets of 16 bytes
- Acknowledgement packets of 4 bytes
- Synchronization preamble of 500 µs
- WiseMAC wake-up interval TW of 200 ms
- 250 kbps radio bit rate
- All traffic takes place on the same FM-UWB subcarrier
- Radio setup times (Rx and Tx): 1 ms
- Radio switching times: 0.1 ms
- CSMA minimum Backoff exponent: 2

- CSMA backoff period length (aUnitBackoffPeriod): 1 ms
- Clear Channel Assessment duration: 0.1 ms
- Short InterFrame Space time (SIFS): 0.11 ms

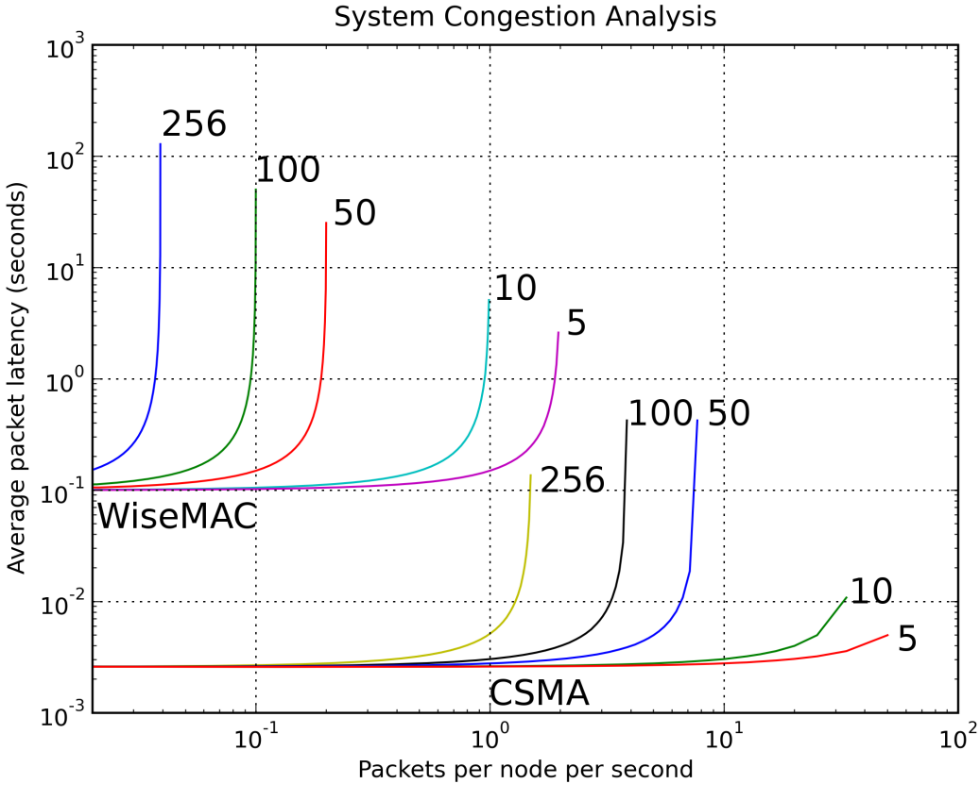


Figure 32: WiseMAC and CSMA average latencies on a single FM-UWB subcarrier (5 to 256 sensors,1 packet per 100 seconds per sensor to 10 packets per second per sensor).

Scalable to 256 or more sensor devices (traffic limited), less than 125 ms delay (traffic and MAC dependent)

In all cases, CSMA decreases latency by more than one order of magnitude compared to WiseMAC. This allows for adequate switching between the two modes depending on network size, traffic intensity and latency requirements. For each case, latency remains stable over a wide range of traffic and finally increases quickly with the traffic intensity. This zone is unstable and should be avoided.

4.5 Mobility support

Medical body area networks are mobile by nature. Several independent networks must be able to coexist in the same room without significant performance degradation. WiseMAC-HA, both in its low power mode WiseMAC and in its High Availability mode CSMA, offers various mechanisms to maintain communications when multiple networks share the same radio spectrum.

WiseMAC and CSMA are both contention based: by monitoring channel usage before transmitting, they can reduce collisions with independent networks. This allows operation of several networks as long as they have low bandwidth requirements. If channel usage increases, packet loss will increase and after some time, the system will automatically switch to another channel (frequency band or FM subcarrier) thanks to its Detect-And-Avoid mechanism.

Mobility support provided by the MAC protocol

4.6 Framing, CRC and retransmissions

The retransmission mechanism is similar to the IEEE 802.15.4 non beacon enabled mode. Concerning framing, the protocol does not have special requirements that would constrain the packet size. Limitations could come from the size of available buffer memory on a system that should be as cheap as possible.

The MAC protocol does not make particular requirements for the addressing space. It only requires setting the source and destination addresses in both data and acknowledgement packets. It should be noted however that for low data rate systems, address fields should not be too large. Or else, the transmission and reception of these addresses will have an impact on power consumption, when considering small packet sizes.

5 Proof of concept and target solution

This section presents measurement results for a 7.5 GHz FM-UWB transceiver prototype realized in the MAGNET Beyond project [MAGB]. Figure 33 depicts the transceiver prototype with bowtie antenna [KIM] and Figure 34 shows the functional components. In total 5 prototypes have been manufactured. Measurement results obtained in prototype testing are provided in Table 8. One of the prototypes is currently in FCC pre-certification.

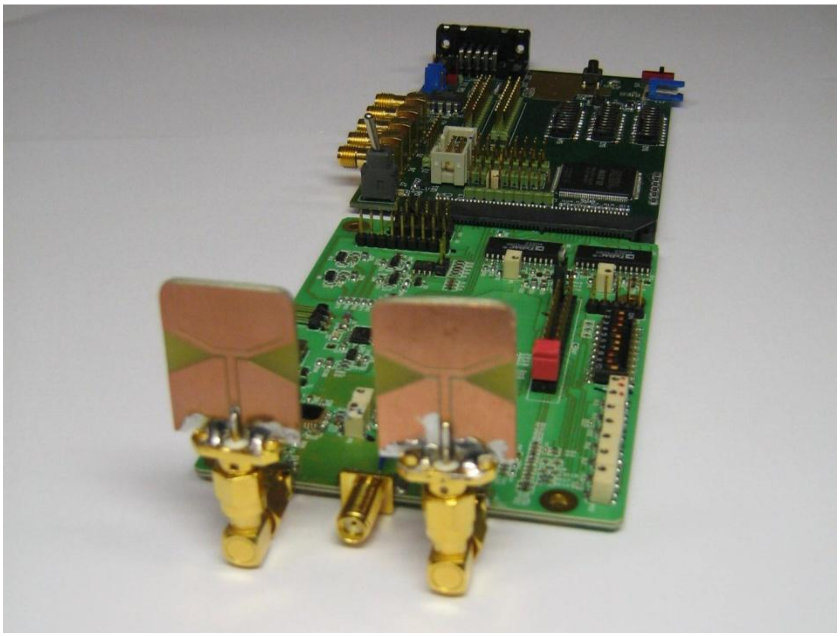


Figure 33: FM-UWB transceiver prototype with antenna.

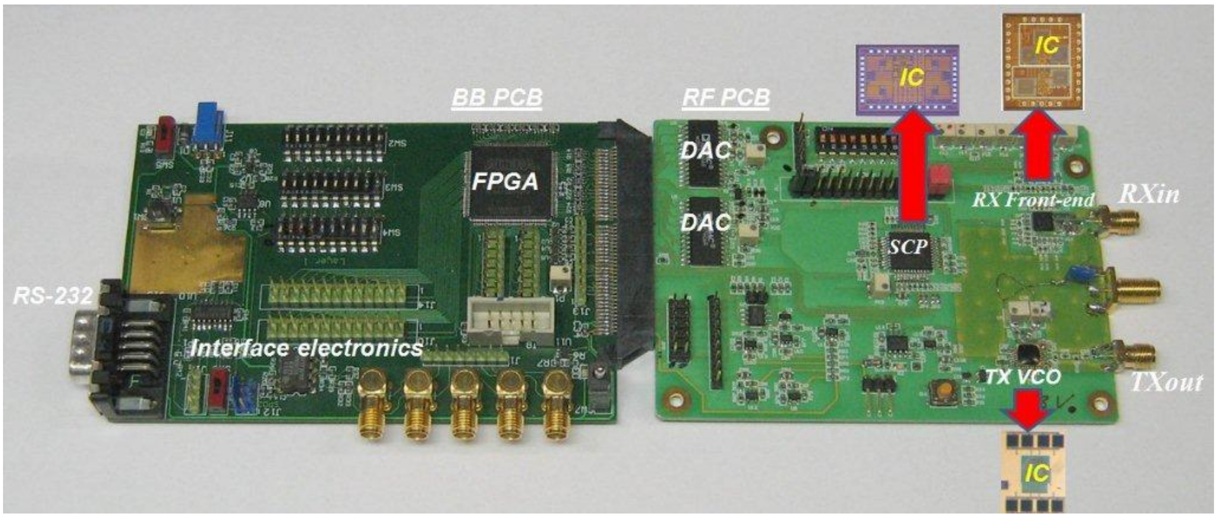


Figure 34: Illustration of the prototype showing functional blocks.

Real working hardware and software

Table 8: Measured FM-UWB transceiver performance (first generation prototype)

Parameter	Value
RF center frequency	7.5 GHz
RF bandwidth	500 MHz
RF output power	-15 dBm
Subcarrier frequency	1- 2 MHz
Subcarrier modulation	FSK, β = 1,
Raw bit rate	31.25, 62.5,125 and 250 kbps
Receiver sensitivity (BER ≤ 10^{-6})	-85 dBm
TX, RX switching time	200 μs
Latency (at PHY level)	150 μs
RX synchronisation time	≤ 400 μs @ 62.5 kbps
Current consumption RX	15 mW
Current consumption TX	5.5 mW

5.1 Power consumption

The hardware implementation for FM-UWB is potentially low power and low cost. Phase noise requirements for the transmitter VCO are relaxed (typically -80 dBc/Hz at 1 MHz offset) and the digital subcarrier generation and constant-envelope RF signal allow for a low supply voltage in the transmitter. A first generation of dedicated integrated circuits has been designed in 0.25 μm SiGe:C BiCMOS technology, manufactured and evaluated.

Figure 35 is a photograph of the receiver front-end chip [ZHAO]. It comprises a 21 dB gain preamplifier and a 1GHz bandwidth FM demodulator. The measured overall receiver sensitivity is -85 dBm (BER ≤ 10^{-6}) and the front-end consumes 9 mW from a 1.8 V supply. A sensitivity of -82 dBm is achieved at 6 mW power consumption. Measured power consumption values of the overall FM-UWB radio prototype are 5.5 mW for the transmitter and 15 mW for the receiver. An overview is provided by Table 9 for a 7.5 GHz transceiver implementation.

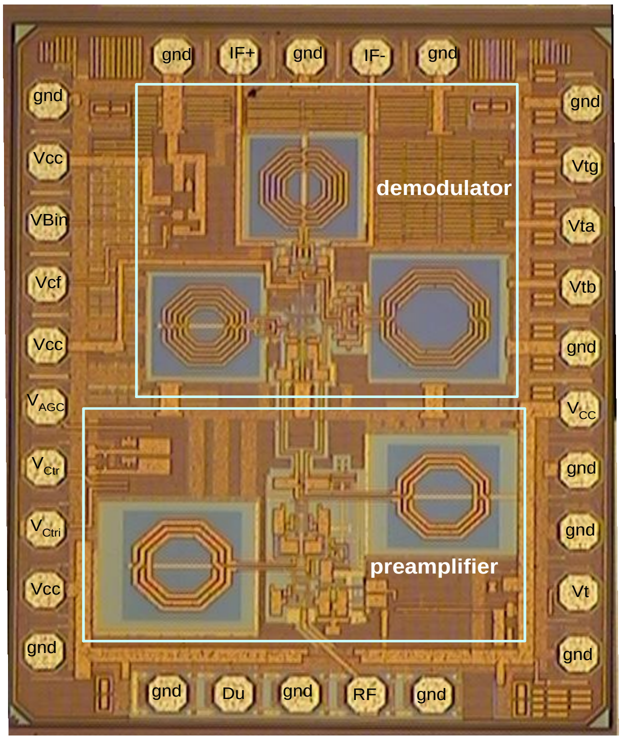


Figure 35: Die photo of the front-end test chip

Table 9: Power consumption of first generation FM-UWB transceiver

Parameter	Value
Transmitter P_{TX}	**5.5 mW**
• RF VCO	2.5 mW
• RF Output stage	2.0 mW
• DDS	1.0 mW
Receiver P_{RX}	**15 mW**
• Low Noise Amplifier	5 mW
• Wideband FM Demodulator	4 mW
• Subcarrier processing	5 mW
• DDS	1 mW

Ultra-low power UWB implementation on target to achieve, P_{TX} ≤ 4 mW and P_{RX} ≤ 8 mW (continuous operation) for a fully integrated solution

It should be noted that the numbers mentioned for the receiver correspond to maximum receiver sensitivity, which is not needed 100% of the time. Lowering the receiver sensitivity also lowers power consumption. By sacrificing 3 dB of receiver sensitivity, a power consumption of 12 mW has been obtained. Based on current results, it is the expectation of the authors that the second generation of FM-UWB ICs will meet the target values of $P_{TX} \leq 4$ mW and $P_{RX} \leq 8$ mW.

5.2 Bit Error Rate and Packet Error Rate

The results of wired BER measurements made on 4 different receiver prototypes are shown in Figure 36. The black solid line is the analytical reference curve for FM-UWB modulation. The colored dashed lines represent the measurement results. Measurement time for the lower BER values was 4 minutes, this corresponds to 4 x 60 x 50,000 = 12 million transmitted bits. Measurement time for the lower BER values was 4 minutes, this corresponds to 4 x 60 x 50,000 = 12 million transmitted bits.

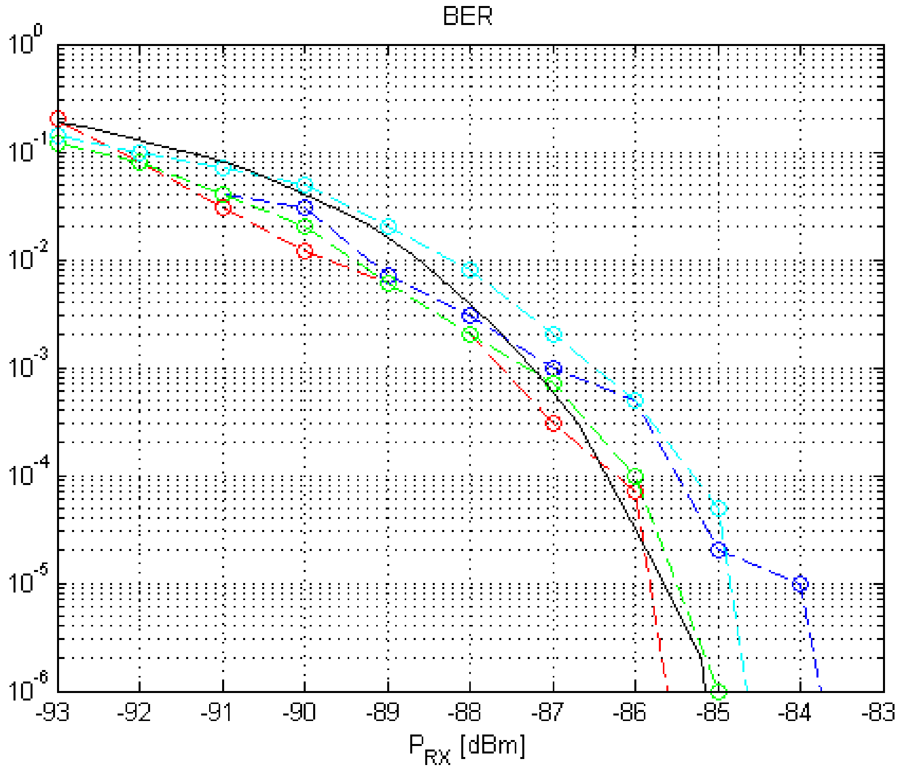


Figure 36: BER measurements made on 4 receivers.

BER ≤ 10^{-6} (PER ≤ 10%) measured at approximately -85 dBm receive power level

From these results it can be concluded that the FM-UWB receiver sensitivity is about -85 dBm (BER ≤10^{-6}), which is more than sufficient to support a Packet Error Rate (PER) of less than 10% (i.e., for a 256 octet packet). All four receivers showed very similar performance in testing. Additionally, receiver sensitivity can be further increased e.g. by increasing LNA gain.

5.3 Transmission range

Next, the transceivers were equipped with antennas. Propagation experiments were next carried out in a laboratory environment (Figure 37) of size 12 x 5 meters and a cafeteria of size 20 x 10 m (Figure 38:). Propagation in these environments is predominantly line of sight (LOS). The laboratory has lots of metallic objects that create multipath fading, the cafeteria is a more an open space.

A first transceiver board is used as transmitter and a second one as receiver. At various distances, the link margin is measured by inserting additional attenuation (implemented by a variable attenuator) between the receiver antenna and receiver until the receiver no longer correctly receives the messages sent.

Results are shown in Figure 39: from which it can be seen that the link margin in the laboratory environment is about 5 dB higher than in the cafeteria. This is probably caused by the strong multipath occurring in the laboratory. The slope of the curves corresponds to a path loss exponent of about 2. The range that could be covered in the cafeteria is almost 20 meters. The laboratory wasn't big enough to reach the system's limits.

5.4 Security

Dependent on security requirements, the FM-UWB PHY-MAC may be used with low complexity security protocols, such as those employed in IEEE802.15.4.

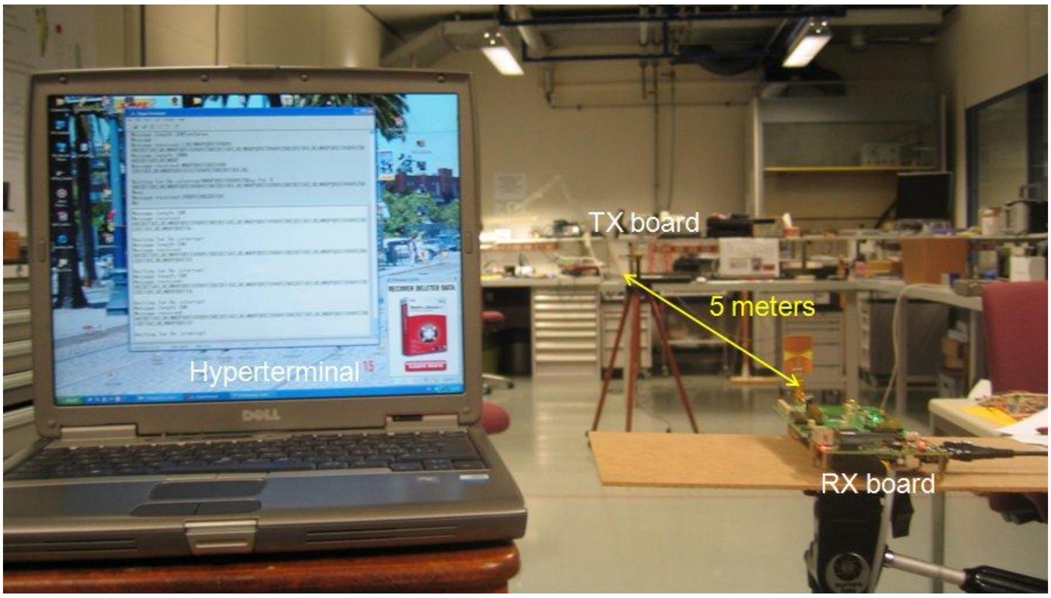


Figure 37: Over the air measurements in laboratory environment.

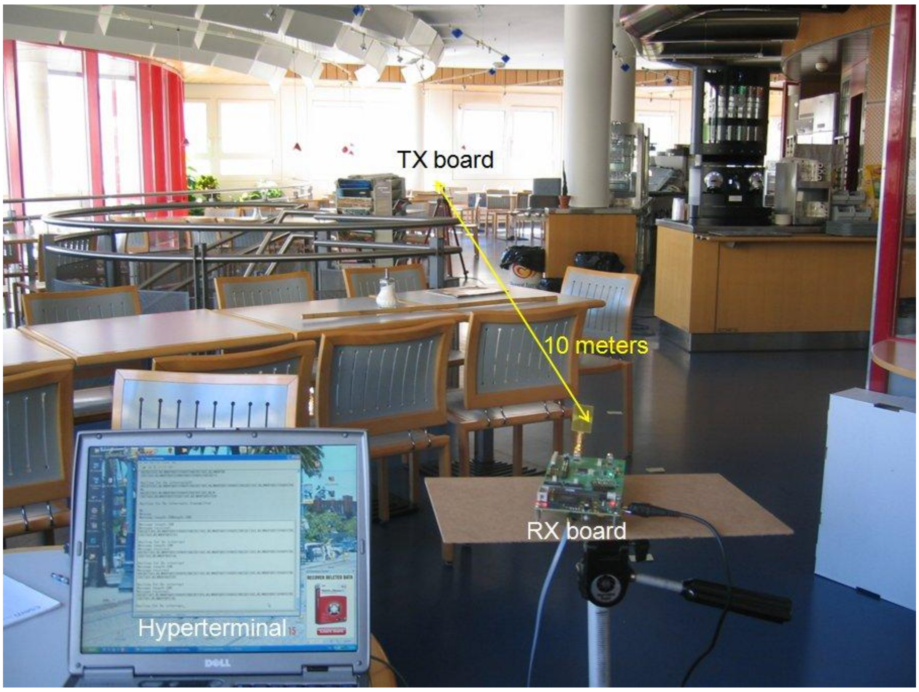


Figure 38: Over the air measurements in the cafeteria

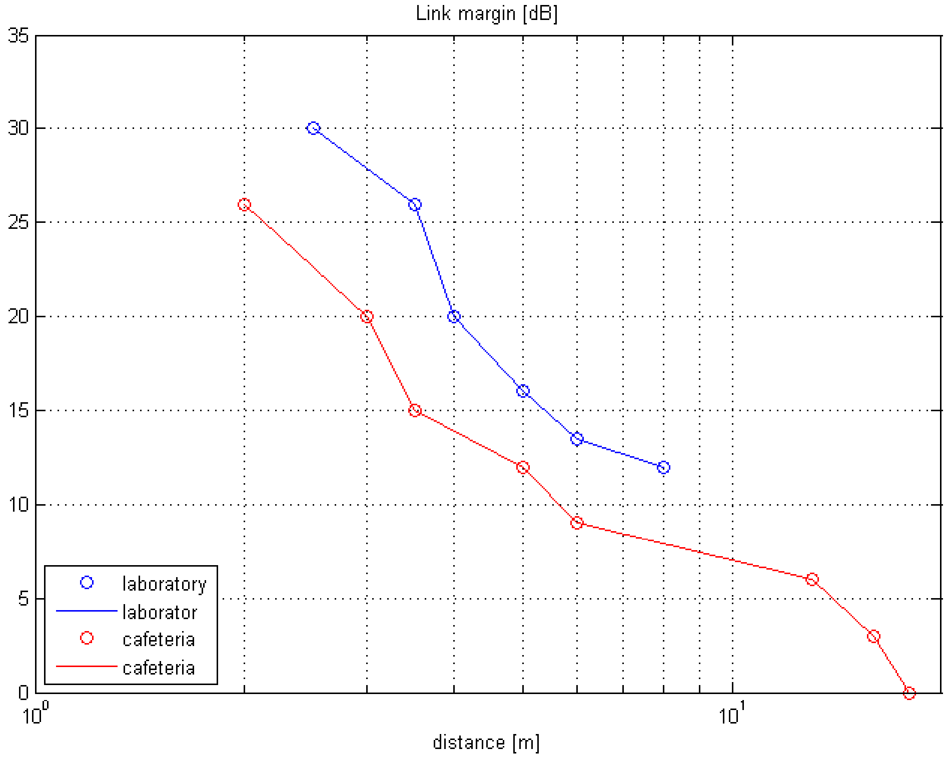


Figure 39: Measured link margin in laboratory and cafeteria environment

Transmission range tested to 20 m

6 Compliance with BAN requirements and technical characteristics

A compliance matrix is provided in Table 10. The proposed for the proposed FM-UWB – WiseMAC-HA PHY-MAC is fully compliant with the IEEE802.15.6 system requirements.

Table 10: Compliance with IEEE802.15.6 BAN system requirements

Criteria	FM-UWB - WiseMAC-HA PHY-MAC Capabilities	Compliance with IEEE802.15.6 system requirements
Topology	Star network (6-12 devices) Mesh network (traffic limited)	Compliant
Bit rate	Data rate - Scalable to 250 kbps (BFSK) Aggregate throughput - 1 Mbps @ N = 4 RF channels	Compliant (wearable medical BAN)
Transmission range	>3 m indoors	Compliant
Security	Compatible with IEEE802.15	Compliant (wearable Medical BAN)
QoS	PER < 10% (256 octet packet) Delay < 125 ms PHY synchronisation ≤ 400 μs Optional FDMA-like MAC mode for near-real-time operation	Compliant (wearable Medical BAN)
Reliability	Robust to multipath interference > 99% link success/availability	Compliant
Power consumption	Low, autonomy > 1 year (e.g. with 1% duty cycle, MAC sleep modes, 500 mAh battery)	Compliant (wearable Medical BAN) Tx ≤ 4 mW (continuous operation) Rx ≤ 8 mW (continuous operation) Average power: dependent on application duty cycle

		Potential for powering via energy harvesting (< 50-100 μW)
Coexistence, resistance to interference	Good (low interference to other systems, high tolerance to interference)	Compliant Low radiated power UWB PHY Analogue spread spectrum MAC protocol “fairness”
Scalability	Up to 256 devices	Compliant (scalable MAC)
Form factor	SoC solution designed for use with small form factor wearable medical BAN devices	Compliant
Antenna	Small size (wearable Medical BAN)	Compliant (FM-UWB antennas can be small. FM-UWB is relatively insensitive to the antenna transfer function, no pulse, link margin limited).
Complexity	Very low complexity FM based solution	Compliant
Mobility	Insertion/de-insertion time: < 3 seconds	Compliant
SAR	< 1.6 mW (US) / < 20 mW (EU)	Compliant
Regulatory matters	Band: UWB (7.25-8.5 GHz) Power: -41.3 dBm/MHz	Compliant

7 Summary and concluding remarks

An FM-UWB PHY-MAC solution for wearable medical BAN applications is described in this document. This solution fully satisfies the IEEE802.15.6 BAN system technical requirements [IEEE3] defined for LDR applications, such as health and medical applications and meets or exceeds the targets identified in the TG6 Proposal Comparison Criteria [IEEE4].

FM-UWB is proposed for standardization in response to the IEEE802.15.6 Call for Proposals, targeting the wearable, LDR BAN applications domain. The proposed low complexity, FM-UWB solution offers advantages with respect to:

- low power consumption
- scalability and flexibility of the PHY and MAC and
- robust performance in BAN propagation environments.

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9 Acronyms

AAF	Anti Aliasing Filter
ACK	Acknowledge
ADC	Analog to Digital Conversion
BAN	Body Area Network
BB	Baseband
BER	Bit Error Rate
BFSK	Binary Frequency Shift Keying
B_{RF}	RF Bandwidth
BT	Bandwidth – Time product
CRC	Cyclic Redundancy Check
CSMA	Carrier Sense Multiple Access
DAA	Detect and Avoid
DAC	Digital to Analog Conversion
dB	Decibel
dBi	dB relative to isotropic radiator
dBm	dB milliwatt
dBW	dB Watt
DDS	Direct Digital Synthesis
EIRP	Effective Isotropic Radiated Power
FDMA	Frequency Division Multiple Access

FM	Frequency Modulation
FM-UWB	Frequency Modulation Ultra wideband
FSK	Frequency Shift Keying
GHz	Gigahertz
Hz	Hertz
IC	Integrated Circuit
Kbps	Kilobit per second
kHz	Kilohertz
LDR	Low Data Rate
LO	Local Oscillator
LOI	LO In-phase
LOQ	LO Quadrature
LOS	Line Of Sight
LPF	Low Pass Filter
LNA	Low Noise Amplifier
M	Meter
Ms	Millisecond
MAC	Medium Access Control
MBOFDM	Multi Band Orthogonal Frequency Division Multiplexing
MHz	Mega Hertz
mW	Milliwatt
PDF	Probability Density Function

PHY	Physical layer
PLL	Phase Lock Loop
P_{RX}	Receiver power consumption
PSD	Power Spectral Density
P_{TX}	Transmitter power consumption
RF	Radio Frequency
Rx	Receive
RXD	Received Data
SIR	Signal to Interference Ratio
SNP	Signal to Noise Ratio
SoC	System on a Chip
Tx	Transmit
TXD	Transmitted Data
µm	Micrometer
µW	MicroWatt
UWB	Ultrawideband
VCO	Voltage Controlled Oscillator
WAN	Wide Area Network
WiseMAC	Wireless Sensor Medium Access Control protocol
WiseMAC-HA	WiseMAC High Availability

10 Annexes

Annex 1 : CDF of narrowband fading for CM3 showing 10 dB of margin required for 90% availability, 20 dB for 99% availability and 30 dB for 99.9% availability; consistent with Rayleigh fading.