Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: **CSEM FM-UWB proposal presentation**

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Source: John F.M. Gerrits & John R. Farserotu
CSEM Systems Engineering
Jaquet Droz 1, CH2002 Neuchatel, Switzerland
Voice: +41 32 720 56 52, FAX: +41 32 720 57 20, E-Mail: john.gerrits@csem.ch

Re: This document is CSEM's response to the Call For Proposal from the IEEE P802.15 Task Group 6 on BAN.

Abstract: This document presents FM-UWB: a constant envelope LDR UWB air interface for short range BAN applications.

FM-UWB Alliance

CSEM, Neuchâtel, Switzerland
John F.M. Gerrits, Dr. John R. Farserotu, Jérôme Rousselot

NXP Semiconductors, Eindhoven, The Netherlands
Gerrit van Veenendaal

ACORDE TECHNOLOGIES S.A., Santander, Spain
Dr. Manuel Lobeira

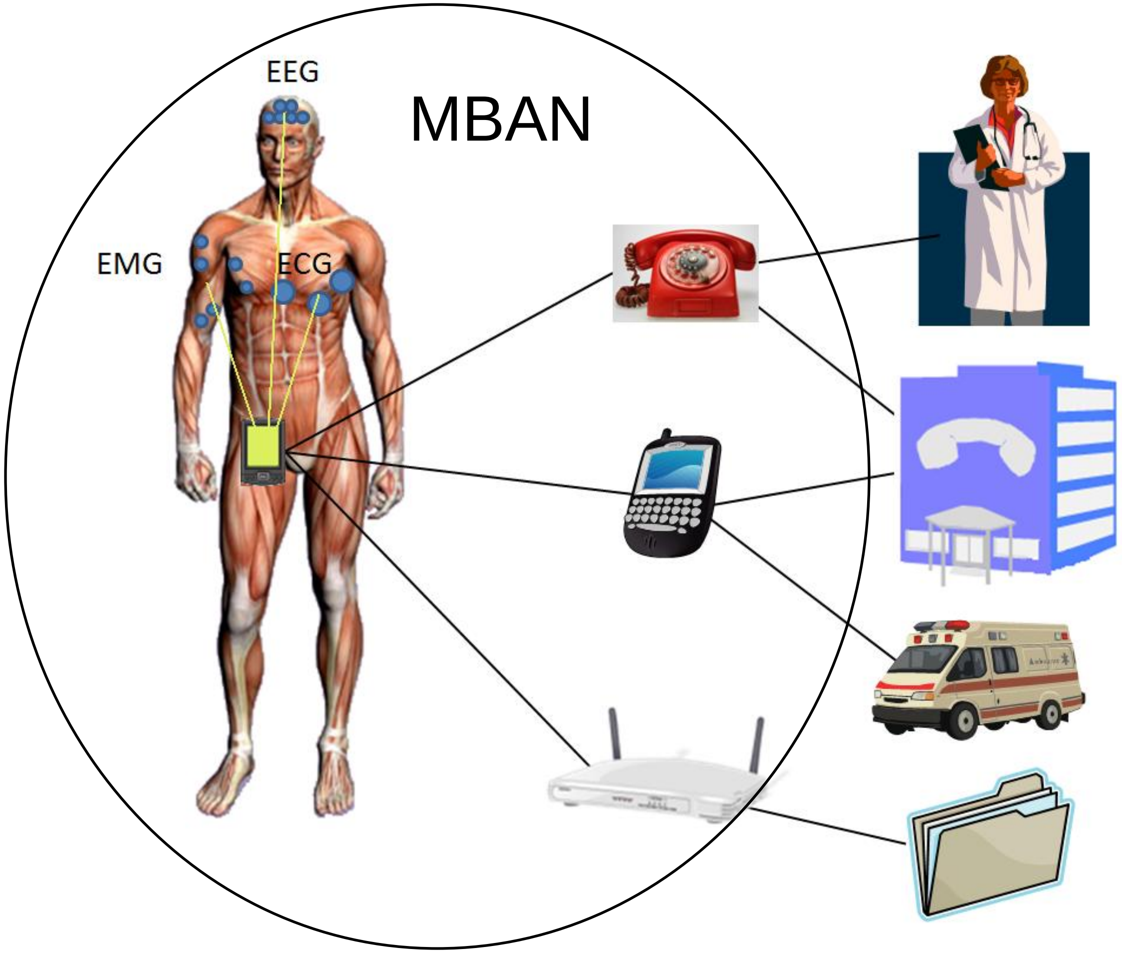
TU Delft, Delft, The Netherlands
Prof. John R. Long

Presentation Outline

1. Wearable MBAN Applications & Requirements
2. Regulations, Coexistence, SAR
3. QoS, Robustness
4. Hardware Prototype
5. Medium Access Control

Wearable Medical BAN applications

- **Bio-Medical**
  - EEG Electroencephalography
  - ECG Electrocardiogram
  - EMG Electromyography (muscular)
  - Blood pressure
  - Blood SpO2
  - Blood pH
  - Glucose sensor
  - Respiration
  - Temperature
  - Fall detection
- **Sports performance**
  - Distance
  - Speed
  - Posture (Body Position)
  - Sports training aid



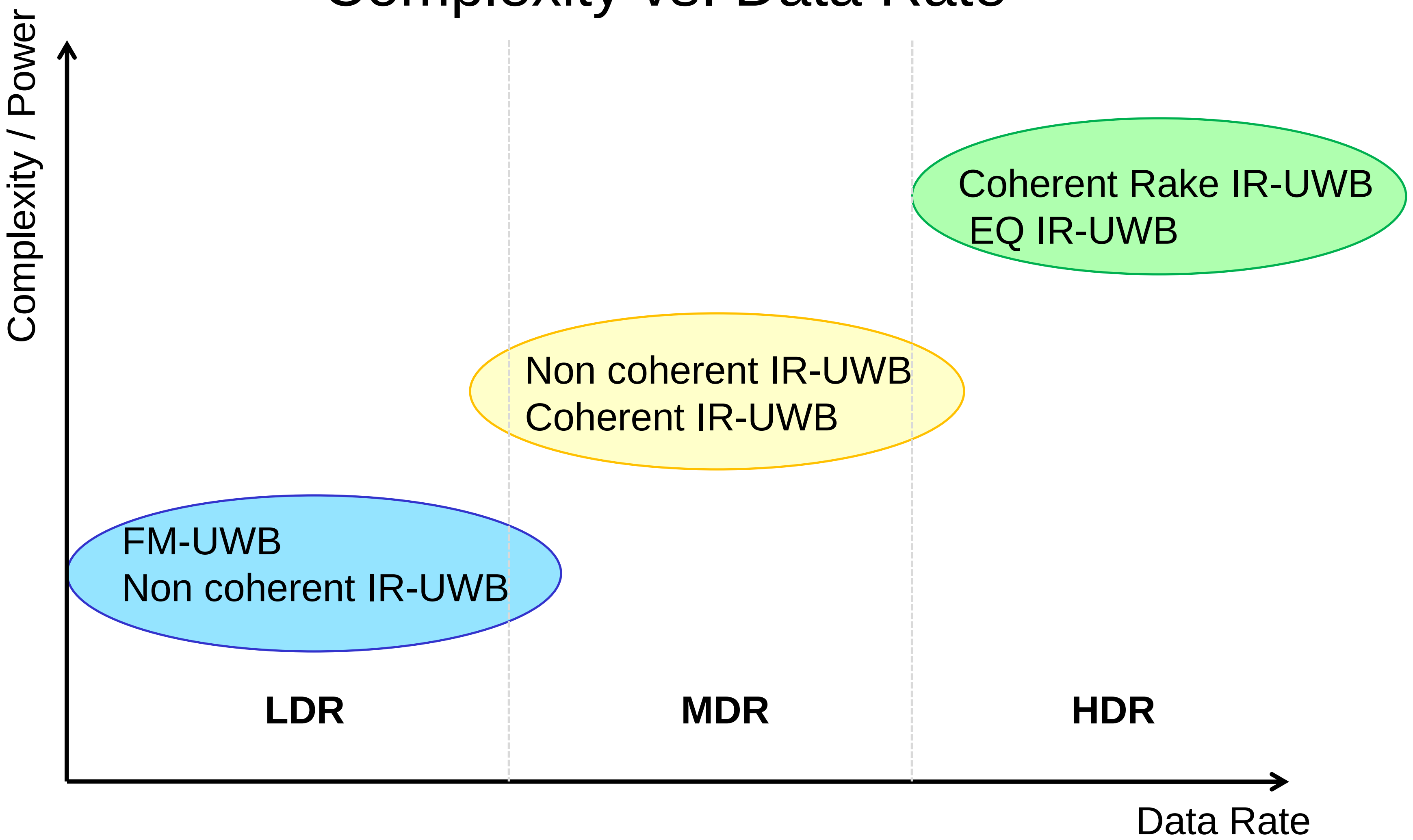
Key Wearable BAN requirements

Parameter	Medical BAN requirement
Coexistence and Robustness	Good (low interference to other systems, high tolerance to interference)
SAR Regulations	< 1.6 mW (US) / < 20 mW (EU)
QoS (Medical BAN)	PER < 10%, delay < 125 ms
Data Rates	10 kbps to 10 Mbps (LDR medical / MDR consumer)
Power Consumption	Low, autonomy > 1 year (e.g. with 1% duty cycle, MAC sleep modes, 500 mAh battery)
Reliability	Robust to multipath interference, > 99% link success/availability
Insertion/de-insertion	< 3 seconds
Transmission range	> 3 m

Advantages of UWB

- **Low radiated power**
  - Low PSD, low interference, low SAR
  - High co-existence with existing 802.x standards
  - Real potential for low power consumption
- **Large bandwidth worldwide**
  - Spectrum is worldwide available
  - Robust to multipath and fast varying channels
- **Flexible, scalable (e.g. data rates, users)**
- **Low complexity HW/SW solutions in advanced development**

Complexity vs. Data Rate



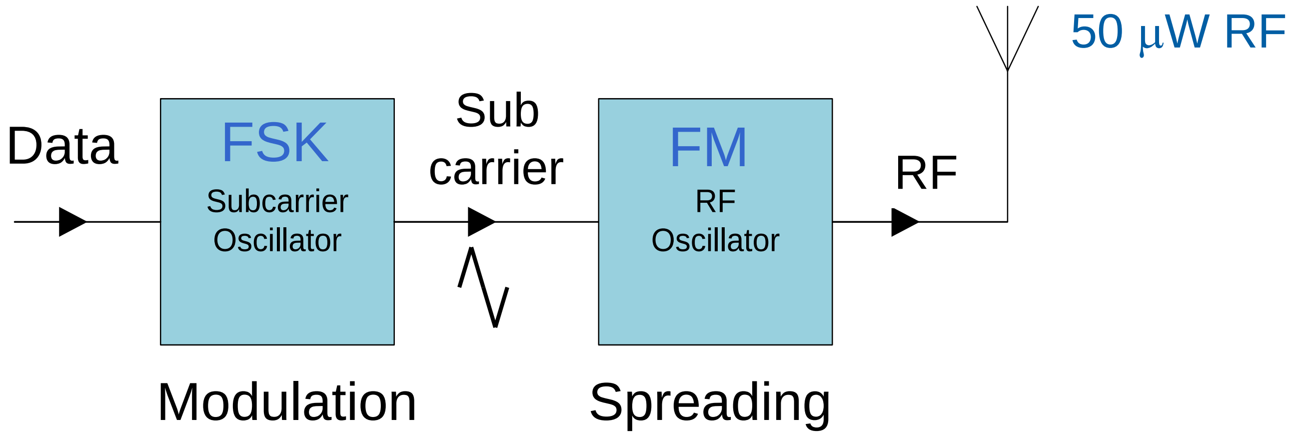
Outline

1. **Wearable MBAN Applications & Requirements**
2. **Regulations, Coexistence, SAR**
3. **QoS, Robustness**
4. **Hardware Prototype**
5. **Medium Access Control**

Transmitter architecture

R = 30 - 250 kbps   BW: 60 - 500 kHz   > 500 MHz

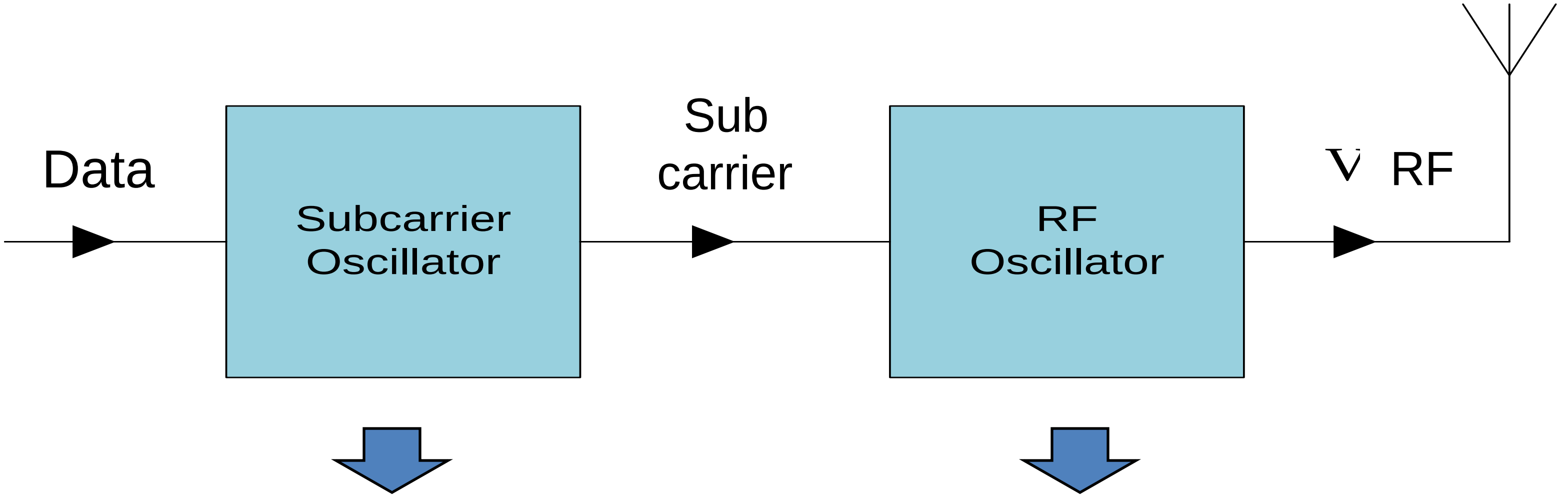
freq: baseband   1 - 2 MHz   6 - 9 GHz



An analog FM signal may have any bandwidth independent of modulation frequency or bit rate. This is analog spread spectrum.

Subcarrier frequency = analog spreading code.

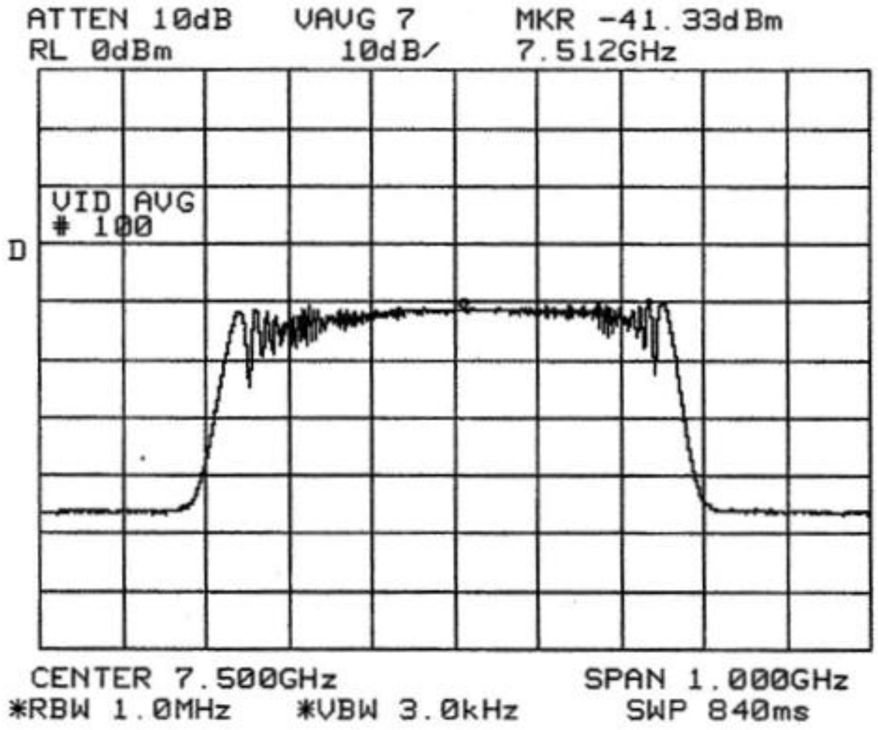
Multiple access techniques: Subcarrier and RF FDMA



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

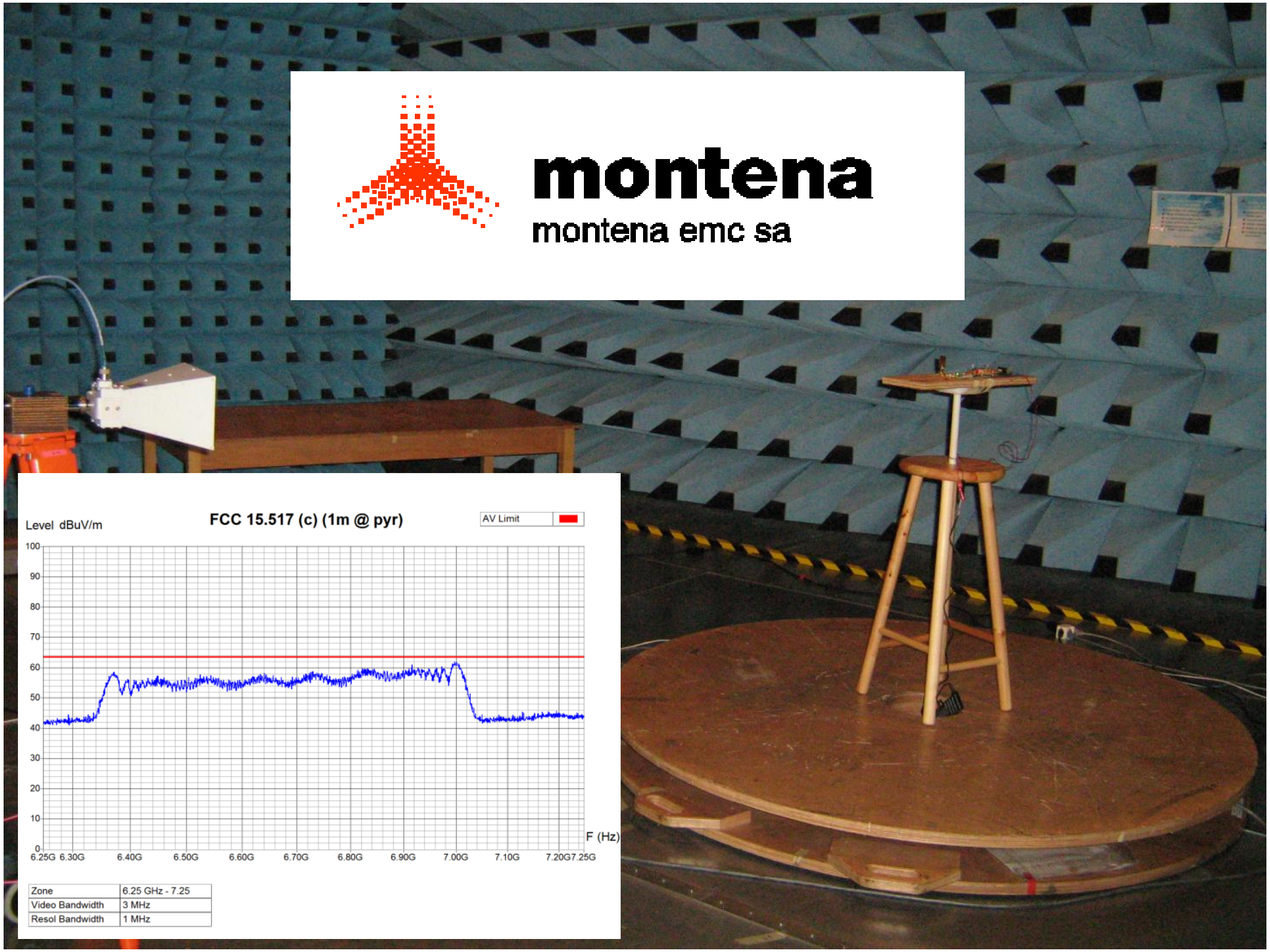
Channel	RF center frequency
H_1	6464 MHz
H_2	6976 MHz
H_3	7488 MHz
H_4	8000 MHz
H_5	8512 MHz

FM-UWB transmitter signal



- Flat power spectral density
- Steep spectral roll-off
- Good coexistence
- SAR compliant

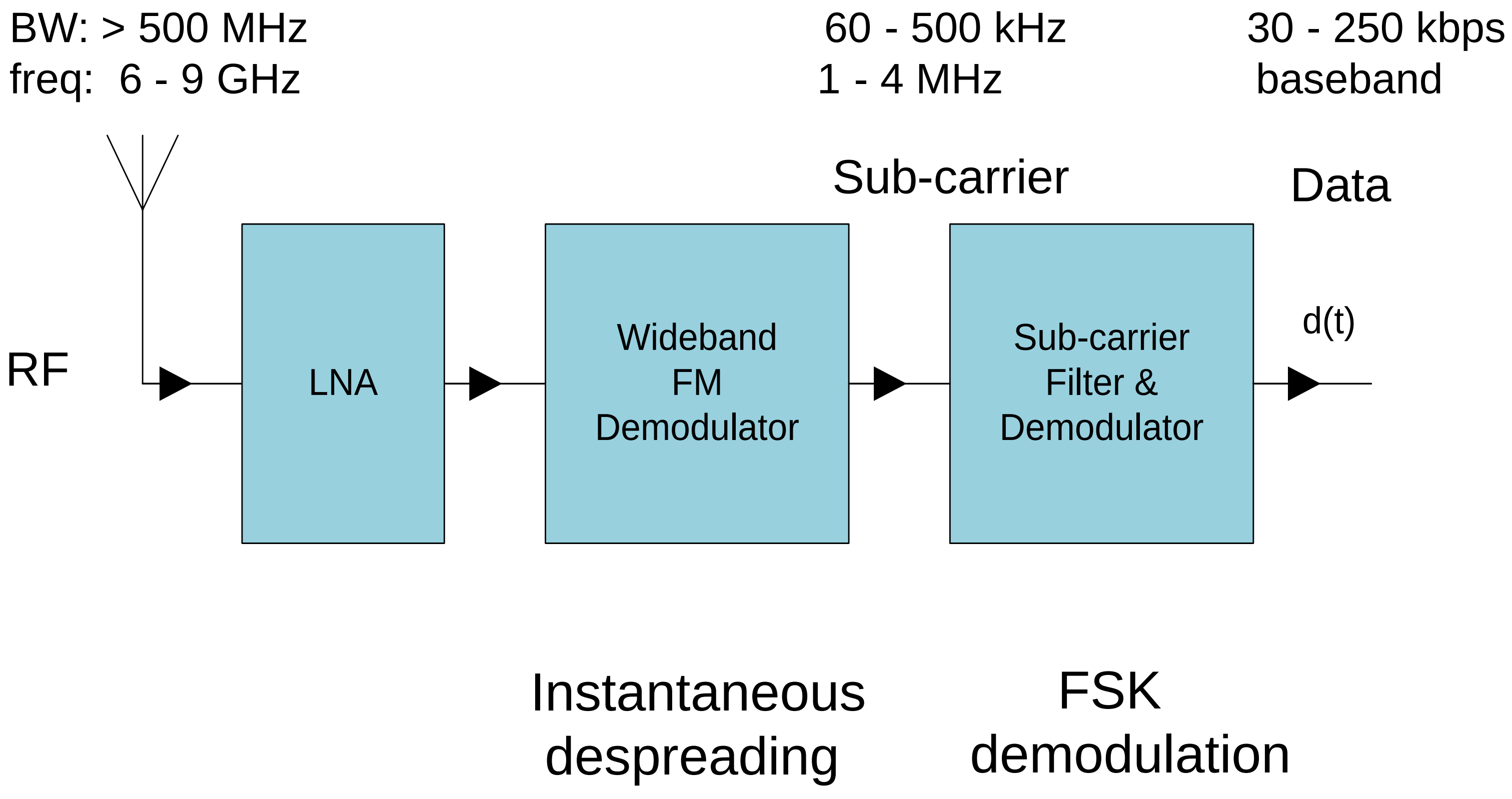
FM-UWB has been FCC pre-certified



Outline

1. Wearable MBAN Applications & Requirements
2. Regulations, Coexistence, SAR
3. QoS, Link Margin, Robustness
4. Hardware Prototype
5. Medium Access Control

Receiver architecture



Receiver processing gain

Only noise/interference in the subcarrier banwidth is taken into account. This bandwidth reduction after the wideband FM demodulator yields real processing gain:

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

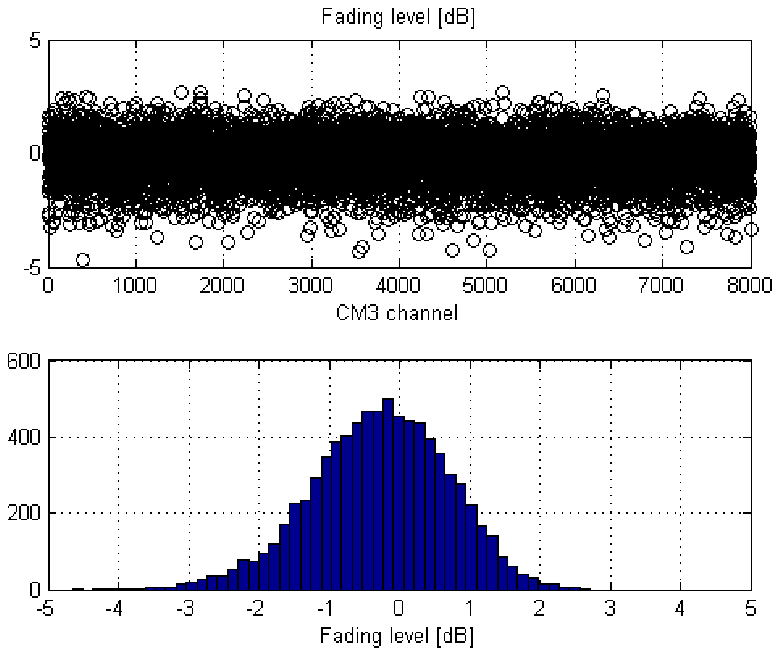
G_{PdB} = 30 dB @ R = 250 kbps
G_{PdB} = 39 dB @ R = 31.25 kbps

Processing gain mitigates interference:

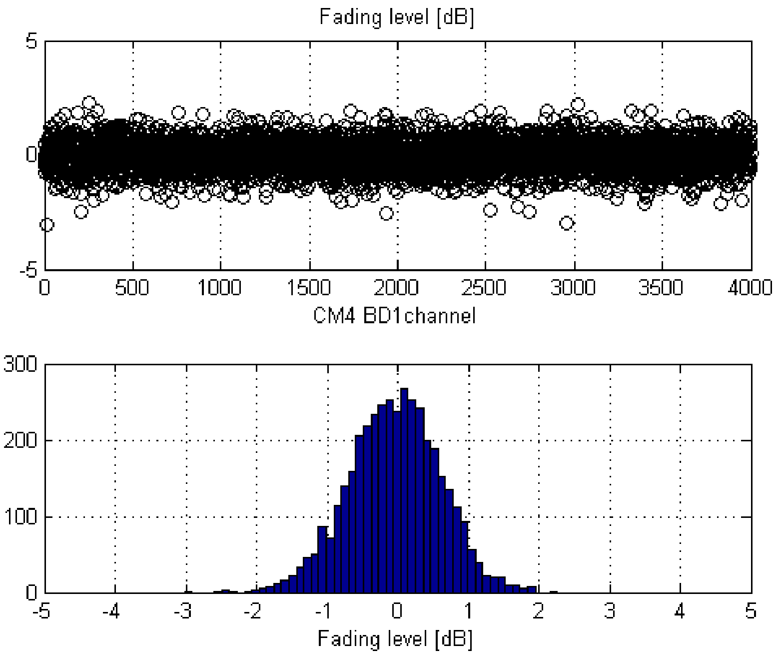
- narrowband
- UWB
- multiple-access

Robustness to frequency-selective multipath

Body surface – body surface
CM3 channel:



Body surface – external
CM4 channel:



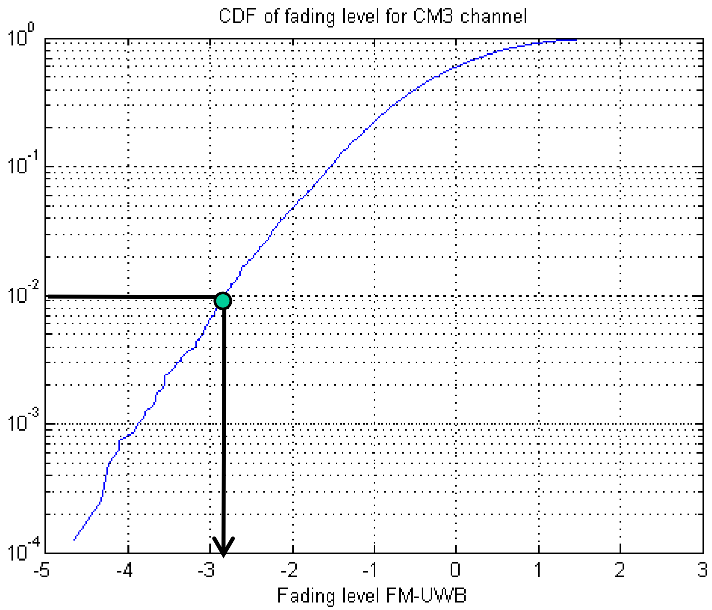
[ICUWB 2007]

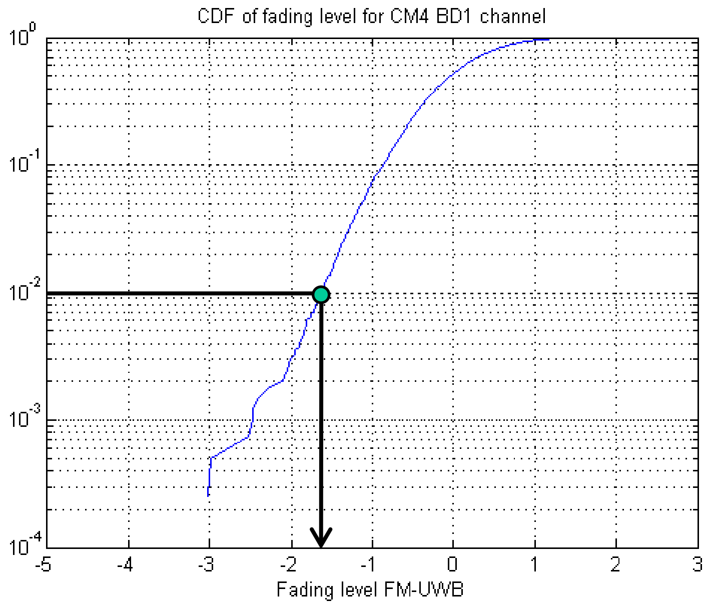
BRF = 500 MHz)

Requirements for 99 % availability:

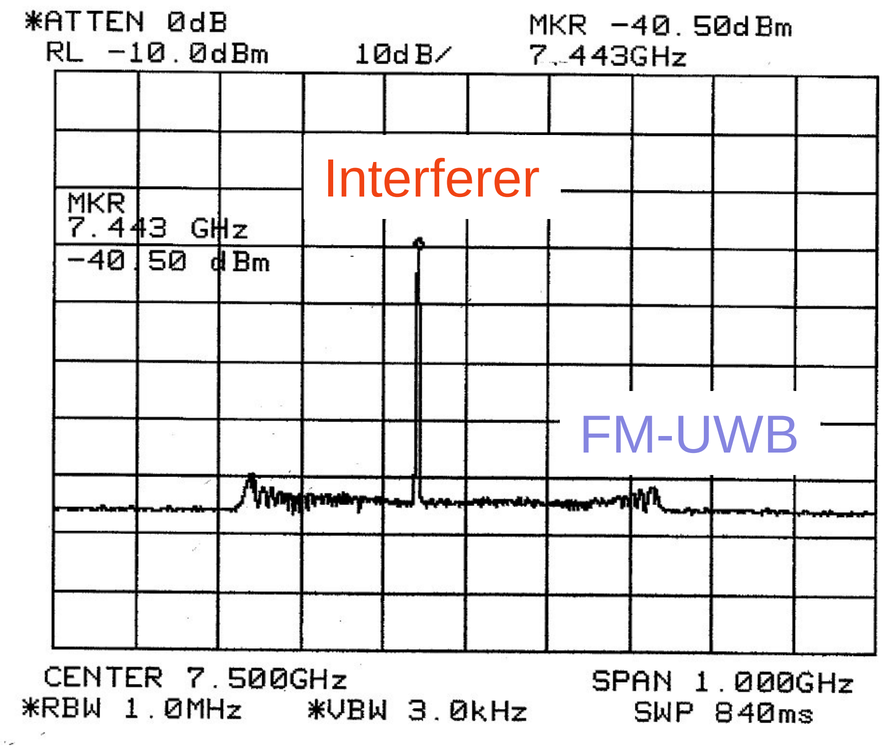
- 2.8 dB of fading margin in the CM3 channel
- 1.7 dB of fading margin in the CM4 channel.

(20 dB fading margin in a narrowband system)



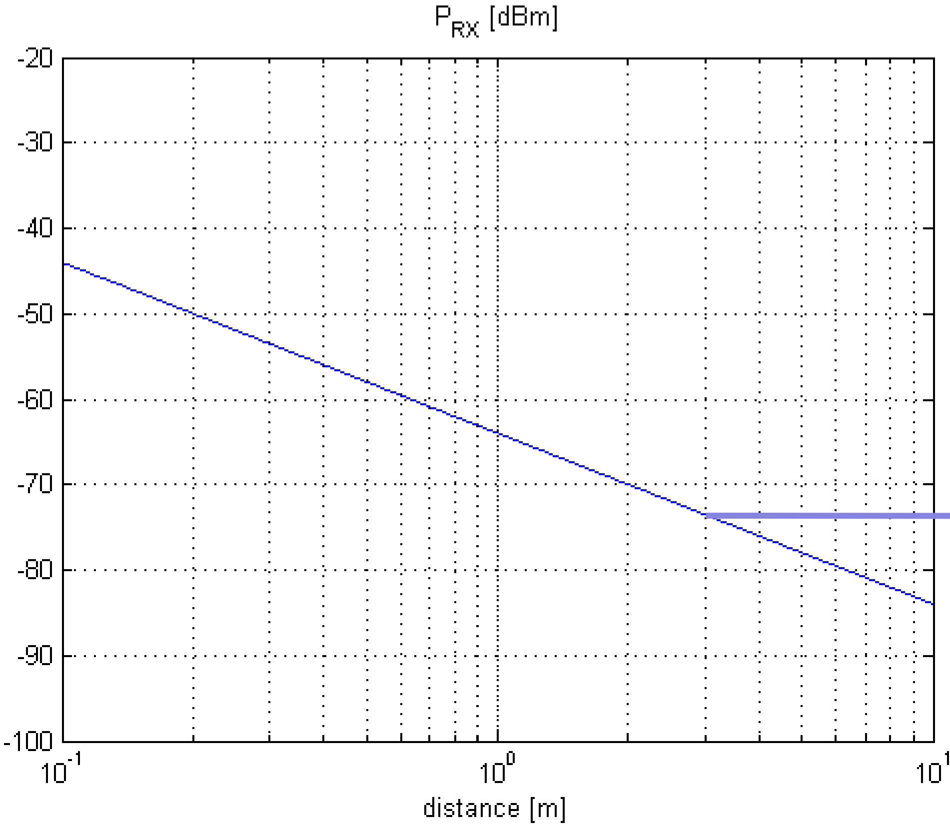


Robustness to narrowband interference



In-band narrowband interference up to 15 dB stronger than the wanted signal is tolerated.

Received signal at 3 meters (CM4).



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

d = 3m, f = 7.5 GHz, λ = 4 cm

P_{RX}(3m) = -74 dBm

Receiver sensitivity

B_{RF} = 500 MHz

NF_{RX} = 5 dB

$P_N = -174 + 10\log_{10}(500 \times 10^6) + 5 = -82$ dBm

SNR_{MIN} = -7 dB

Theoretical receiver sensitivity -89 dBm

Implementation loss and fading margin

P_{RX}(3m) = -74 dBm +15 dB of theoretical link margin

4 dB implementation losses

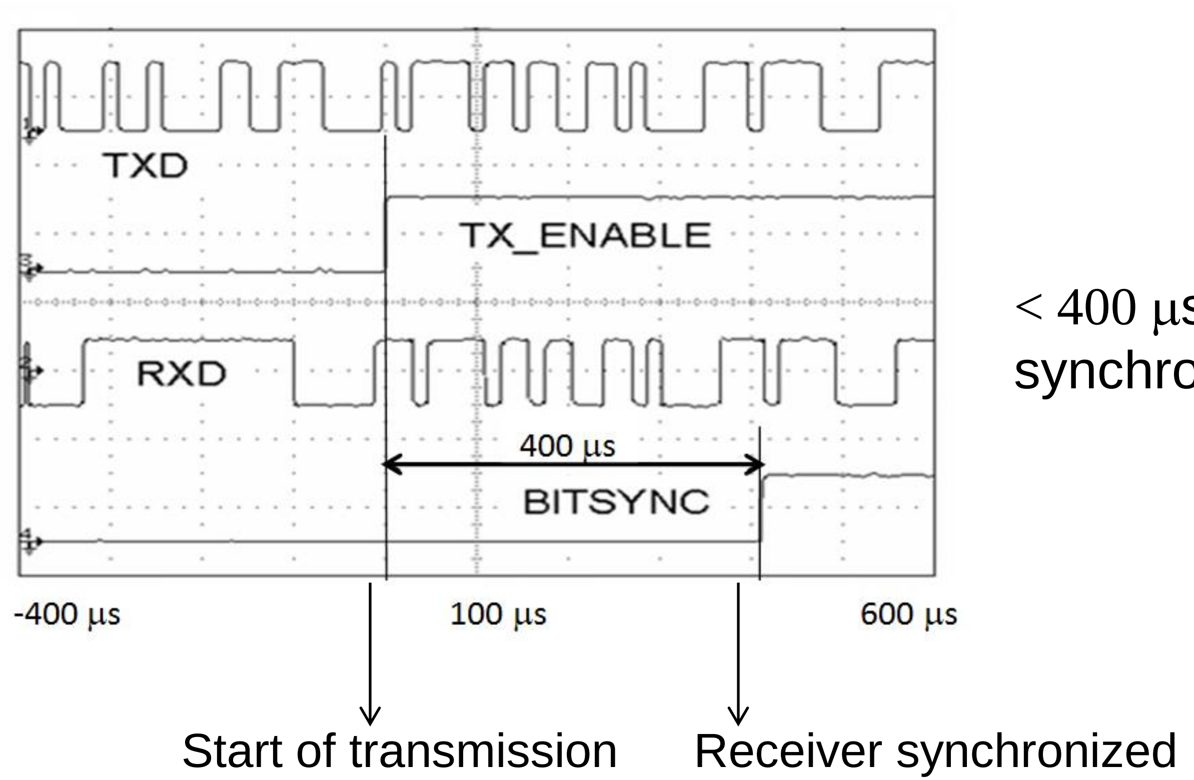
\- 3 dB fading margin for multipath

8 dB positive margin = link closed

Link budget summary

Parameter	Symbol	Value	Units	Comments
Tx bandwidth	B_{RF}	500	MHz	Nominal UWB signal bandwidth
Tx power	P_{TX}	-14.3	dBm	< 40 mW (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 $\leq 10^{-6}$
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

PHY Synchronization



< 400 μs (25 bits) synchronization time

- Synchronization like a narrowband FSK system
- Fast clear channel assessment
- Actual performance depends upon the MAC protocol

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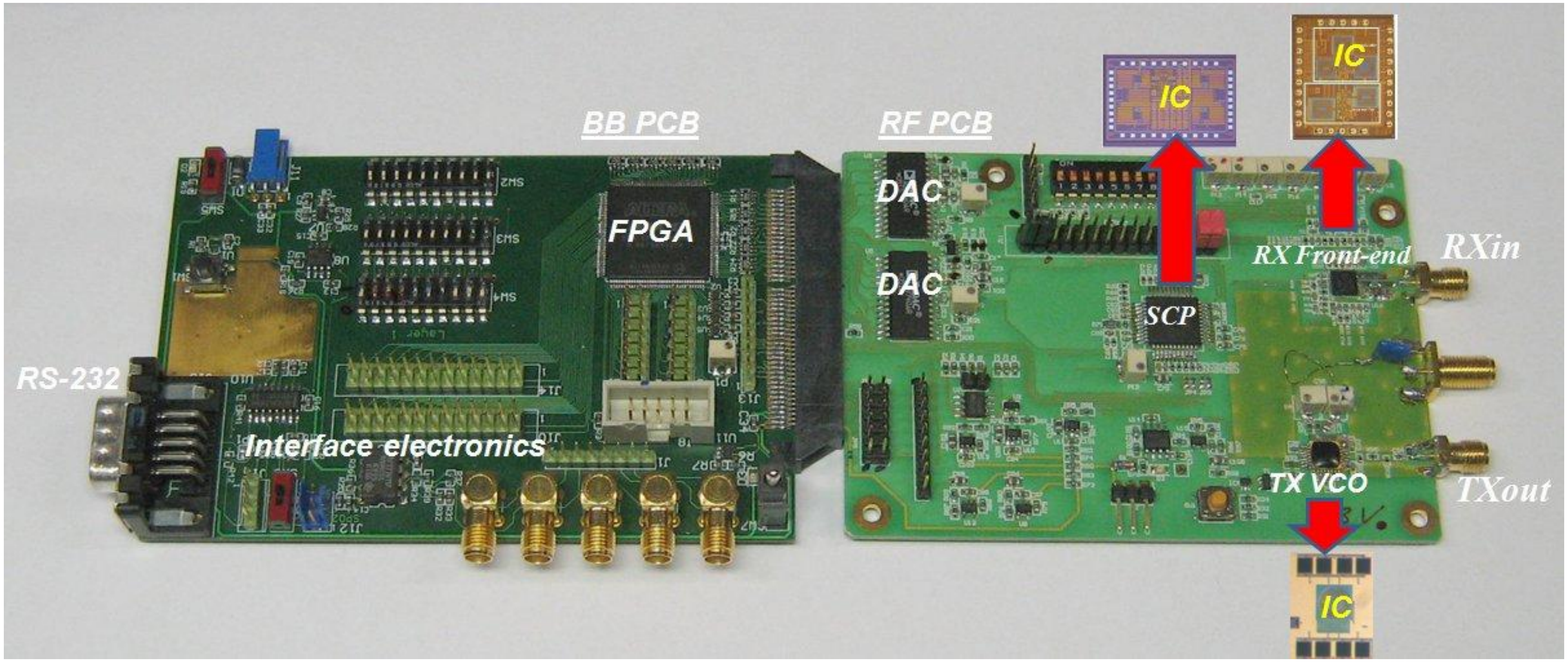
Today´s FM-UWB High Band Prototype (ready for worldwide 7.25 – 8.5 GHz operation).



Prototype Characteristics

RF center frequency	6.2 – 8.7 GHz
RF bandwidth	500 MHz
RF output power	-15 dBm
Subcarrier frequency	1 - 2 MHz
Subcarrier modulation	FSK
Raw bit rate	31.25 - 250 kbps
Receiver sensitivity	< -85 dBm
TX, RX switching time	$< 100\ \mu s$
RX synchronization time	$< 400\ \mu s$
Power consumption(*)	12 -15 mW Rx 5.5 mW Tx

Target power consumption
4 mW Tx, 8 mW Rx

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	5.0 mW
Wideband FM Demodulator	4.0 mW
Subcarrier processing	5.0 mW
DDS	1.0 mW

(*): First Generation Multi-chip set

Final Product Size

Usually product size is determined by antenna and battery.
Example: wireless SpO_2 sensor.

Concluding remarks on the FM-UWB PHY

- **Good co-existence**
  - with existing air interfaces
- **Robustness**
  - interference, multipath
- **Spectral properities**
  - flatness, spectral roll-off

- **Simple radio architecture**
  - no frequency conversion
  - relaxed HW specifications enable low power consumption
  - fast synchronization

FM-UWB is a true low-complexity LDR UWB radio technology designed to meet the requirements for Wearable Medical BAN and compatible with requirements of other standardization bodies, e.g. ETSI eHealth.

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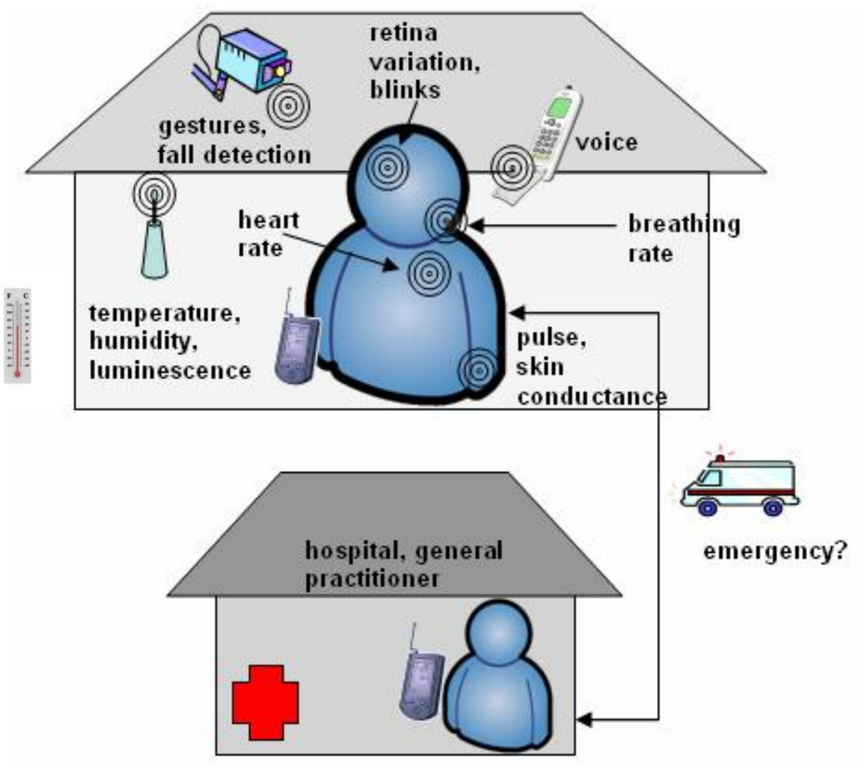
Targeted Applications and Requirements

Medical Body Area Networks

Continuous measurements

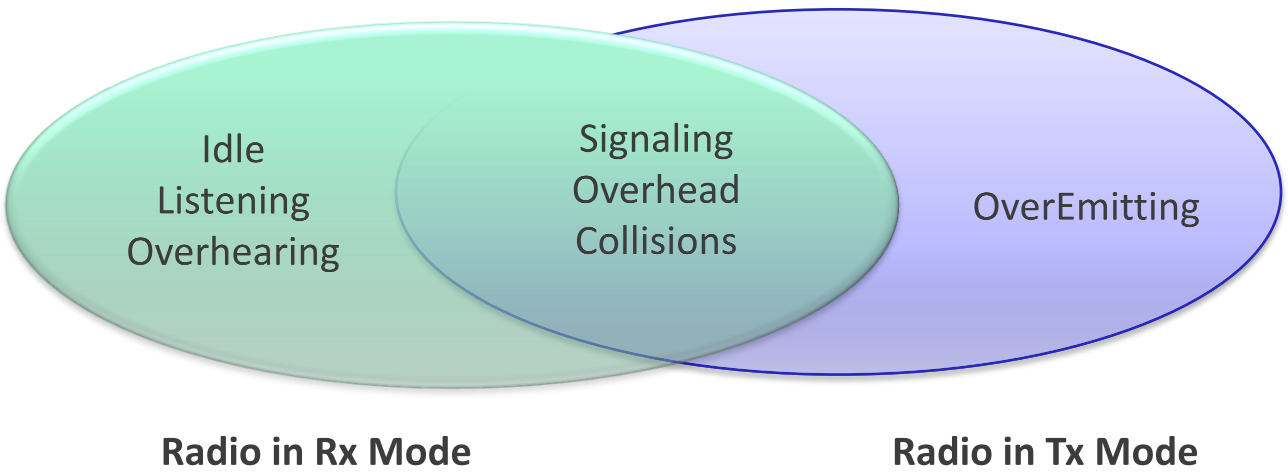


Main Requirements

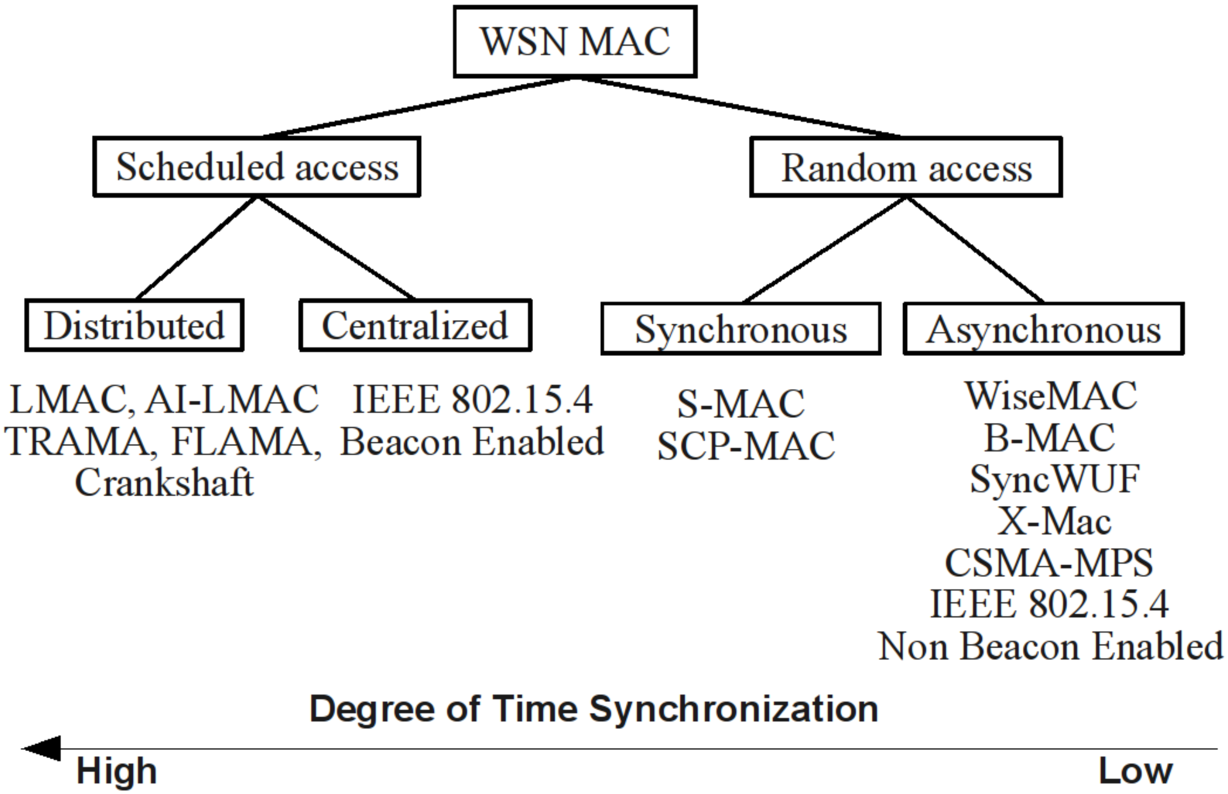
- Low Power
- Scalability
- Robustness
- Coexistence

[IEEE1]

Ultra Low Power MAC design
Types of energy waste

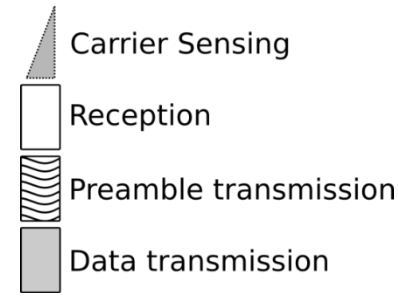


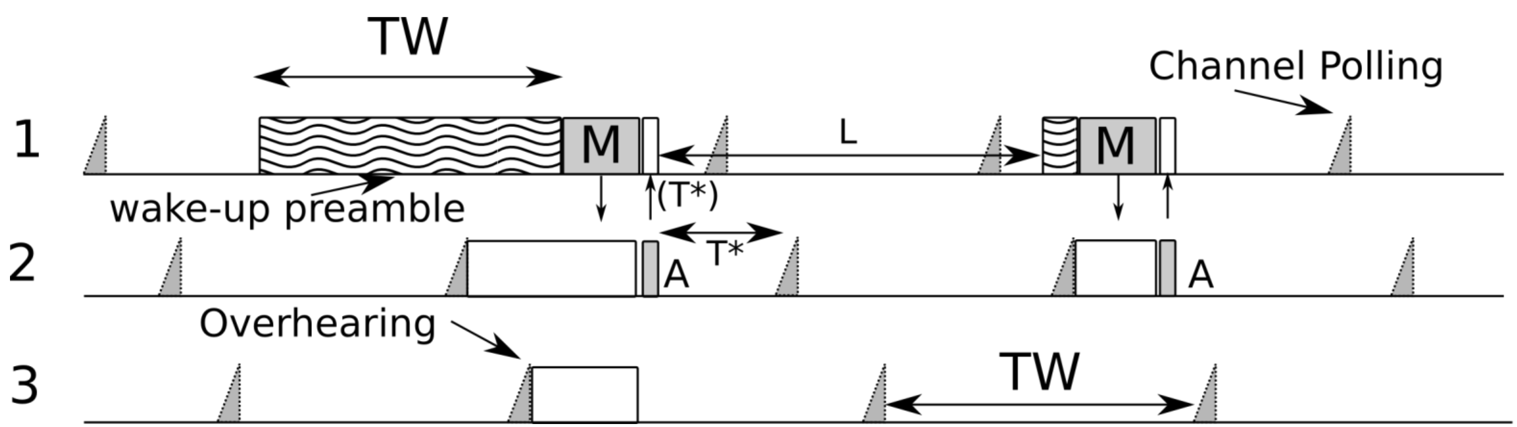
Ultra Low Power MAC Design
MAC protocol families



WiseMAC Ultra Low Power MAC Scheme

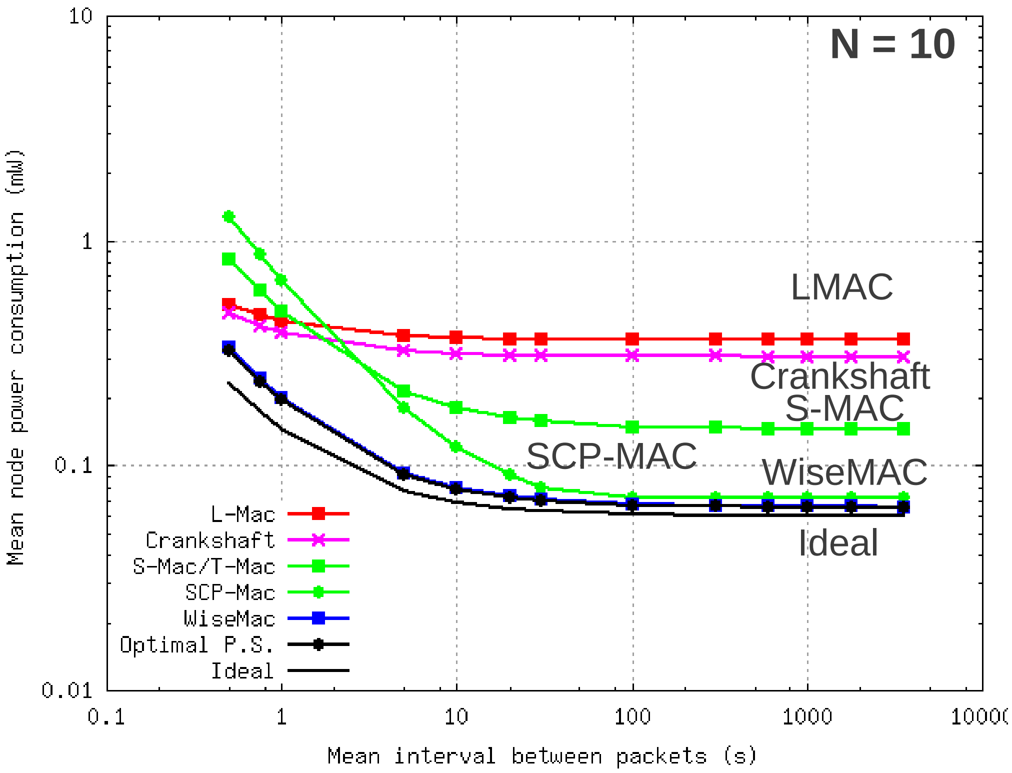
- Periodic sampling
- Opportunistic Link-local Synchronization

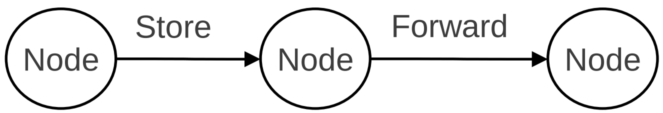




[WISENET2004], [WISEMAC2004]

WiseMAC Ultra Low Power MAC Scheme



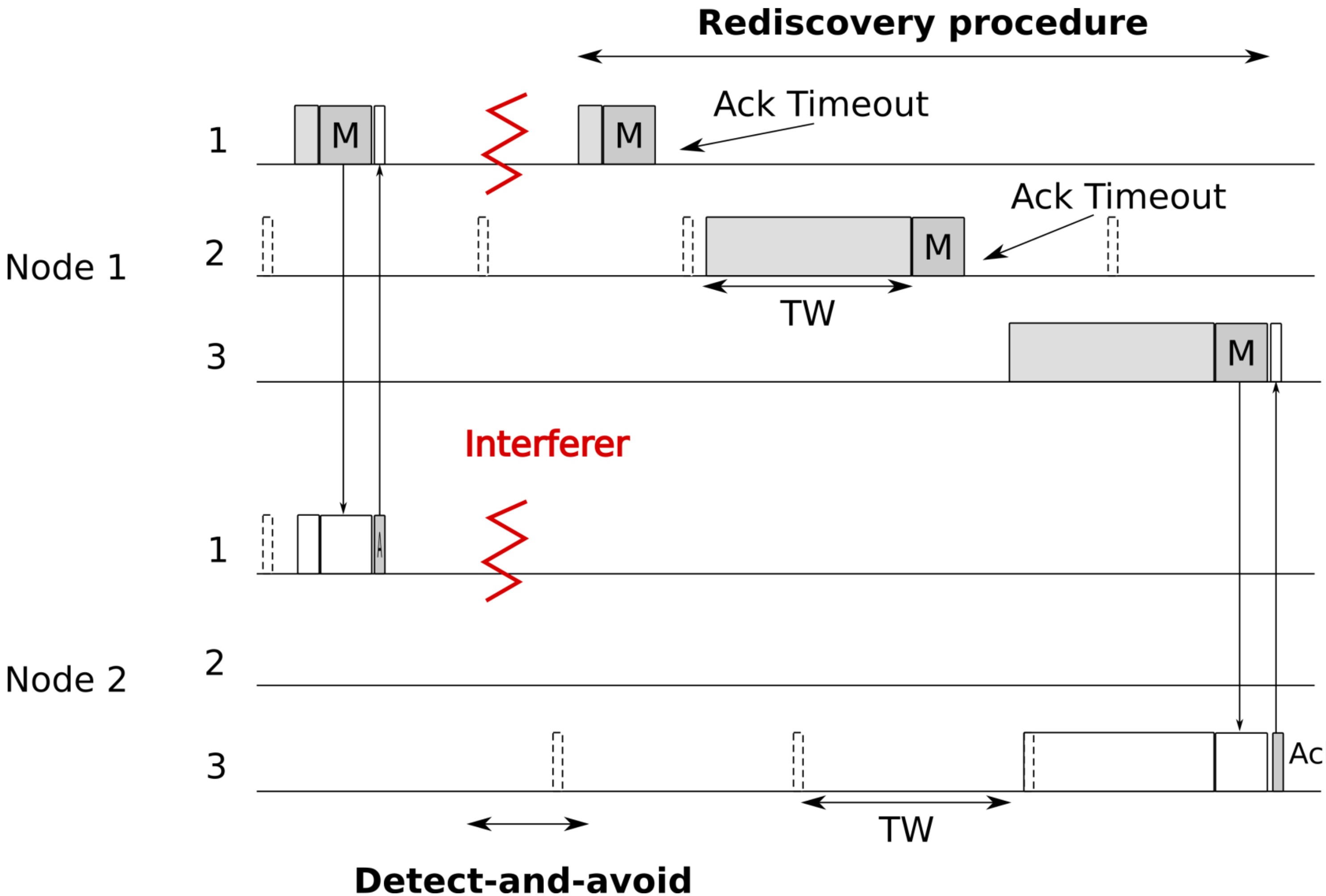


WiseMAC Deviations from Ideality

- High Traffic: low cost of wake-up preamble
- Low Traffic: only the cost of sampling

[EW2008]

MultiChannel WiseMAC, 3-channel example



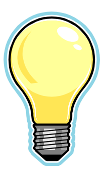
MultiChannel WiseMAC

Advantages

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

Drawbacks

- Inefficient Broadcasts
- Limited Throughput
- Sub-optimal for heterogeneous networks

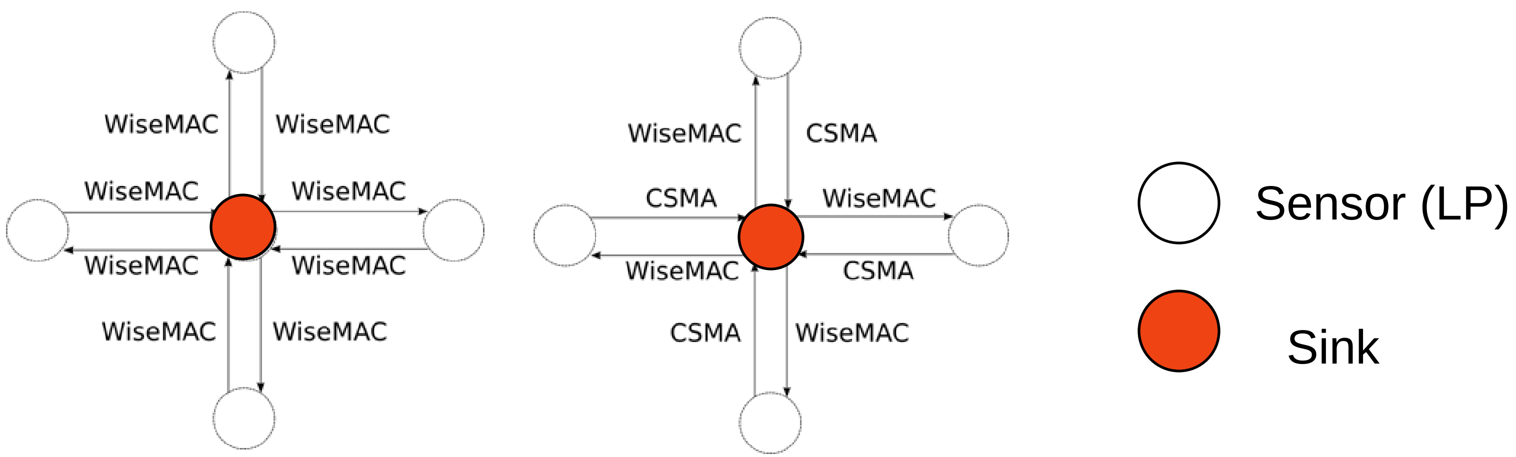


Have some nodes switch to an interoperable mode that does not exhibit limited throughput = CSMA (IEEE 802.15.4 Non Beacon Enabled Mode)

WiseMAC High Availability

WiseMAC-HA

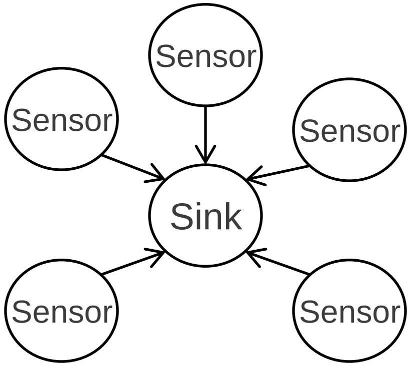
- Star or mesh topology
- No. of devices is scalable (traffic limited e.g. 6 to 256)
- Robust and reliable: DAA
- Ability to decide on efficient modes changes
  (Low Power WiseMAC or High Throughput CSMA)

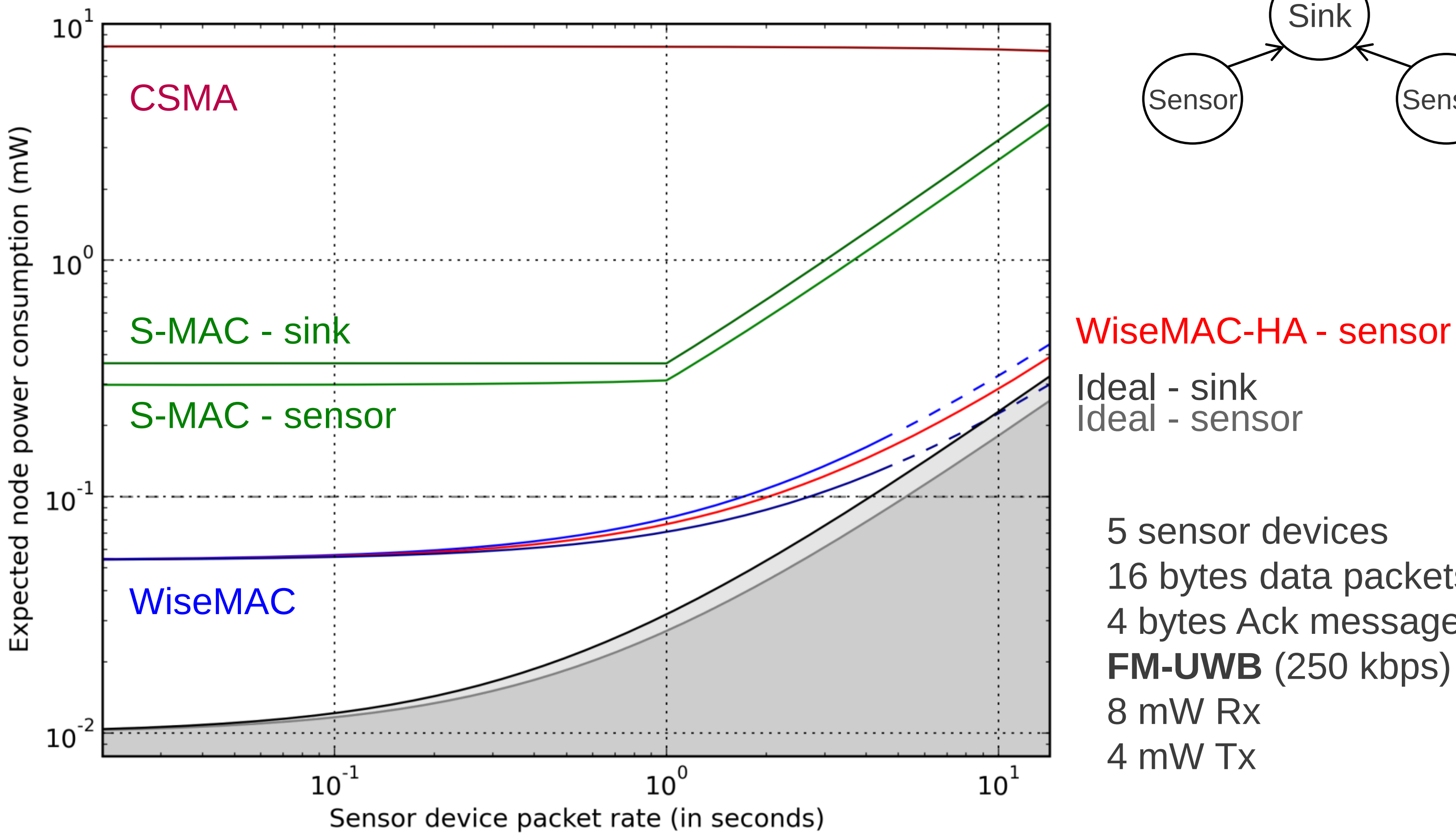


a) Low power downlinks and uplinks.

b) Low power downlinks and low latency uplinks.

Power Consumption

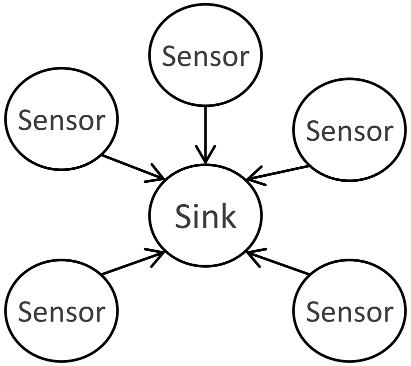


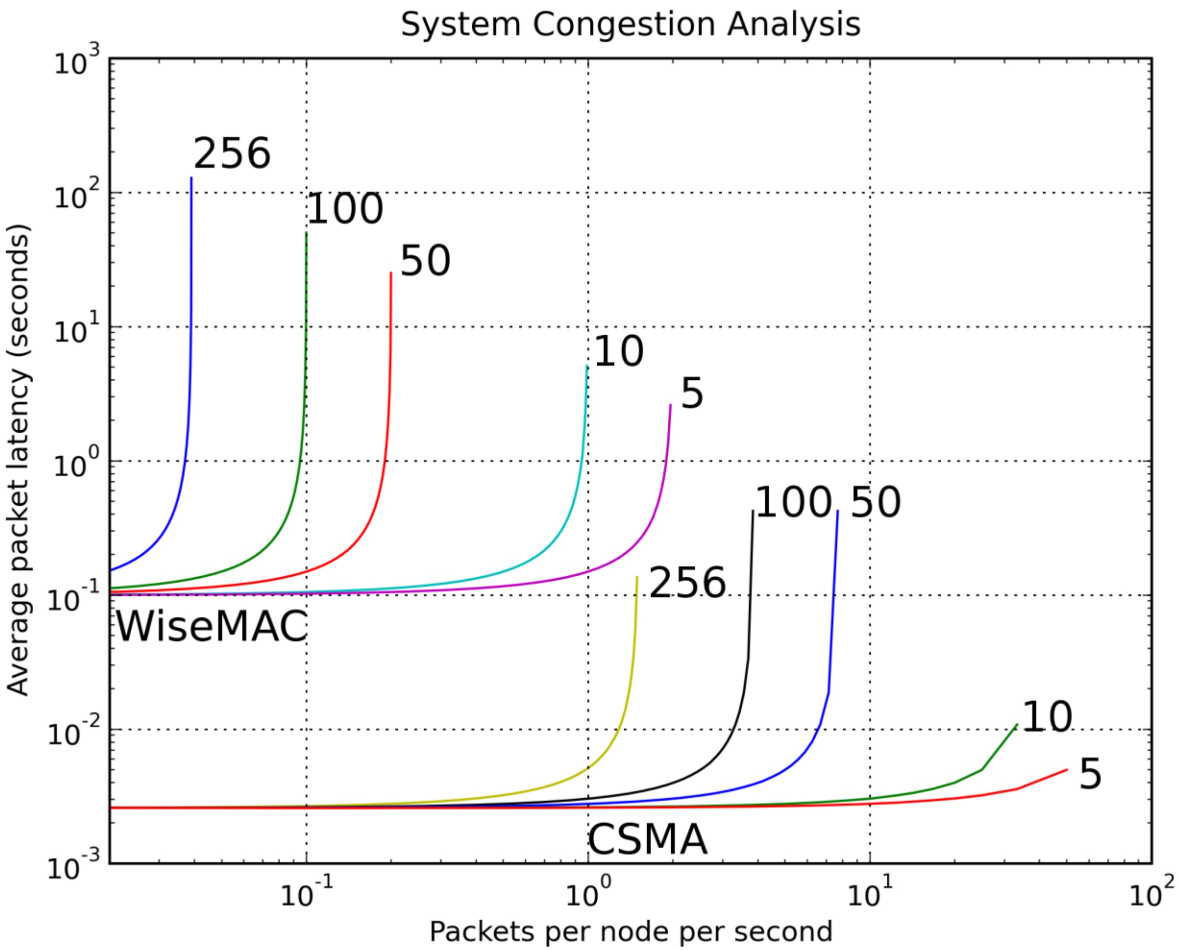


5 sensor devices
16 bytes data packets
4 bytes Ack messages
FM-UWB (250 kbps)
8 mW Rx
4 mW Tx

ICUWB2009

Latency





Smooth latency degradation with network size and traffic growths: No hard limits

Concluding remarks on the WiseMAC-HA MAC protocol

- Multi-mode protocol (WiseMAC – CSMA)
- Robust and reliable: Detect-and-Avoid interferers (by changing RF or subcarrier frequency)
- Ultra Low Power for all nodes: no need to synchronize
- Scales well with network size and traffic (no hard lmits)
- Coexistence: the protocol's fairness allows simultaneous operation of independent networks
- Throughput and latency vs. energy trade-off
- Flexibility to decide mode changes
- Flexibility to accomodate other operating modes

FM-UWB together with WiseMAC-HA are well suited for LDR Medical BAN applications

Possible ways of merging with other radios

- **At the PHY level**
  - Optimized UWB air interfaces (e.g. for commercial BAN/medical BAN applications data rates and coverage)
  - Exploit common radio front-ends blocks
    - TX: RF VCO, output stage
    - RX: LNA, down conversion mixer
- **At the MAC level**
  - LDR FM-UWB LDR and MDR IR-UWB radio (e.g. coherent)
  - FM-UWB 7.25-8.5 GHz, narrowband 2.4 GHz
- **At the system level**
  - FM common control cross UWB and narrowband radio

FM-UWB

IR-UWB
Narrowband FM
….

Annexes

References

[EW2008] Jérôme Rousselot, Amre El-Hoiydi and Jean-Dominique Decotignie, “Low Power Medium Access Control Protocols for Wireless Sensor Networks”, European Wireless Conference 2008 (EW 2008), 22-25 June 2008, Prague, Czech Republic.

[EURASIP2005] John F.M. Gerrits, Michiel H.L. Kouwenhoven, Paul R. van der Meer, John R. Farserotu, John R. Long, “Principles and Limitations of Ultra Wideband FM Communications Systems”, EURASIP Journal on Applied Signal Processing, Volume 2005, Number 3, 1 March 2005, pp. 382 - 396.

[ICUWB2007] John F.M. Gerrits, John R. Farserotu and John R. Long, "Multipath Behavior of FM-UWB Signals", ICUWB2007, Singapore, September 2007.

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[IEEE1] IEEE 802.15.6, Technical Requirements Document (TRD), IEEE802.15-08-0037-04-0006

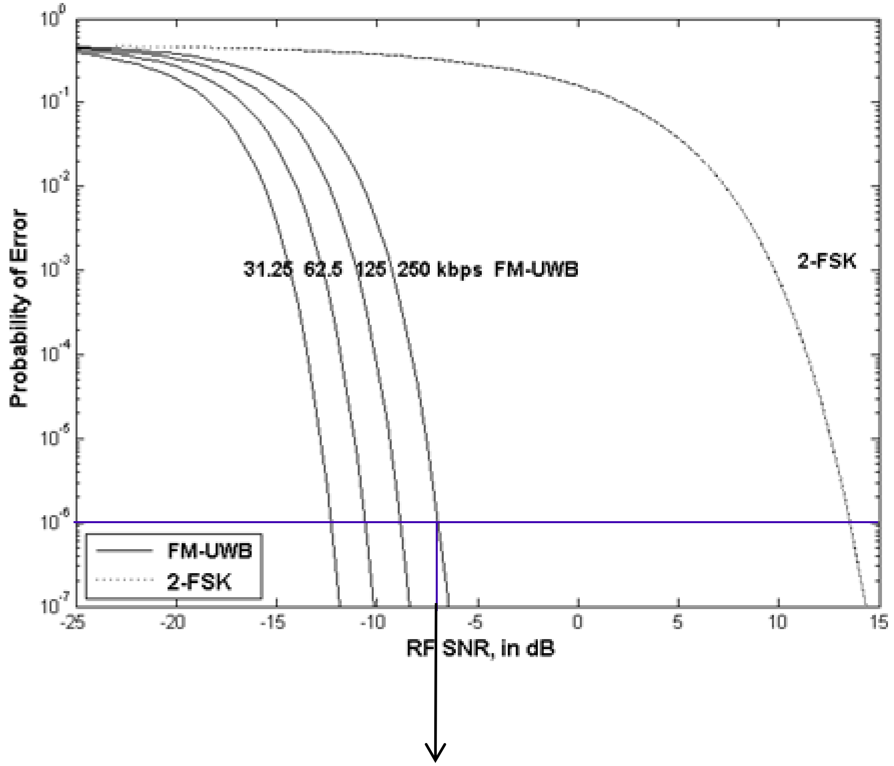
[IEEE2] K. Y. Yazdandoost, K. Sayrafian-Pour, “Channel Model for Body Area Network (BAN), ” IEEE 802.15-08-0780-05-0006, February 2009.

[TCAS2008] John F.M. Gerrits, John R. Farserotu and John R. Long, "Low-Complexity Ultra Wideband Communications", IEEE Transactions on Circuits and Systems-II, Vol. 55, No. 4, April 2008, pp. 329 - 333.

[WISENET2004] Enz, C.C.; El-Hoiydi, A.; Decotignie, J.-D.; Peiris, V.,“ WiseNET: an ultralow-power wireless sensor network solution“ , IEEE transactions Computer Science, Volume 37, Issue 8, Aug. 2004, pp. 62 – 70.

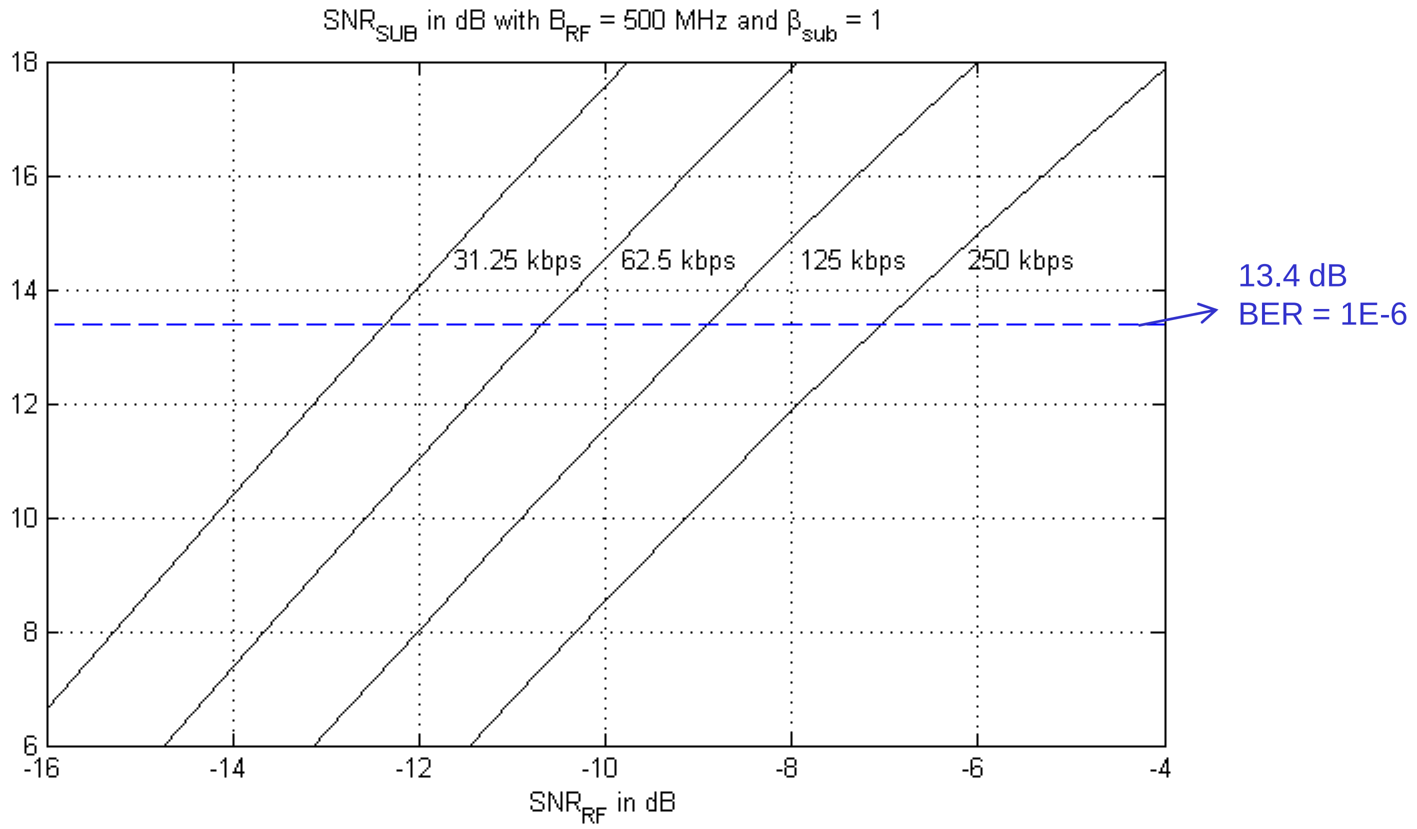
[WISEMAC2004] A. El-Hoiydi, and J.-D. Decotignie, " WiseMAC: An Ultra Low Power MAC Protocol for Multi-hop Wireless Sensor Network,“ Proc. of the First International Workshop on Algorithmic Aspects of Wireless Sensor Networks (ALGOSENSORS 2004), Lecture Notes in Computer Science, LNCS 3121, pp. 18-31, Springer-Verlag, July 2004.

Sensitivity of FM-UWB receiver



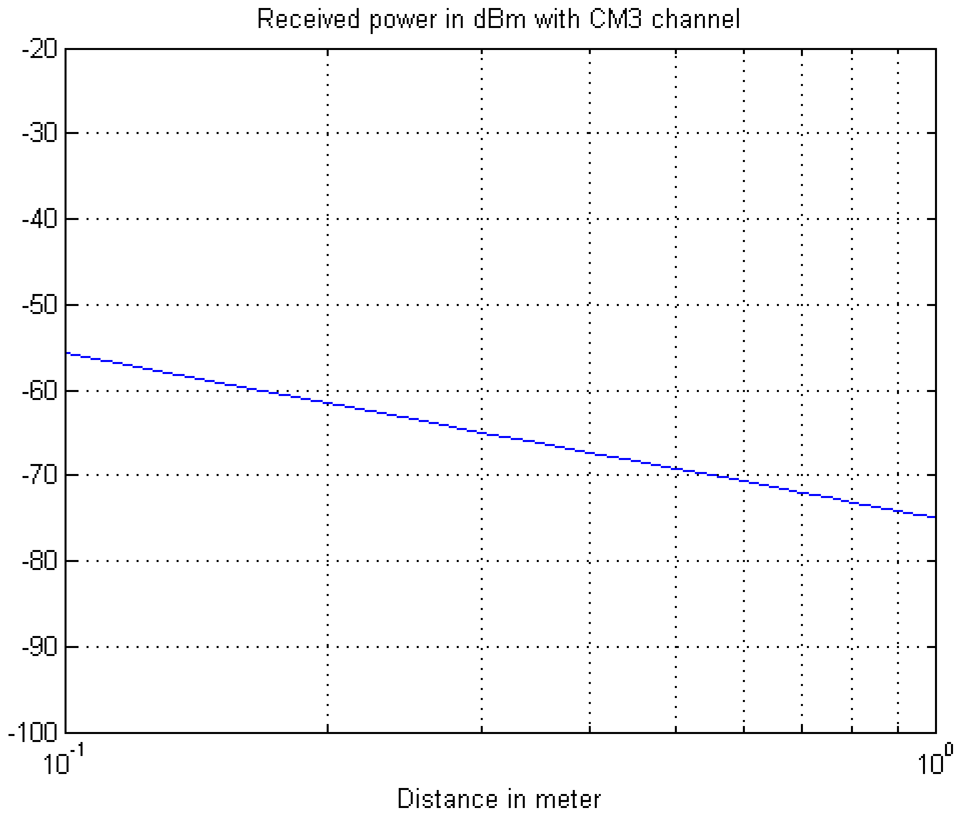
SNR_{MIN} = -7dB for BER 1×10^{-6} at 250 kbps [Eurasip 2005]

SNR conversion in FM-UWB radio

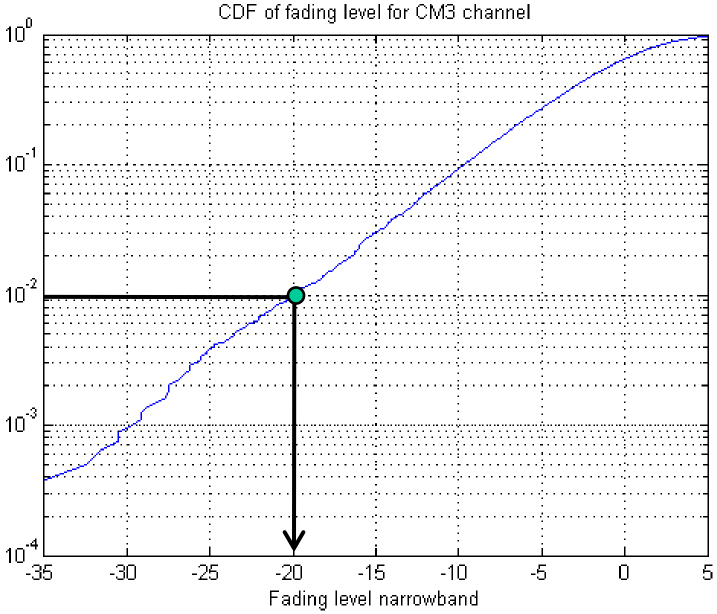


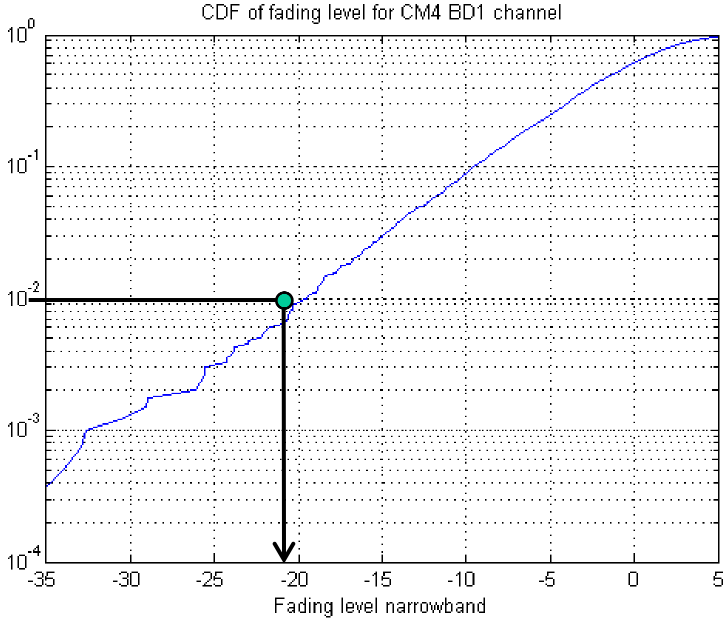
John F.M. Gerrits / John R. Farserotu, CSEM

Received power in CM3 channel (body surface – body surface)



Fading margin required in narrowband system





Fading margin FM-UWB, 96,000 CM3 realizations