

Project:

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

Submission Title: CSEM FM-UWB proposal presentation

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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.

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FM-UWB Alliance

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Presentation Outline

1. Wearable MBAN Applications & Requirements

2. Regulations, Coexistence, SAR

3. QoS, Robustness

4. Hardware Prototype

5. Medium Access Control

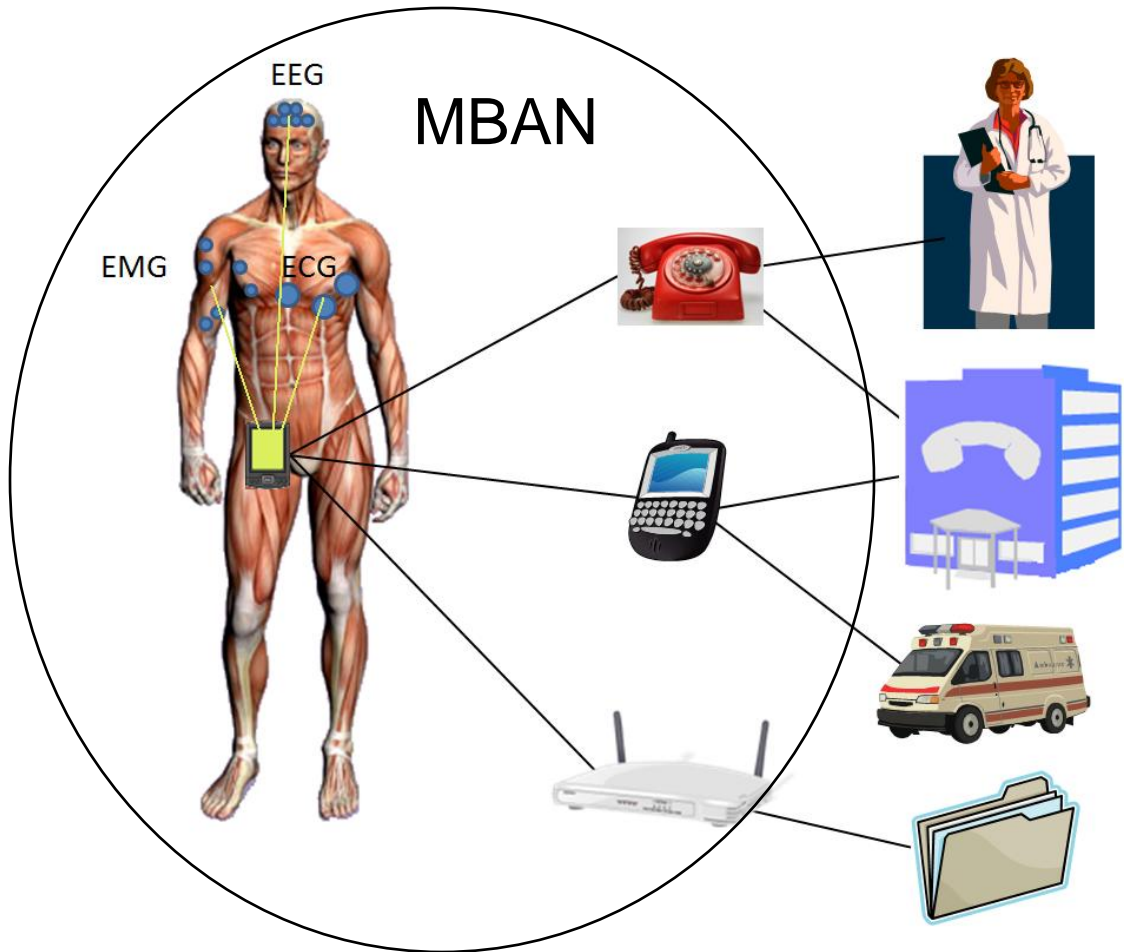
Wearable Medical BAN applications

- **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



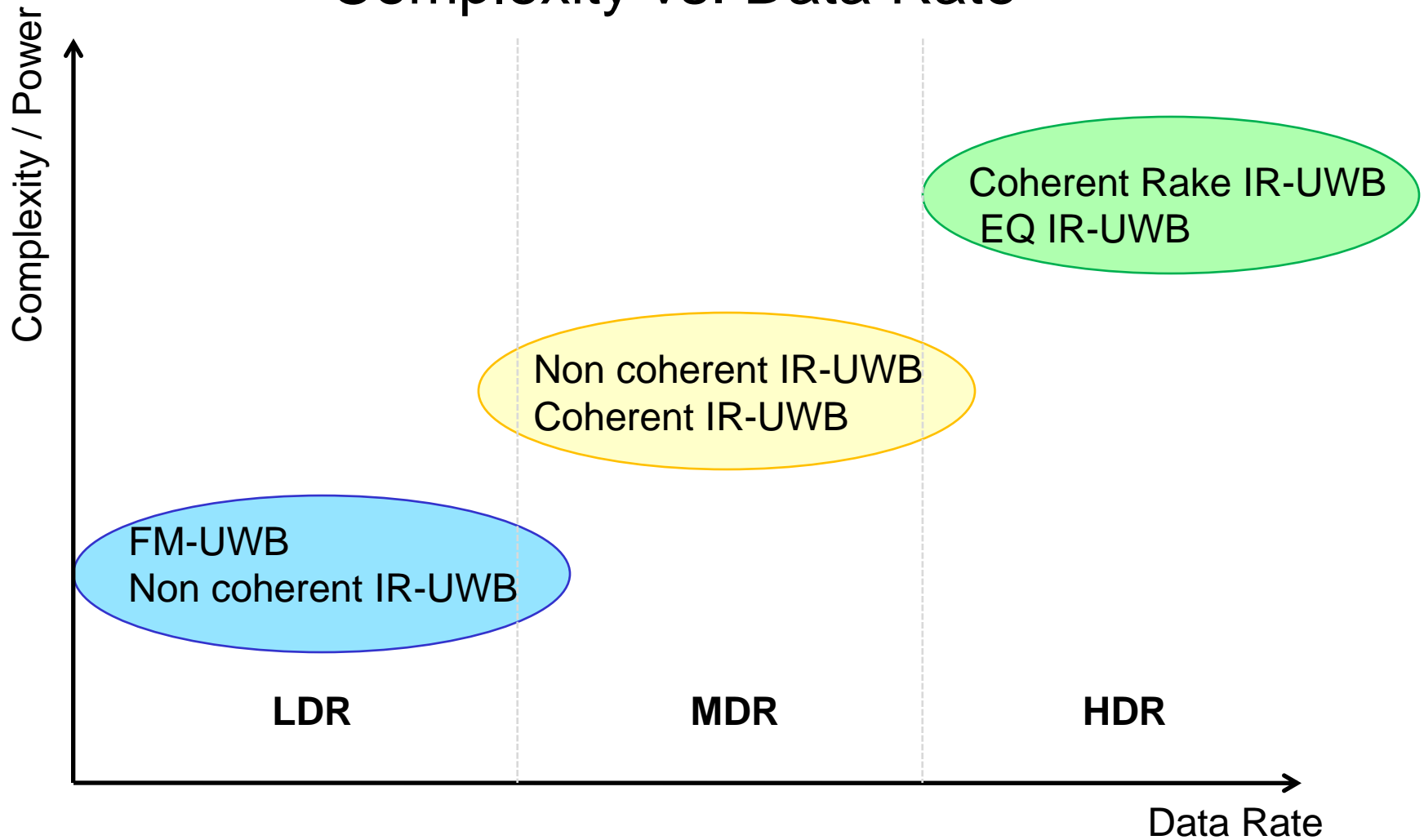
Key Wearable BAN requirements

| 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

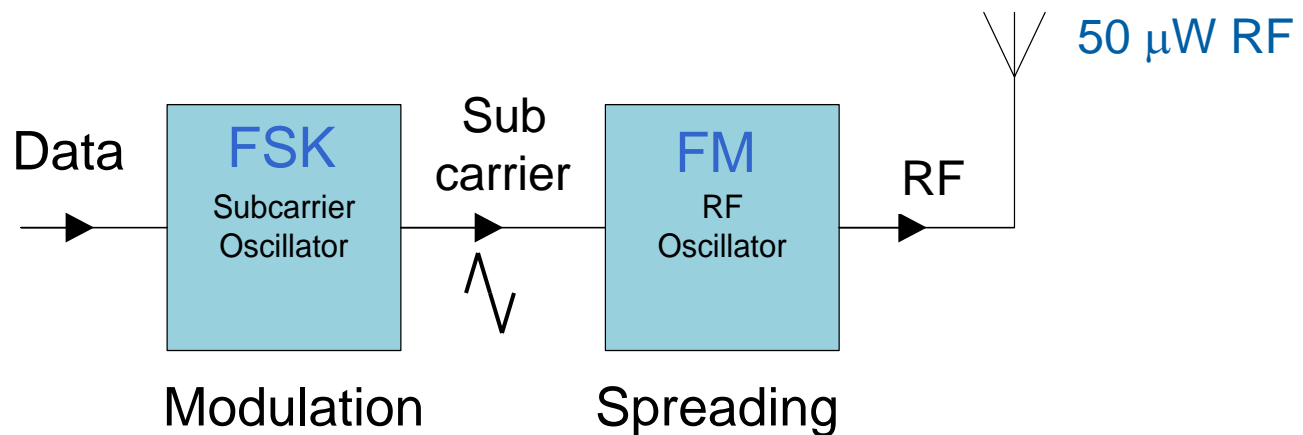
3. QoS, Robustness

4. Hardware Prototype

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Transmitter architecture

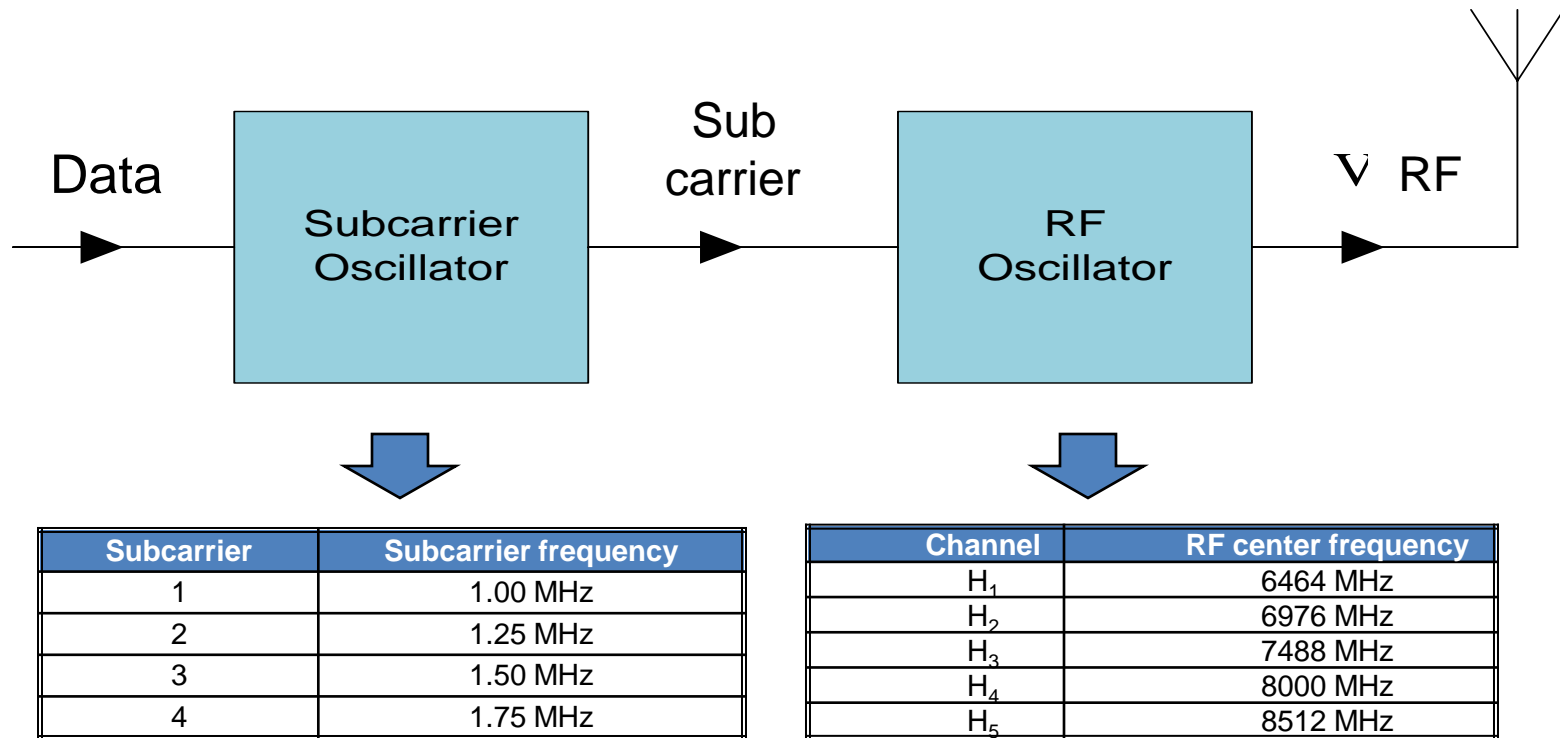
R = 30 - 250 kbps BW: 60 - 500 kHz > 500 MHz
freq: baseband 1 - 2 MHz 6 - 9 GHz



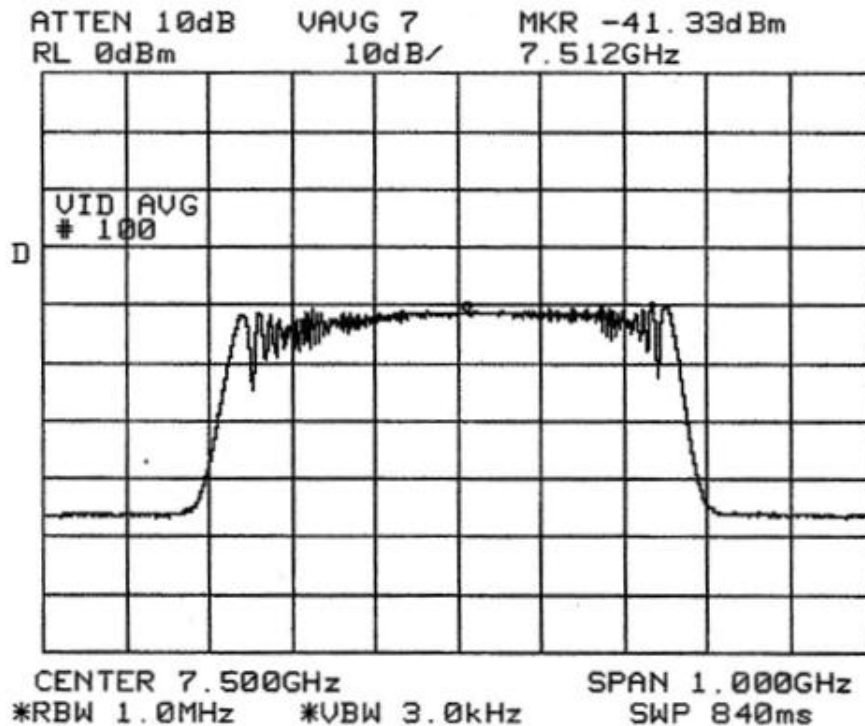
An analog FM signal may have any bandwidth independent of modulation frequency or bit rate. This is analog spread spectrum.

Subcarrier frequency = analog spreading code.

Multiple access techniques: Subcarrier and RF FDMA

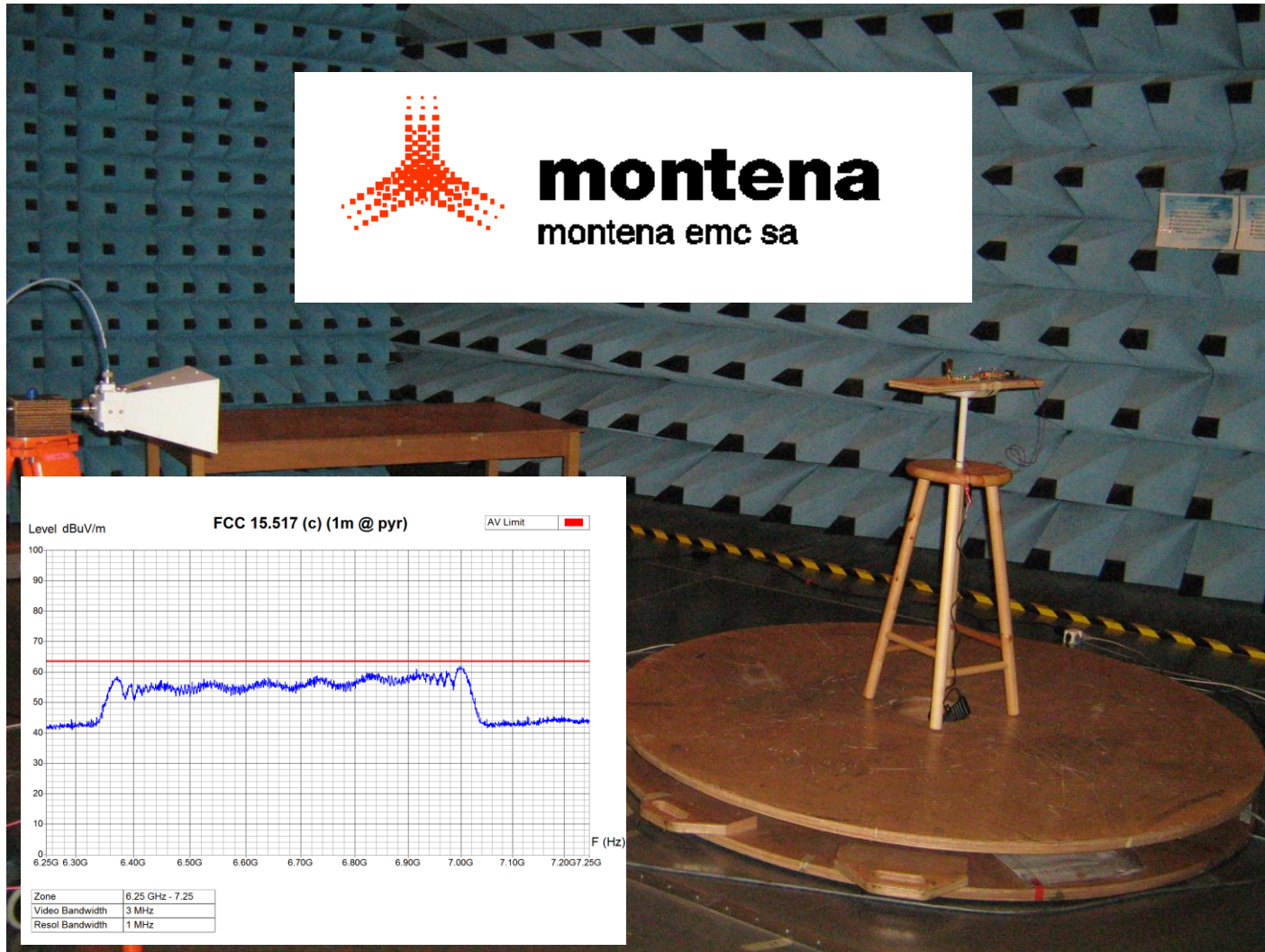


FM-UWB transmitter signal



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

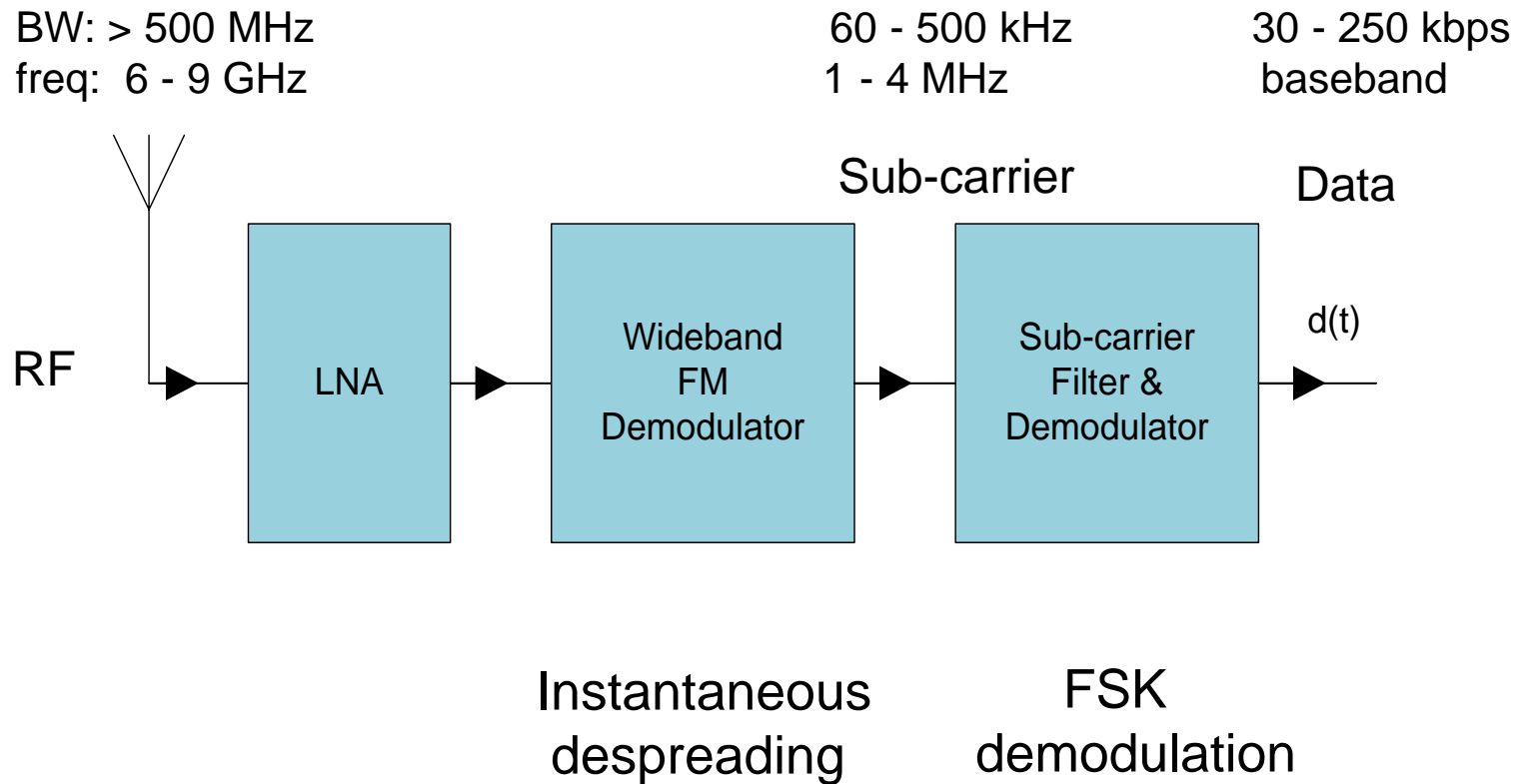
FM-UWB has been FCC pre-certified



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 bandwidth is taken into account. This bandwidth reduction after the wideband FM demodulator yields real processing gain:

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

$$G_{PdB} = 30 \text{ dB @ } R = 250 \text{ kbps}$$

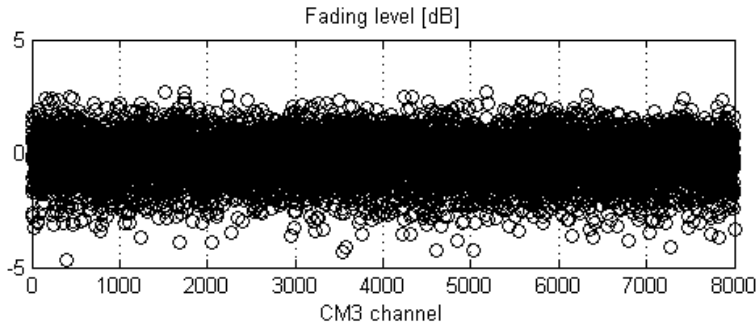
$$G_{PdB} = 39 \text{ dB @ } R = 31.25 \text{ kbps}$$

Processing gain mitigates interference

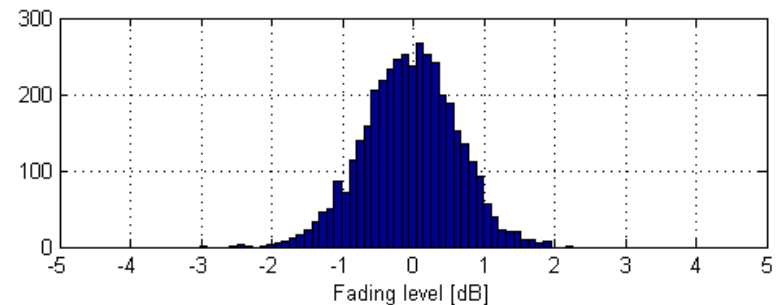
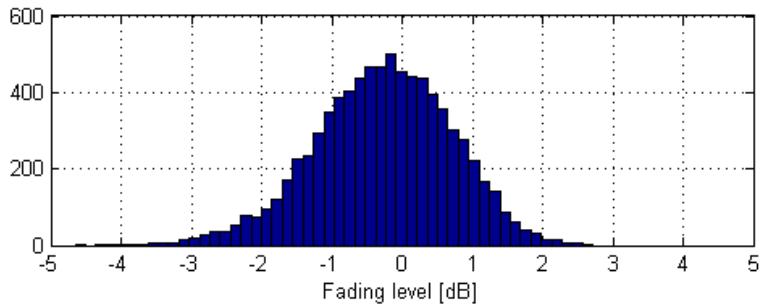
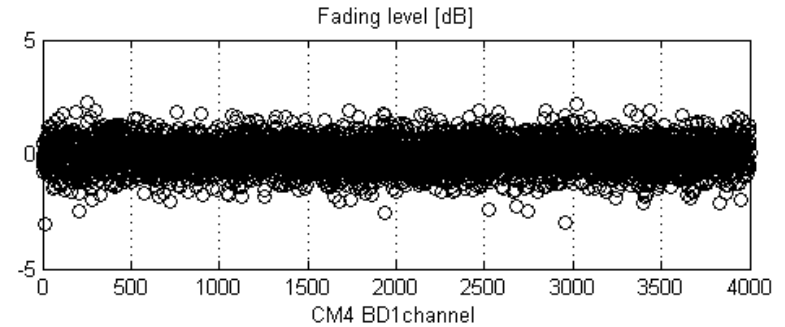
- narrowband
- UWB
- multiple-access

Robustness to frequency-selective multipath

Body surface – body surface
CM3 channel:



Body surface – external
CM4 channel:



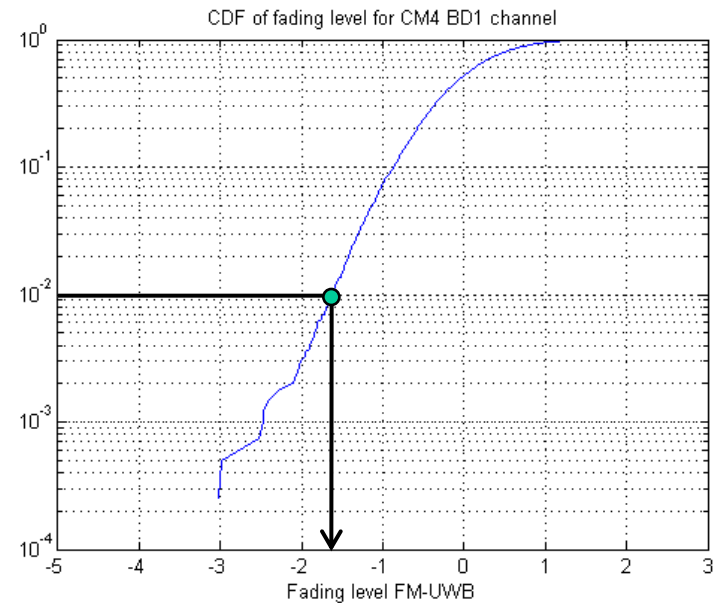
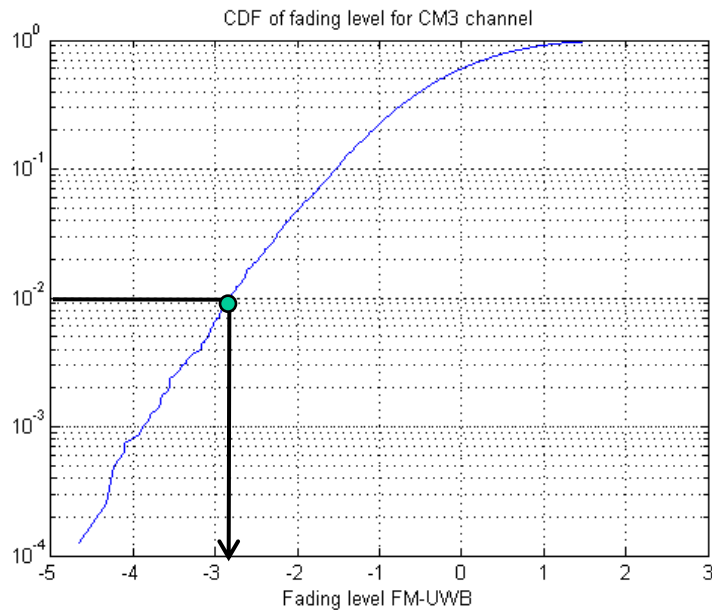
[ICUWB 2007]

BRF = 500 MHz)

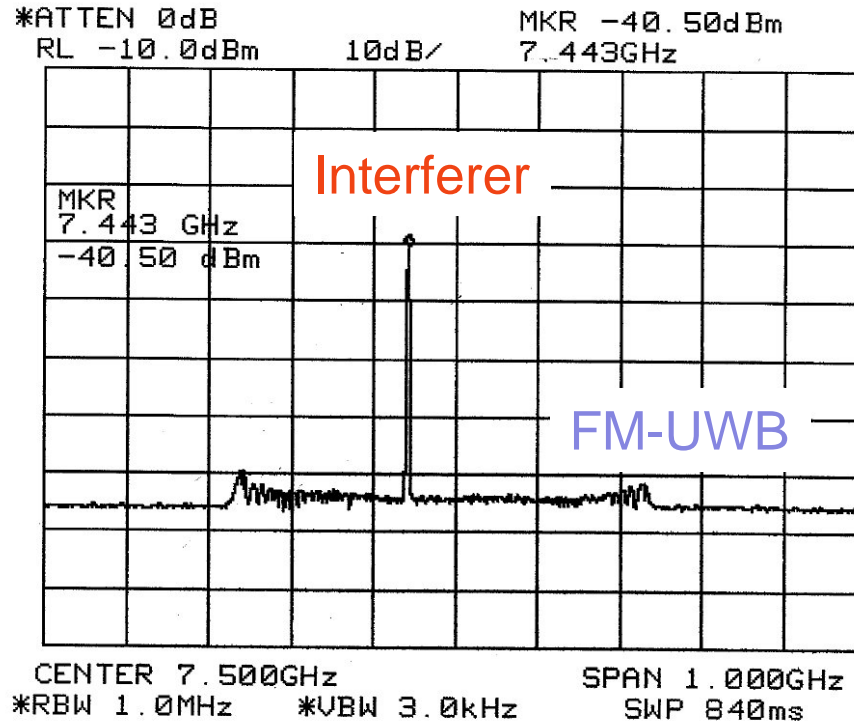
Requirements for 99 % availability:

- 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)

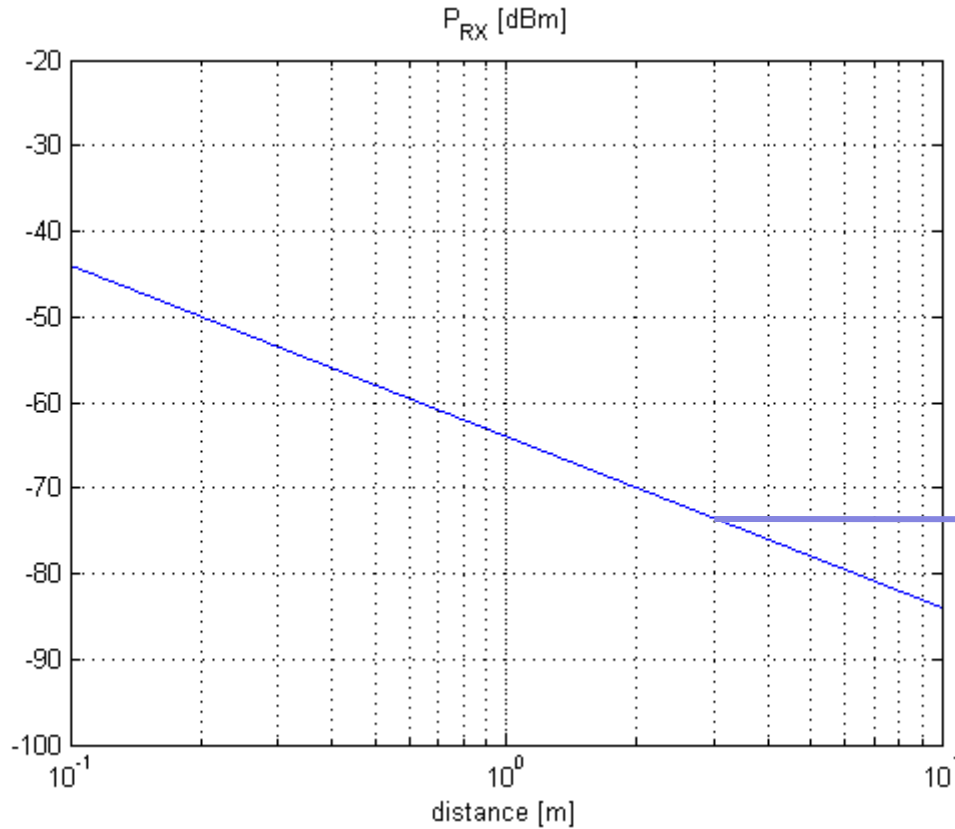


Robustness to narrowband interference



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

Received signal at 3 meters (CM4).



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

$$d = 3\text{m}, f = 7.5 \text{ GHz}, \lambda = 4 \text{ cm}$$

$$\rightarrow P_{RX}(3\text{m}) = -74 \text{ dBm}$$

Receiver sensitivity

$$B_{RF} = 500 \text{ MHz}$$

$$N_{RX} = 5 \text{ dB}$$

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

$$\text{SNR}_{\text{MIN}} = \frac{\quad}{-7 \text{ dB}}$$

$$\text{Theoretical receiver sensitivity} \quad -89 \text{ dBm}$$

Implementation loss and fading margin

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

$$4 \text{ dB implementation losses}$$

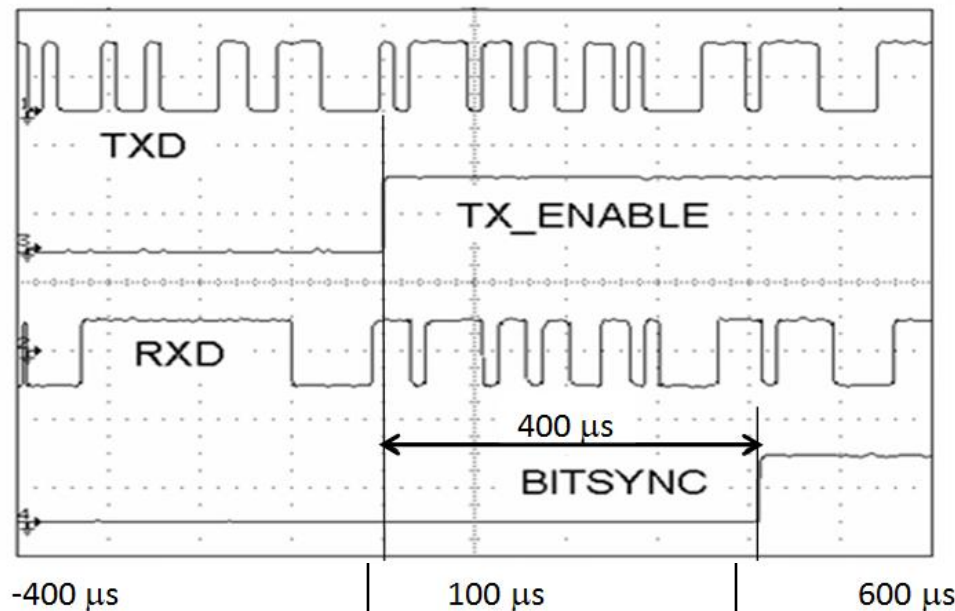
$$- \quad 3 \text{ dB fading margin for multipath}$$

$$\frac{\quad}{8 \text{ dB positive margin} = \text{link closed}}$$

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 | L_p | -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 | N_0 | -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 | L_i | 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



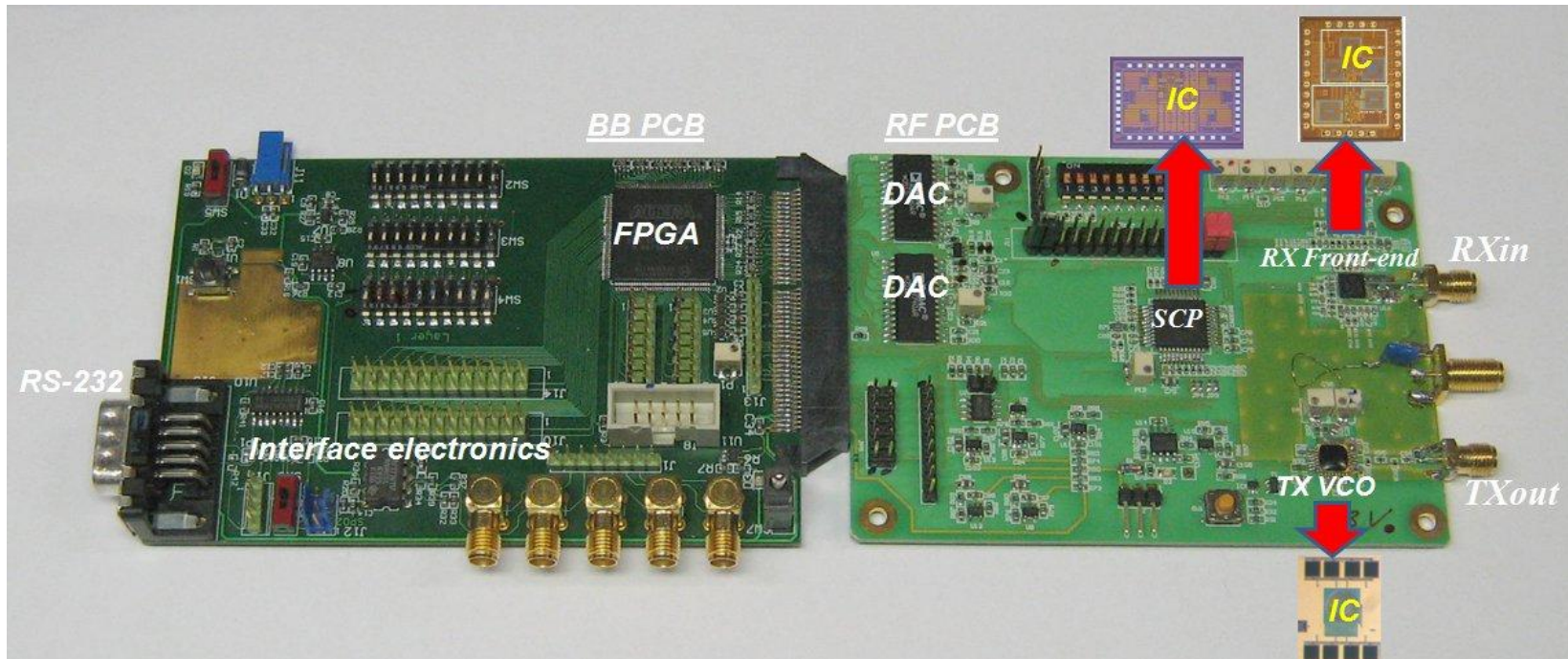
< 25 bits
(400 us @ 62.5 kbps
100 us @ 250 kbps)
synchronization time

- 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 μ s |
| RX synchronization time | < 400 μ 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 SpO₂ sensor.

Concluding remarks on the FM-UWB PHY

- **Good co-existence**
 - with existing air interfaces
- **Robustness**
 - interference, multipath
- **Spectral properties**
 - 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.

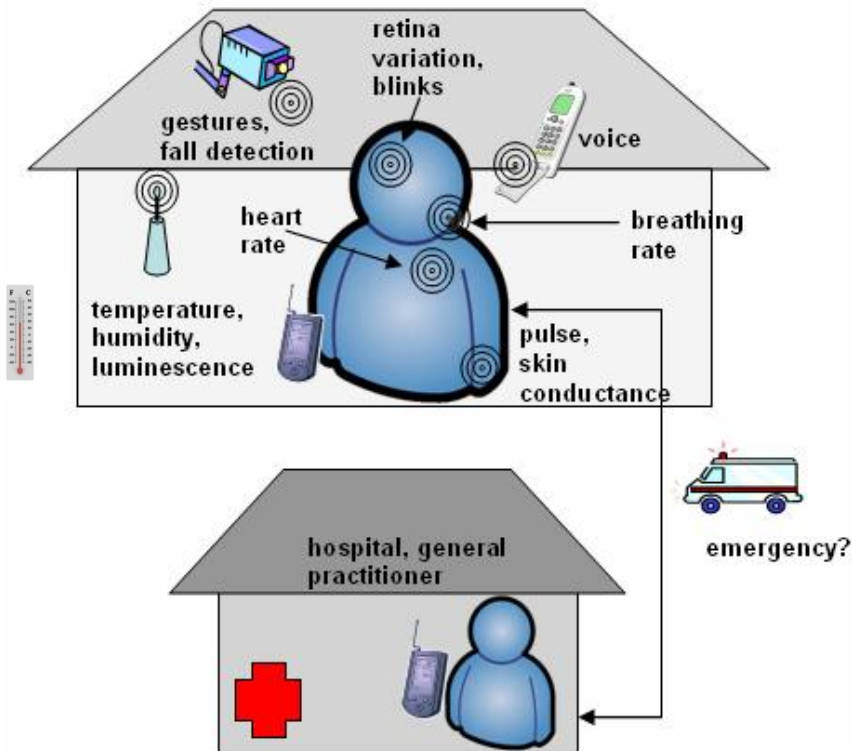
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Targeted Applications and Requirements

Medical Body Area Networks

Continuous measurements



Main Requirements

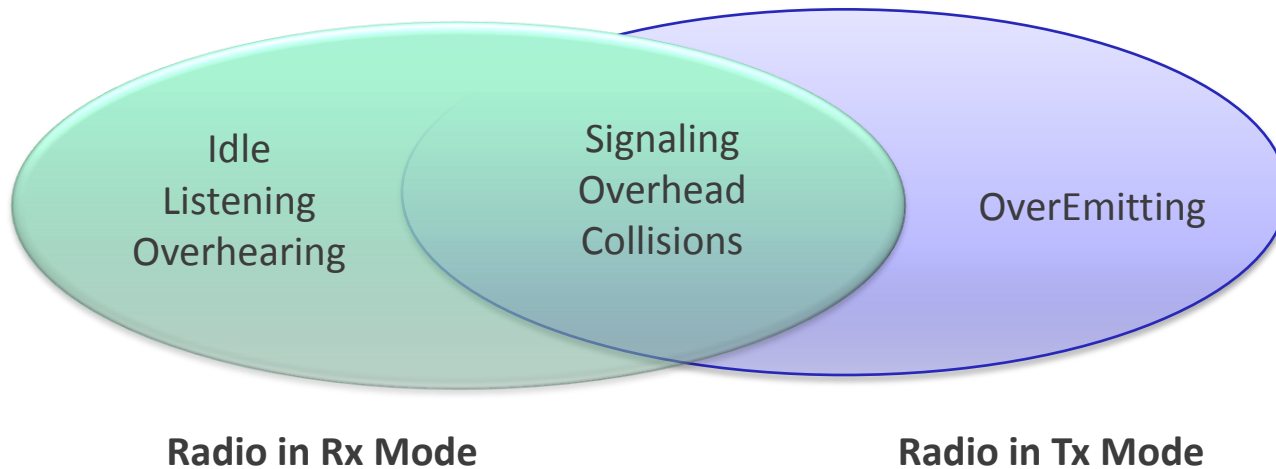
- Low Power
- Scalability
- Robustness
- Coexistence



[IEEE1]

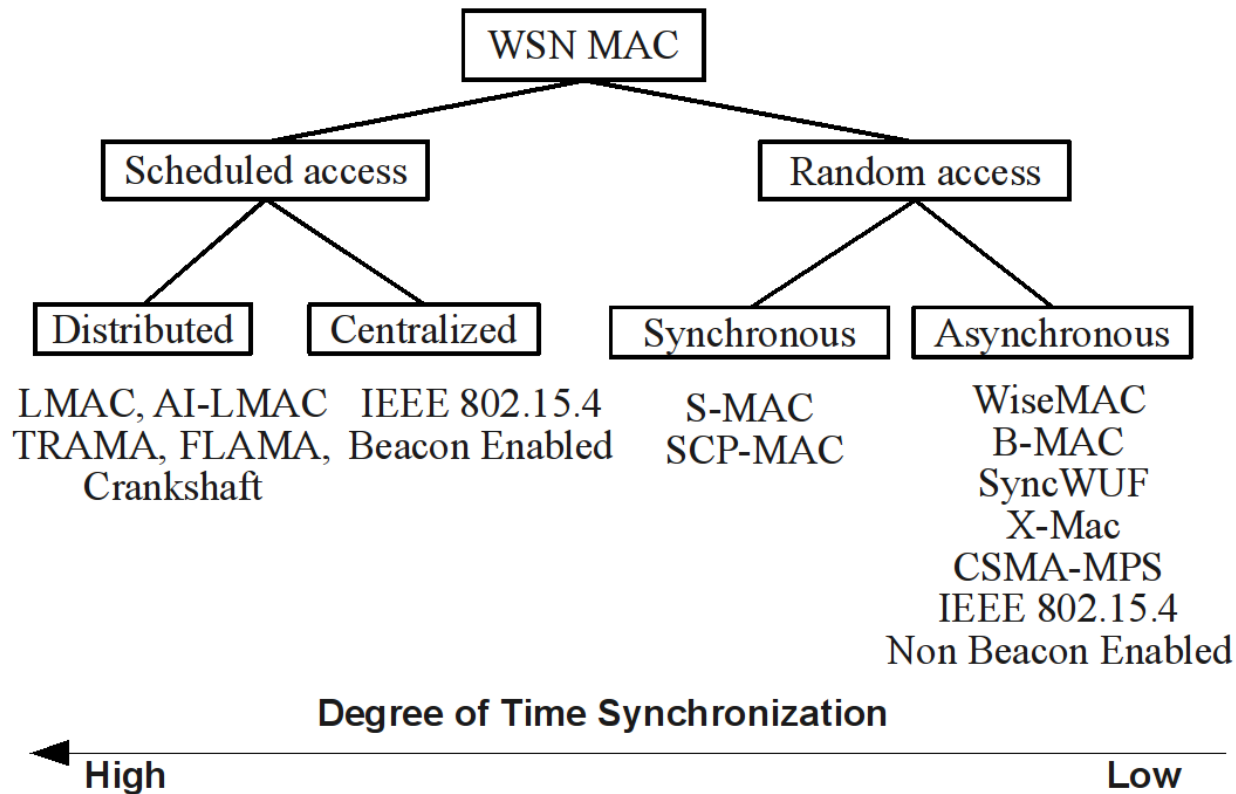
Ultra Low Power MAC design

Types of energy waste



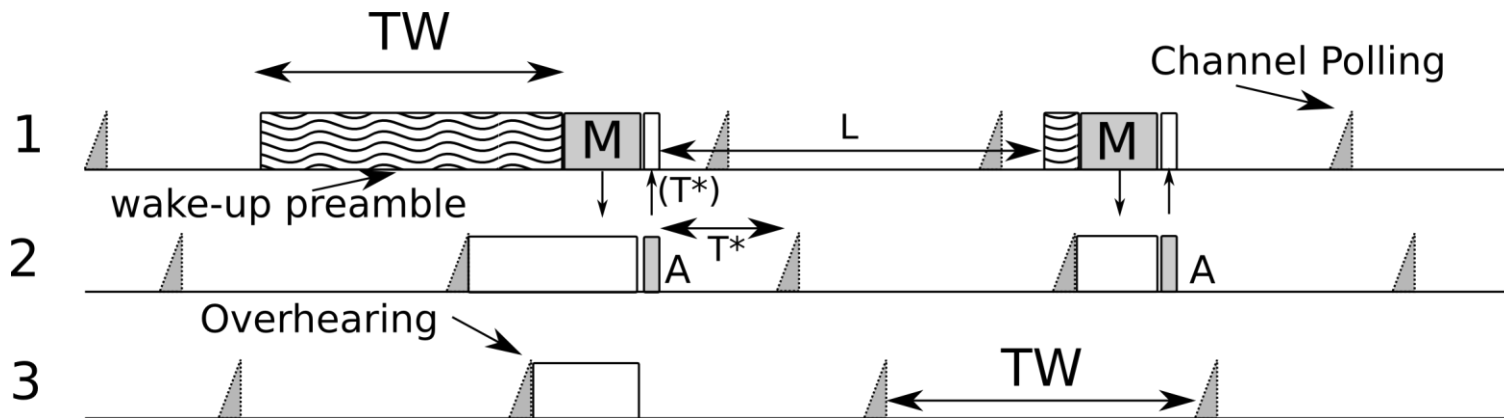
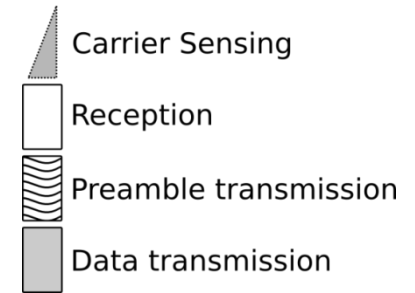
Ultra Low Power MAC Design

MAC protocol families



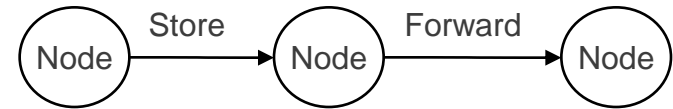
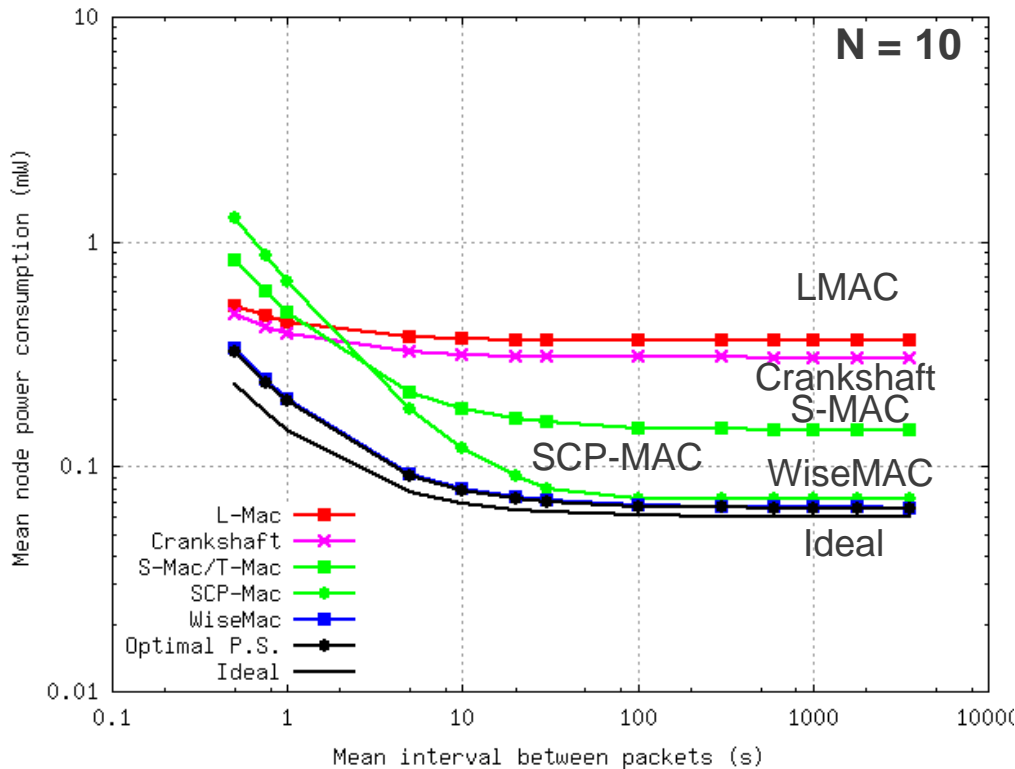
WiseMAC Ultra Low Power MAC Scheme

- Periodic sampling
- Opportunistic Link-local Synchronization



[WISENET2004], [WISEMAC2004]

WiseMAC Ultra Low Power MAC Scheme



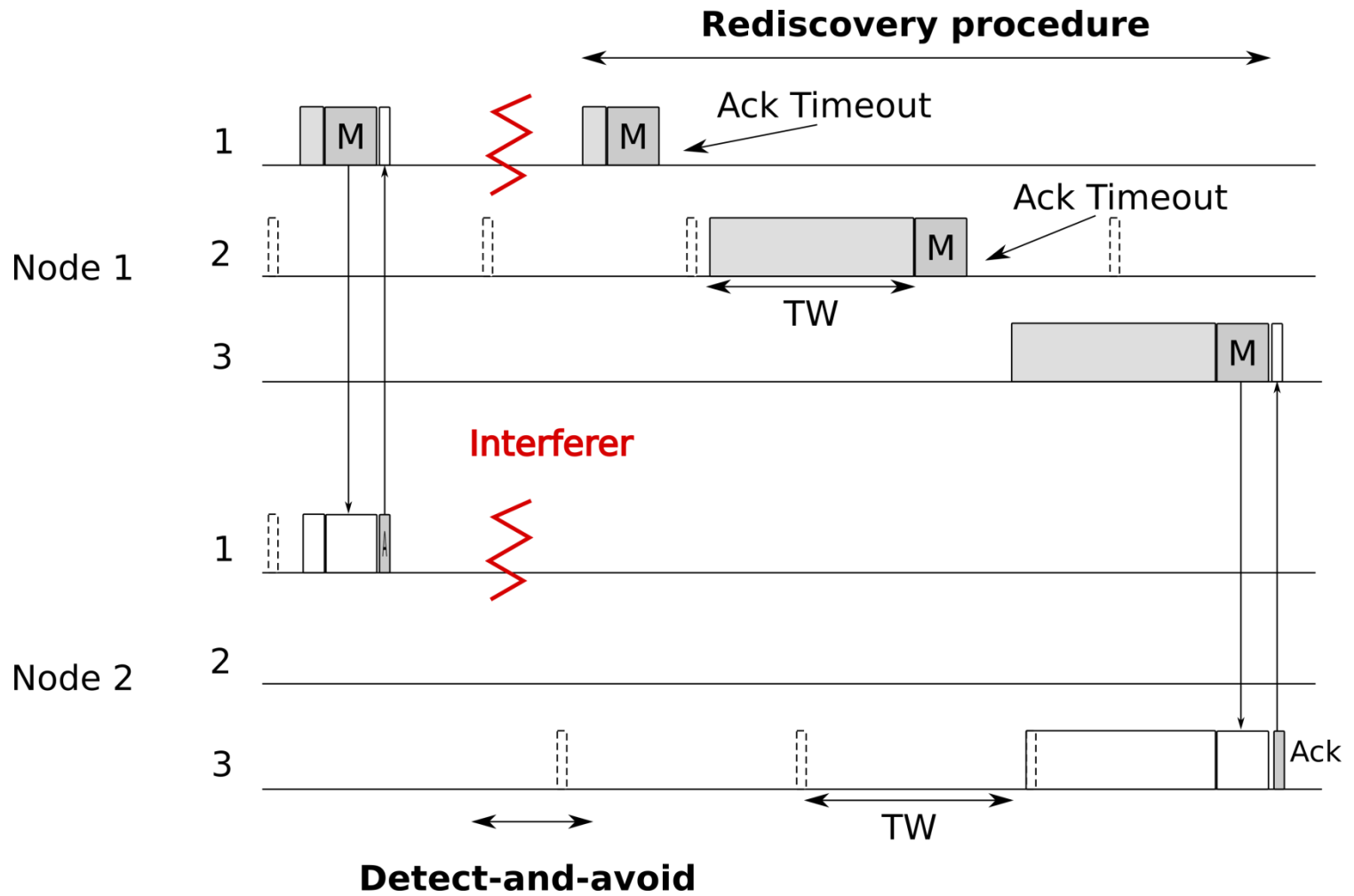
WiseMAC Deviations from Ideality

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

[EW2008]

Slide 33

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

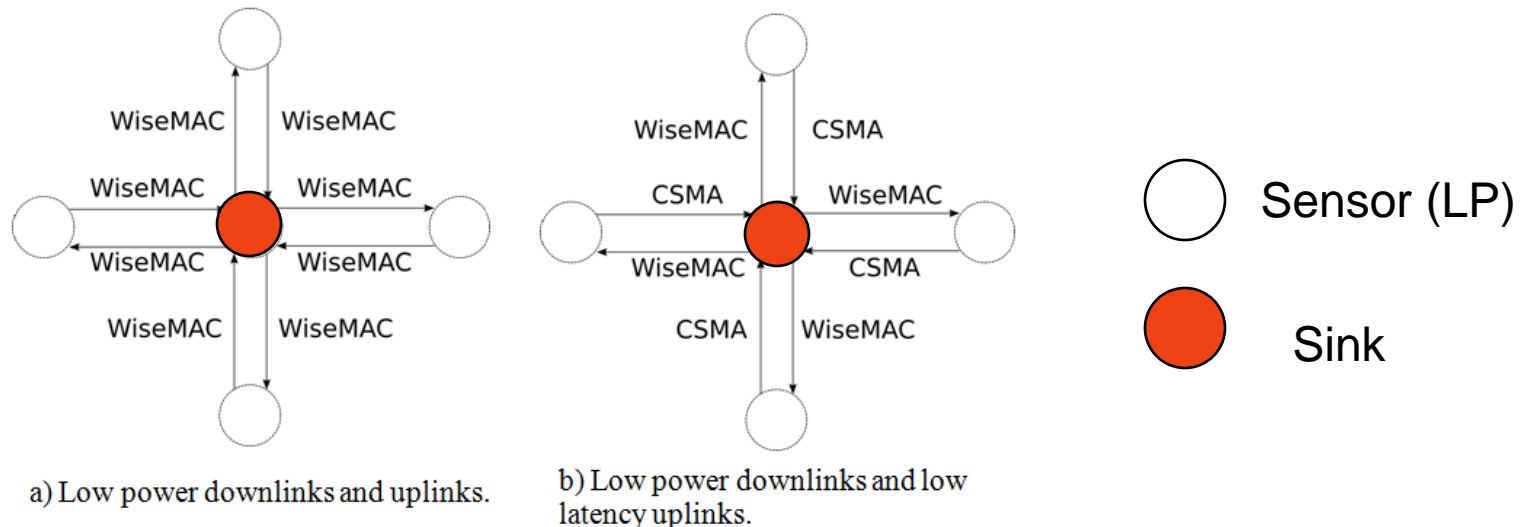
Have some nodes switch to an interoperable mode that does not exhibit limited throughput
= CSMA (IEEE 802.15.4 Non Beacon Enabled Mode)



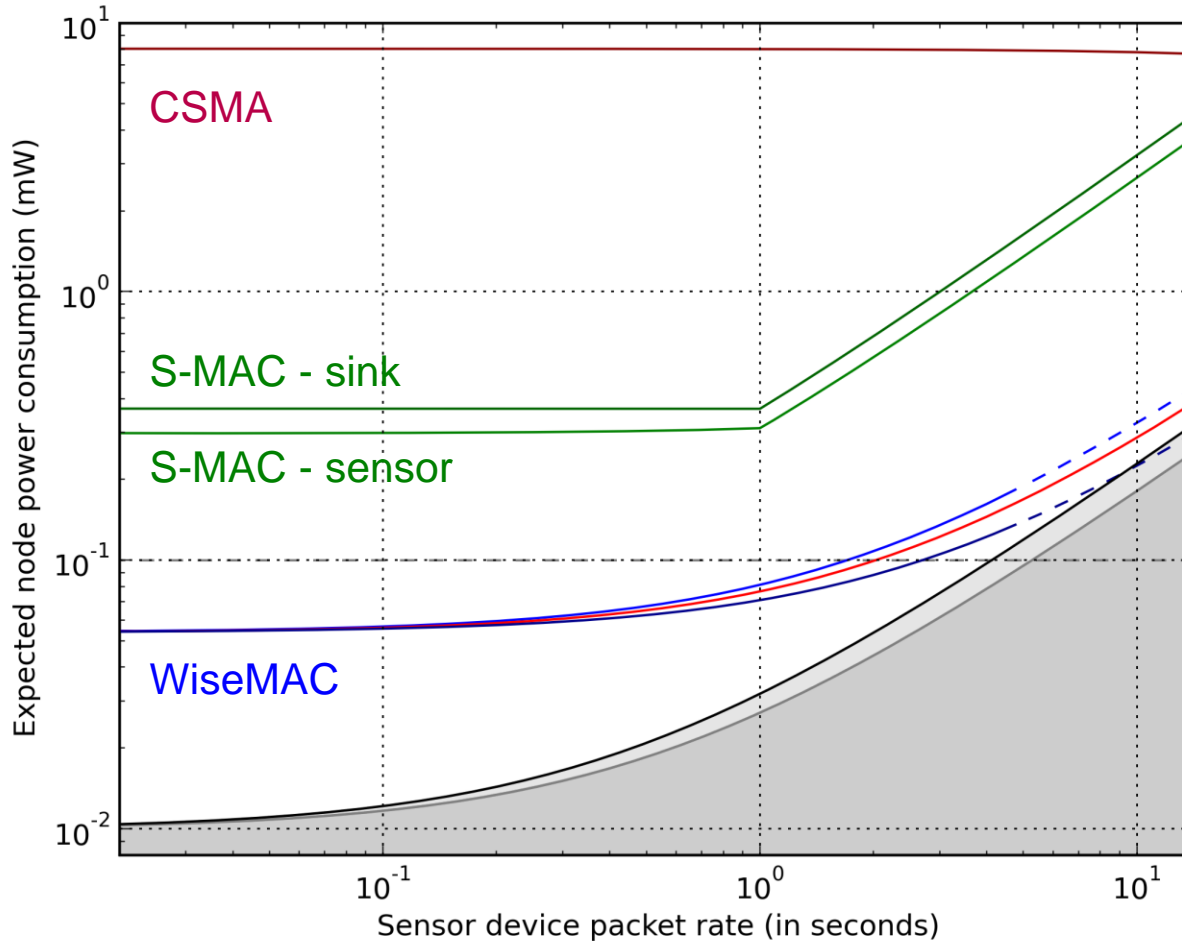
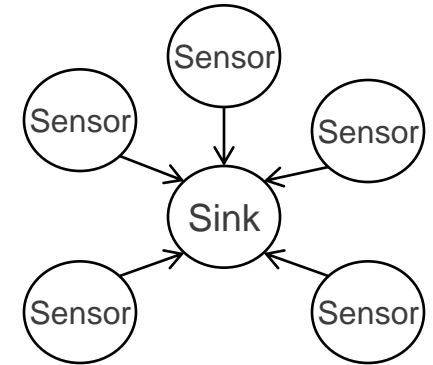
WiseMAC High Availability

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)



Power Consumption



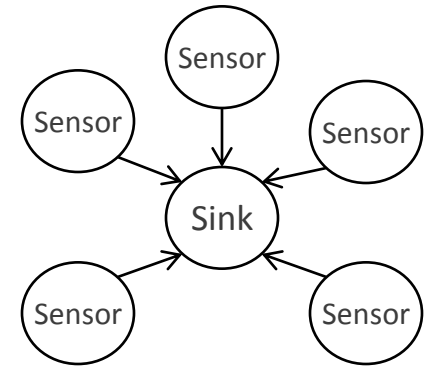
WiseMAC-HA - sensor

Ideal - sink
Ideal - sensor

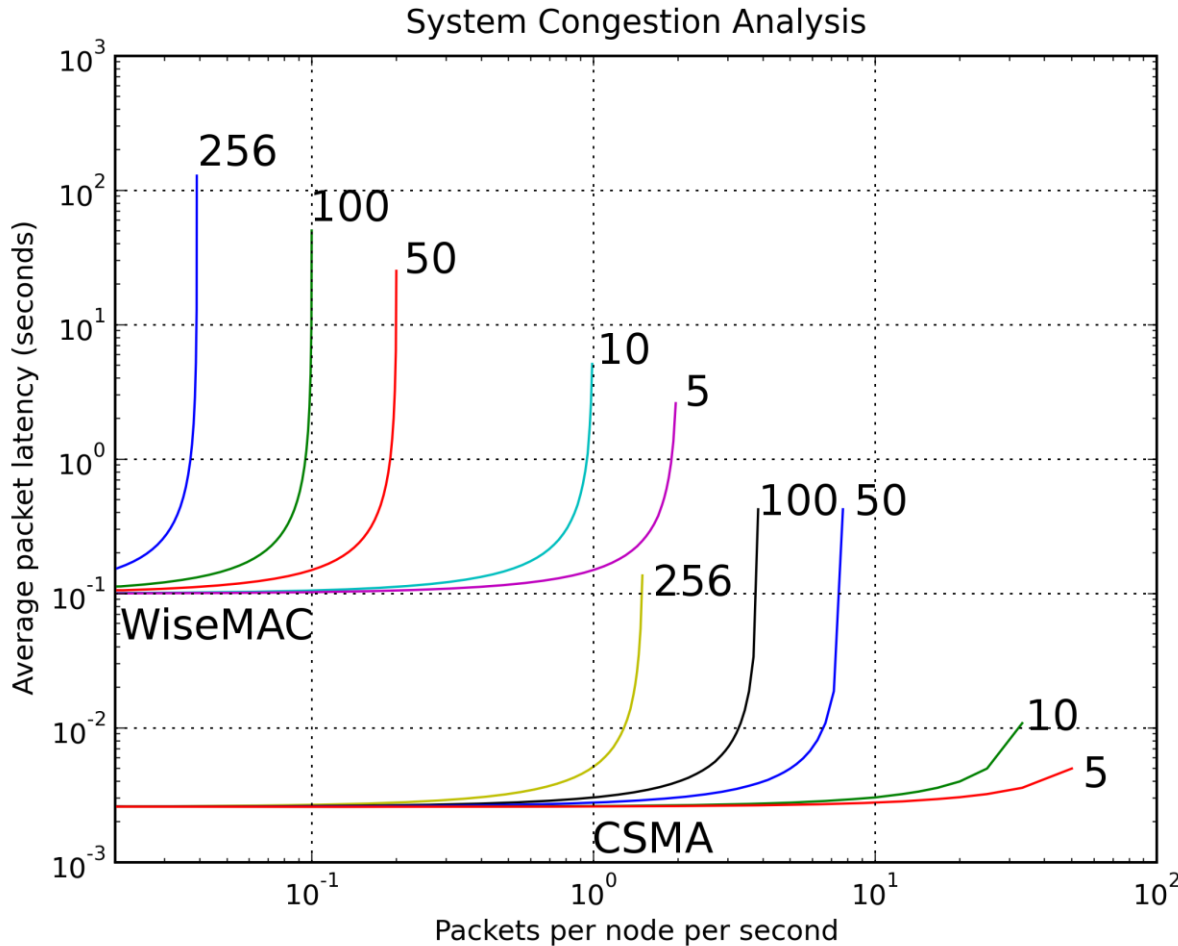
- 5 sensor devices
- 16 bytes data packets
- 4 bytes Ack messages
- FM-UWB** (250 kbps)
- 8 mW Rx
- 4 mW Tx

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 limits)
- 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 accommodate other operating modes



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

Proposal Evaluation Criteria



Regulatory

- FCC pre-certified



Raw PHY data rate

- LDR Medical BAN



Transmission distance

- ≥ 3 m



PER

- $\leq 10\%$ (256 octet packet)



Link budget

- Closed (CM3/CM4)



Power emission level



Interference and coexistence

- UWB, analogue spread-spectrum



Security

- Compatible IEEE802.15.4



Reliability

- $\geq 99\%$ availability (CM3/CM4)



QoS

- Fast acquisition (25 bit)
- < 1 s delay



Scalability

- e.g. 256 devices



MAC transparency



Power efficiency

- Continuous: ≤ 4 mW Tx, ≤ 8 mW Rx
- ≤ 60 μ W (low duty cycle)



Topology

- Star (or mesh)



Bonus point

- Real HW, real SW!

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



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.
- [ICUWB2009] Jérôme Rousselot and Jean-Dominique Decotignie, "Wireless Communication Systems for Continuous Multiparameter Health Monitoring", invited paper, ICUWB 2009, Vancouver, Sept. 2009.
- [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.

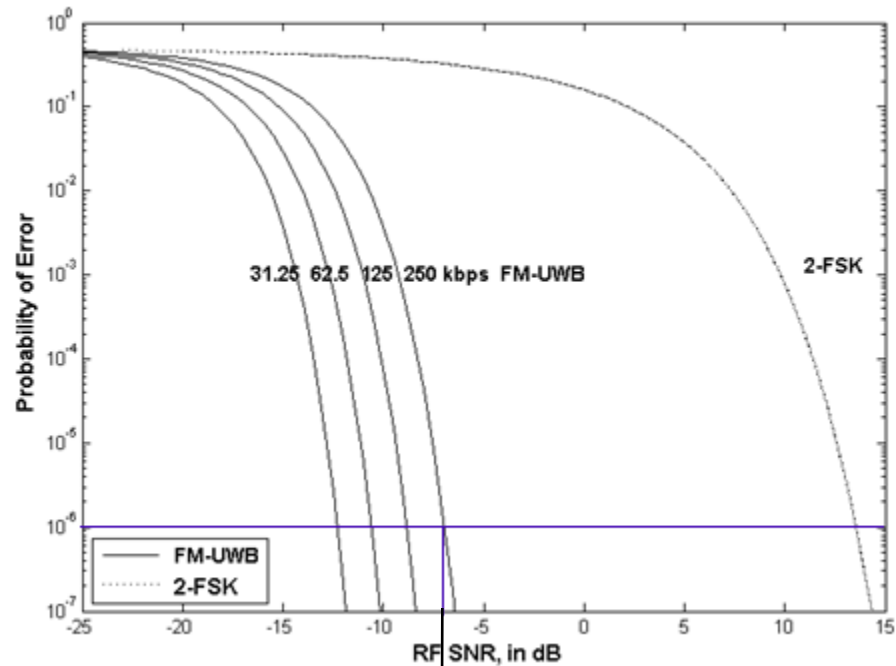
[WISENET2004]

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]

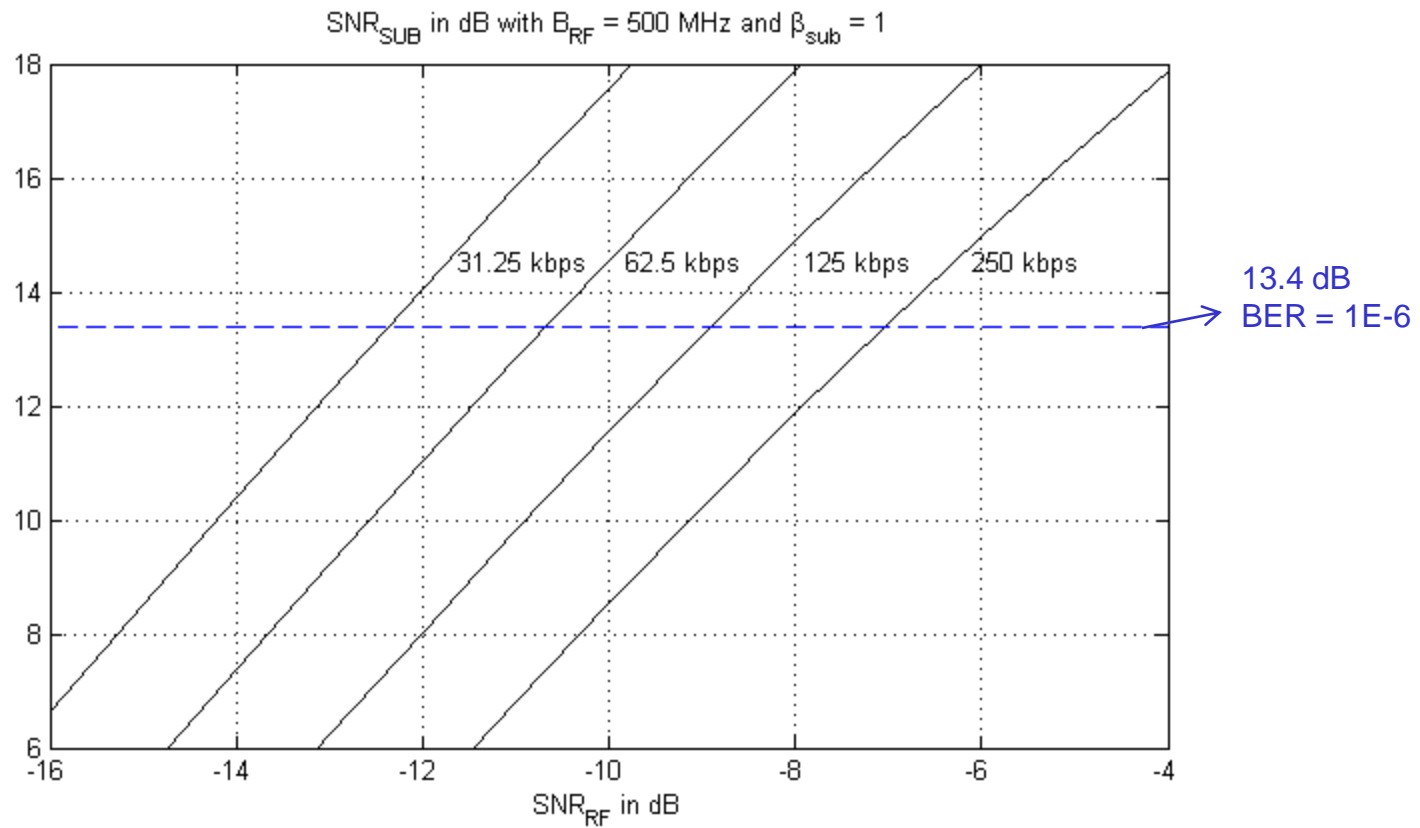
A. El-Hoiydi, and J.-D. Decotignie, " WiseMAC: An Ultra Low Power MAC Protocol for Multi-hop Wireless Sensor Network," Proc. of the First International Workshop on Algorithmic Aspects of Wireless Sensor Networks (ALGOSENSORS 2004), Lecture Notes in Computer Science, LNCS 3121, pp. 18-31, Springer-Verlag,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

Sensitivity of FM-UWB receiver

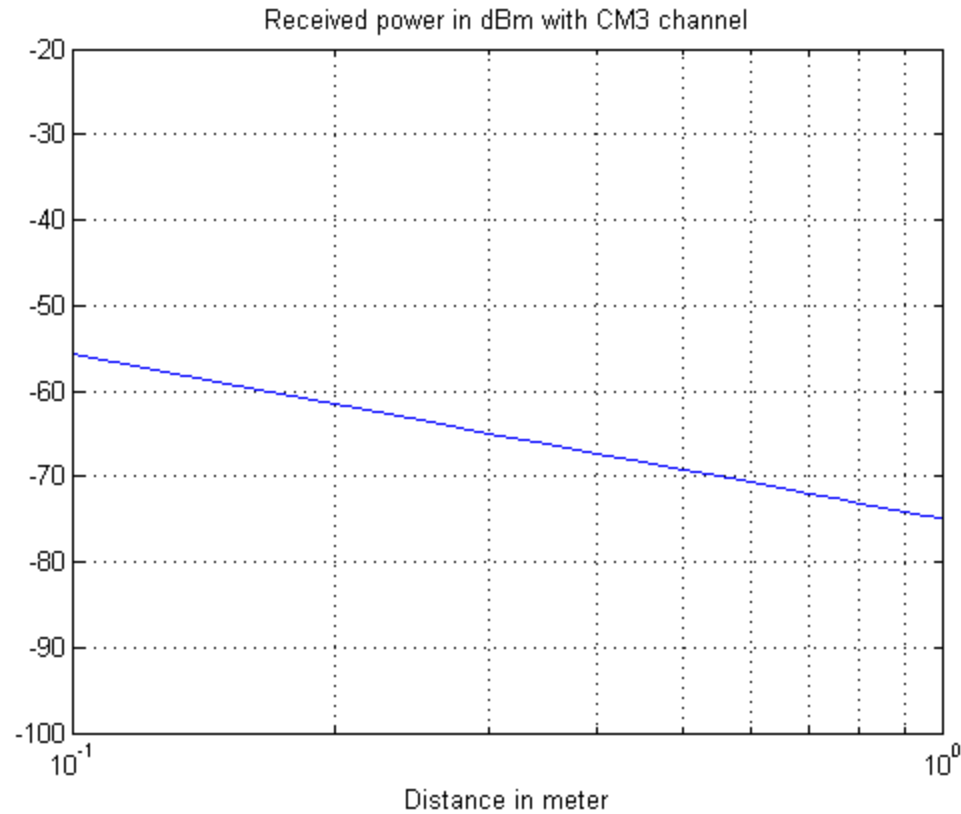


$\text{SNR}_{\text{MIN}} = -7\text{dB}$ for BER 1×10^{-6} at 250 kbps [Eurasip 2005]

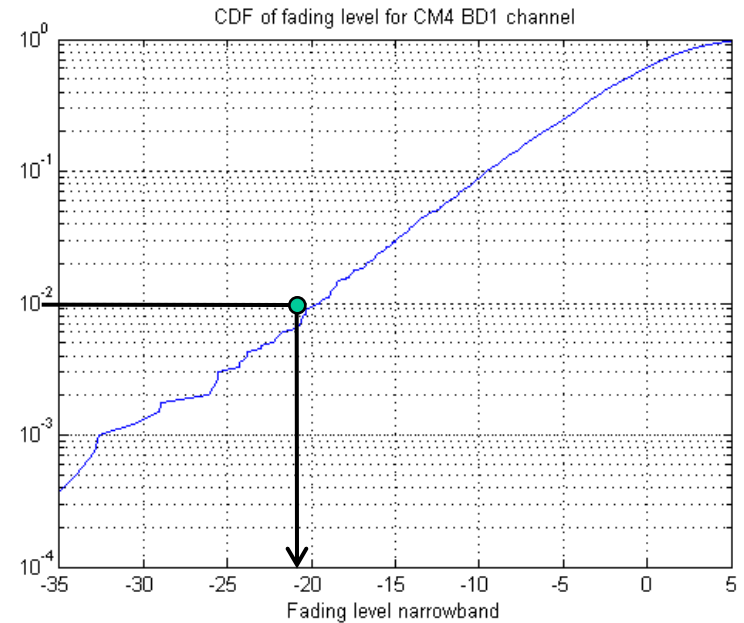
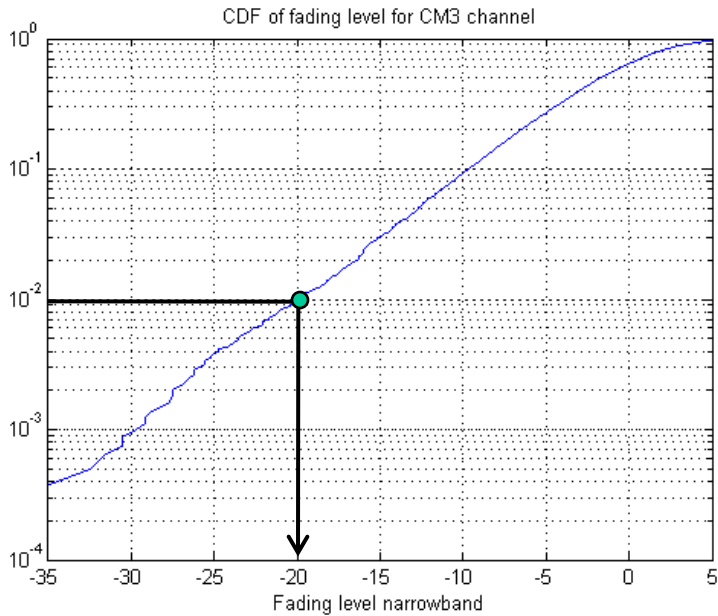
SNR conversion in FM-UWB radio



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



Fading margin required in narrowband system



Fading margin FM-UWB, 96,000 CM3 realizations

