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# Low Power and Robust PHY-MAC Solution for Medical BAN

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**SUMMARY**    This paper provides an overview of CSEMs FM-UWB PHY-MAC proposal to IEEE802.15.6, Task Group 6, Body Area Networks. The proposed solution provides for an ultra low power, yet robust and reliable solution for low data rate medical BAN. The paper examines the key features and performance aspects of the proposal.
*key words:  BAN, FM-UWB, FSK, narrowband, hybrid radio*

## 1.  Introduction

Ultra-wideband (UWB) communications systems are poised to play an increasingly important role in today's short-range communications systems, especially in personal area (PAN) and body area network (BAN) applications. UWB systems have demonstrated greater robustness than traditional narrowband schemes to frequency-selective multipath and interference.  The low transmit power of UWB radios extends operating time from a single battery and eases coexistence with existing wireless communication systems. The IEEE802.15 Task Group 6 (IEEE802.15.6) is currently developing a BAN communication standard [1].  Health monitoring and body-area network (BAN) applications require tetherless connectivity at data rates below 250 kbps, a range less than 10 m, and operational lifetime from a single battery charge of weeks or months.  In addition, cost and size constraints envisioned for short-range applications require low-complexity RF interfaces.

In Europe, the European Telecommunication Standards Institute (ETSI) Project eHealth (ETSI EP eHealth) is responsible to:
- collect and define the Health ICT related requirements from relevant stakeholders and to input the requirements to the concerned ETSI Technical Bodies;
- identify gaps, where existing ETSI standards do not fulfill the Health ICT requirements, and suggest further standardization activities to fill those gaps [2];
- develop Health ICT related deliverables in all areas not covered by existing system specific and horizontal Technical Bodies or other SDO;
- ensure that activities within EP eHealth are coordinated with both the relevant ETSI Technical Bodies and other European and International Standards making bodies to avoid duplication of effort and deliverables;
- coordinate ETSI positions on Health ICT related issues and

**Table 1**    European research projects on BAN/PAN.

| Project | Medical BAN/PAN aspects |
|---|---|
| MyHeart and HeartCycle | Research spanning the whole value chain from textile research, via fashion and electronic design, towards medical and home-based applications to improve the quality of life for coronary heart disease and heart failure patients by monitoring their condition and involving them in the daily management of their disease. |
| MAGNET and MAGNET Beyond | FM-UWB based PAN and BAN for, e.g., health and wellness applications. |
| eSENSE and SENSEI | Wireless Sensor Networks (WSN) including medical telemonitoring applications. |
| PULSERS | IR-UWB based PAN and BAN for applications including health and wellness. |

represent ETSI externally.

In addition to standardization activities, there are a substantial number of European research projects involving medical applications of BAN/PAN. Major projects include: MyHeart [3], HeartCycle [4], MAGNET and MAGNET Beyond [5], eSENSE and SENSEI. An overview is provided in Table 1.

CSEM is proposing a Frequency Modulation UltraWideband (FM-UWB) physical layer (PHY) together with a WiseMAC based Medium Access Control (MAC) layer for wearable medical Body Area Network (BAN) applications. This ultra low power, yet robust PHY-MAC solution is ideal for low data rate (LDR) medical BAN operating at data rates of up to 250 kbps.

IEEE802.15 Task Group 6 is expected to deliver a multi-radio standard including both narrowband and UWB solutions and operating at various frequencies: e.g., FSK at 400 MHz (implanted devices), 868 MHz and 2.4 GHz; UWB in the 7.25 to 8.5 GHz band. A hybrid FSK/FM-UWB radio solution combining the best of narrowband Frequency Shift Keying (FSK) and wideband FM-UWB is herein proposed.

This solution offers higher reliability for users through radio and spectrum diversity, as well as, increased system capacity and enhanced interoperability.  It offers the potential to facilitate the convergence of narrowband and UWB wearable Medical BAN solutions.

A discussion of the FM-UWB PHY-MAC, its perfor-

mance and the proposed hybrid FSK/FM-UWB solution is provided in the sections that follow.

## 2. FM-UWB PHY

### 2.1 Transmitter

The FM-UWB physical layer (PHY) 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 $\beta$ that can be chosen freely. This yields either a bandwidth efficient narrow-band FM signal ($\beta < 1$) or a (ultra) wideband signal ($\beta \gg 1$) that may be scaled to fit the available 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 proposed PHY solution is designed to operate in the 7.25–8.5 GHz band, which is suited for international operation and mobility. It may also be adapted to operate in other frequency bands (e.g. the 4.2–4.8 GHz band). Figure 1 provides a 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 [6]. The transmitter consists of a 1–2 MHz subcarrier oscillator generating a triangular signal that is FSK modulated by the transmit data. The subcarrier signal m(t) modulates the RF VCO, yielding a constant-envelope UWB signal with flat power spectral density and steep spectral rolloff.

Figure 2 illustrates the power spectral density (PSD) of an ideal FM-UWB signal. The signal is compliant with the relevant regulatory limits [7] and [8]. The radiated power is −15 dBm (112 mV$_{pp}$ in a 50 Ω load). The subcarrier frequency is 1 MHz and the deviation $\Delta f$ is 250 MHz, yielding a modulation index $\beta$ of 250 and a signal bandwidth (−10 dB) of 500 MHz.

The PSD of a wideband FM signal is determined by, and has the shape of, the probability density function (PDF) of the modulating signal m(t) [9]. The use of a triangular subcarrier waveform, which is characterized by a uniform PDF, results in a flat RF spectrum, suited for efficient use of the available spectrum. From an implementation perspective the triangular waveform is straightforward to generate using
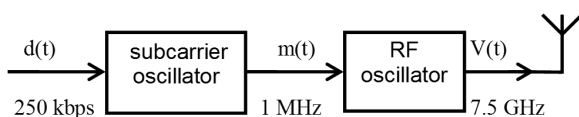
either analog or digital circuit techniques.

### 2.2 Receiver

The receiver demodulates the FM-UWB signal without the need for frequency translation (i.e., no mixing). Figure 3 illustrates the receiver block diagram. The low complexity receiver comprises a LNA, a wideband FM demodulator, and low-frequency subcarrier filtering, amplification and demodulation circuitry.

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 (Fig. 4).

The key receiver building block is the wideband FM demodulator, which is 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 [10] and [11].

The receiver processing gain (PG) is equal to the ratio of RF and subcarrier bandwidth.

$$G_{PdB} = 10 \log_{10}\left(\frac{B_{RF}}{B_{SUB}}\right) = 10 \log_{10}\left(\frac{2\Delta f_{RF}}{(\beta_{SUB}+1)R}\right) \quad (1)$$
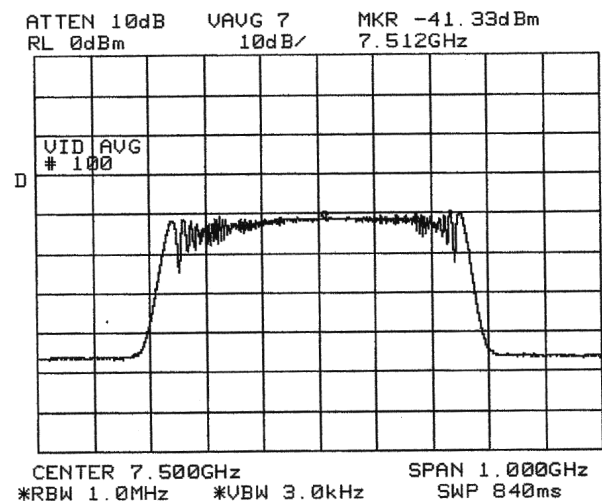
In a 250 kbps LDR system with a RF bandwidth of



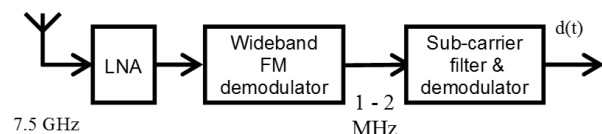**Fig. 2** Measured transmitter output signal.
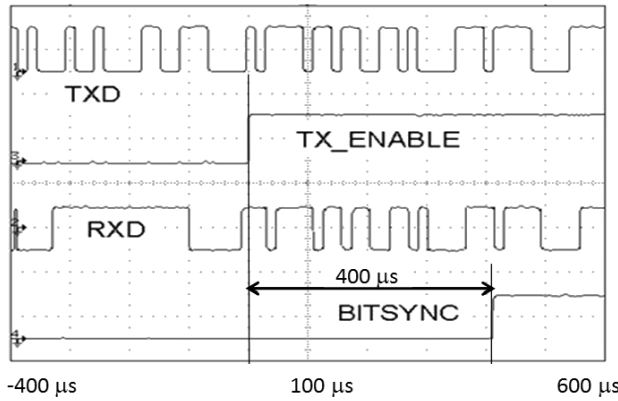


**Fig. 1** FM-UWB transmitter block diagram.



**Fig. 3** FM-UWB receiver block diagram.

**Fig. 4** Measured FM-UWB receiver synchronization time.

**Table 2** Link margin assumptions.

| Parameter | Symbol | Value | Units |
|---|---|---|---|
| Tx bandwidth | $B_{RF}$ | 500 | MHz |
| Tx power | $P_{TX}$ | -14.3 | dBm |
| Tx antenna gain | $G_{TX}$ | 0.0 | dBi |
| EIRP (peak) | EIRP | -14.3 | dBm |
| Center frequency | $f_C$ | 7.5 | GHz |
| Distance | D | 3.0 | m |
| 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 |
| Noise power density | N0 | -169.0 | dBm/Hz |
| Noise power | N | -82.0 | dBm |
| Data rate | R | 250 | Kbps |
| Subcarrier SNR | $SNR_{SC}$ | 13.4 | dB |
| RF SNR | $SNR_{RF}$ | -7.0 | dB |
| Implementation losses | $L_i$ | 4.0 | dB |
| Link margin | M | 3.0 | dB |
| Remaining margin | $M_{rem}$ | 8.2 | dB |

500 MHz, the PG is 30 dB which allows the system to tolerate a 17 dB stronger FM-UWB interferer before the probability of error degrades to $1 \times 10^{-6}$ [12]. Higher PG and more protection are possible at lower data rates.

## 2.3 Link Analysis

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 0 dBi gain. The received signal power $P_{RX}$ is given by Friis' transmission equation

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

where $\lambda$ 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 (UWB limits in the 7.25–8.5 GHz band), the transmit power $P_{TX}$ is equal to −15 dBm and the resulting received signal power from (1) of −74 dBm. Assuming a 50 Ω antenna, 500 MHz bandwidth and a receiver noise figure (NF) of 5 dB, the equivalent noise power at the receiver input is −82 dBm.

The minimum required SNR to obtain an error rate of $1 \times 10^{-6}$ at 250 kbps is −7 dB [6], 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).

A link analysis is provided in Table 2, 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 [6] and considers a BER of less than $10^{-3}$ with BFSK modulation in a fading channel.

## 2.4 Frequency-Selective Fading Channel

BAN communication is subject to frequency-selective fad-

ing. 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 [13].

FM-UWB signals are robust to frequency-selective multipath [14]. MATLAB simulation results of the RF fading level, show 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. These figures compare 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 signal transmitted over the frequency selective multipath fading channel (i.e., IEEE 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.

## 2.5 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 2 shows the spectrum of the transmitter output signal as observed on a spectrum analyzer. The noise floor observed is originating from the spectrum analyzer.

## 2.6 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 PG is equal to the ratio of RF and subcarrier bandwidth

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

In a 250 kbps LDR system with a RF bandwidth of 500 MHz a PG 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 $1 \times 10^{-6}$ [12].

Additionally, interference from in-band UWB users benefits from the receiver PG. Simulations indicate that Impulse Radio and MBOFDM interference up to 15 dB stronger than the FM-UWB signal degrades the probability of error to $1 \times 10^{-6}$.

## 2.7 Power Consumption of the FM-UWB PHY

Based on the results of [15] and [16], the projected power consumption for the second generation of the FM-UWB radio in the UWB high band (7.25–8.5 GHz) is:

- Transmit: 1 mW
- Receive: 4–5 mW

Average power consumption is dependent on duty cycle and may be much less e.g. 10 microwatts average transmit power consumption for 1% duty cycle.

## 3. FM-UWB MAC

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

The network thus adopts the form of a single-hop or two-hops star topology. Traffic is typically asymmetric and this is matched by the asymmetry of resources 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. The MAC that we propose for use with our FM-UWB PHY for IEEE802.15.6, is based on the WiseMAC (Wireless Sensor MAC) protocol [17] optimized for BAN. It extends WiseMAC to operate on multiple channels for increased robustness to interference and it defines a high availability mode with improved adaptivity to traffic intensity variations to make better use of available energy resources. The new protocol is referred to as WiseMAC High Availability (WiseMAC-HA).

In the remainder of this section, an overview of the MAC is provided including a description of the operation of the low power and the high availability modes. Scalability features are discussed and a performance analysis is provided.

## 3.1 High Availability Mode

Some devices may have more energy resources than others. As such, 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.
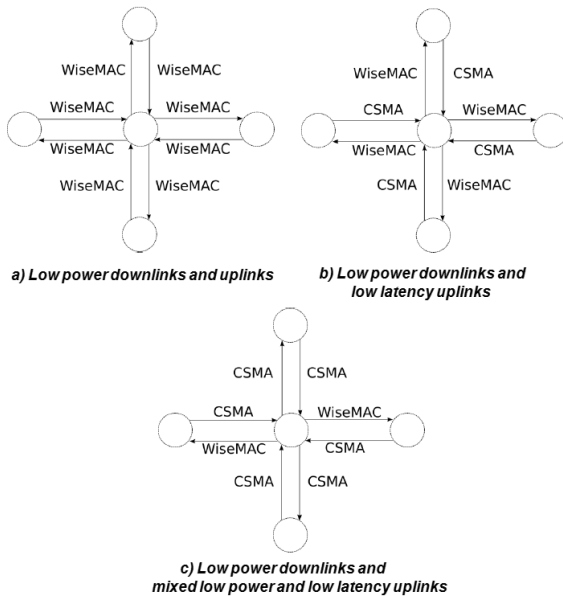
Also, some low power network applications have two operation modes. The first mode is a low power, low duty-cycle monitoring mode, and the other one is an emergency or alert mode. While in the first case, power consumption is the main issue, in the latter case it does not matter anymore (for instance with fire detection systems) and all the remaining energy should be used to obtain 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). This also allows all devices 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 limiting case of WiseMAC in which the wakeup time 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 5 shows three possible configurations for a network of four sensor nodes and one data collector at the center. In Fig. 5(a), all links use the WiseMAC low power scheme.

In Fig. 5(b), 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 5(c) depicts a hybrid configuration in which the

**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**

**Fig. 5** Possible network configurations for WiseMAC-HA.

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 use scenario for this mode is when sensors are not resource constrained: In this case, the sensors can always operate in CSMA mode.

### 3.2 Multiple Channels

In addition to saving energy, a low power MAC protocol must also deliver messages as reliably as possible. Several mechanisms are used 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 occur more frequently. Both factors increase the latency, and the latter also decreases the system's reliability. From the perspective of energy, an increase of traffic leads to overhearing and collisions, which increase power consumption. Therefore, switching to another communication channel is interesting from the perspective of performance, as latency and reliability will both be improved, and with respect to power consumption, 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.

### 3.3 Detect-and-Avoid

Operation over multiple channels enables increased reliability and lower power consumption. If a device wakes up often 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. The same procedure is 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.

### 3.4 Network Architecture, Topology and Scalability

Data collection in a star topology network is the main application currently envisioned. However, the solution should avoid introducing a single point failure mechanism as this makes it difficult to achieve high levels of reliability. Due to the low radiated power levels for UWB 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 star and mesh topologies equally well, both with low power consumption. This has been demonstrated in real-world deployments lasting several years.
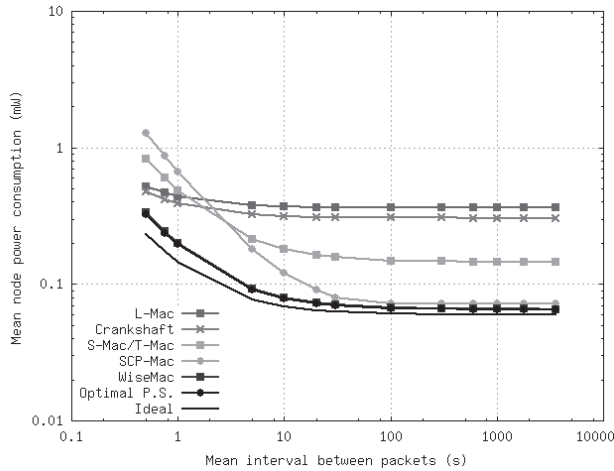
**Fig. 6** Comparison of power consumption for the FM-UWB radio using different MAC protocols (store and foreward scenario).

**Table 3** Parameters for PHY-MAC power consumption analysis.

| Parameter | Value | Units |
|---|---|---|
| Number of nodes | 20 | --- |
| Data packet size | 50 | bytes |
| Acknowledgement packet size | 4 | bytes |
| Quartz accuracy | 30 | ppm |
| Radio transmission rate | 250 | kbps |
| Power consumption in Rx mode | 8 | mW |
| Power consumption in Tx mode | 4 | mW |
| Power consumption in sleep mode | 60 | μW |
| WiseMAC wake-up interval ($T_W$) | 500 | ms |

- Scalability is not an issue as the protocol requires only local information exchange. There is no network wide signalling traffic. Multiple hop communication is supported without any special mechanism (e.g. synchronization of signalling traffic).

### 3.5 PHY-MAC Power Consumption

Figure 6 compares the power consumption of the FM-UWB PHY using various MAC protocols as a function of traffic intensity. The assumptions made for the main MAC parameters are listed in Table 3. Other MAC parameters are chosen in such a way that they offer an average latency similar to WiseMAC, i.e., $1/2T_W$ or 250 ms.

The ideal power consumption is shown in black at the bottom of the figure. L-MAC and CrankShaft, two distributed TDMA protocols [18], 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.
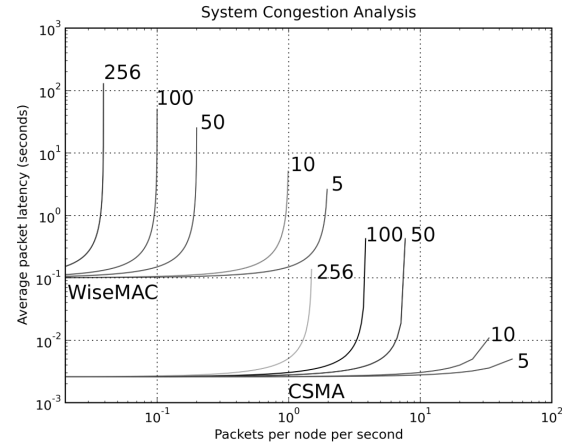


**Fig. 7** WiseMAC and CSMA average latencies on a single FM-UWB subcarrier (5 to 256 sensors, 1 packet per 100 seconds per sensor to 10 packets per second per sensor).

**Table 4** Parameters for latency analysis.

| Parameter | Value | Units |
|---|---|---|
| Data packet length | 16 | bytes |
| Acknowledgement packet length | 4 | bytes |
| Synchronization preamble | 500 | μs |
| WiseMAC wake-up interval (TW) | 200 | ms |
| Radio transmission rate | 250 | kbps |
| All traffic is on (N x FM-UWB subcarriers) | 1 | subcarrier |
| Radio setup time (Rx and Tx) | 1 | ms |
| Radio switching time | 0.1 | ms |
| CSMA min back-off exponent | 2 | --- |
| CSMA back-off period | 1 | ms |
| Clear channel assessment duration | 0.1 | ms |
| Short Inter-Frame Space time (SIFS) | 0.11 | ms |

### 3.6 Latency

The average latency is an important system parameter, especially for medical BAN and other highly reactive systems. Figure 7 shows the average latency for the low power WiseMAC mode and the High Availability CSMA mode. The considered network has a star topology with one sink and a number of sensor devices between 5 and 256. The assumptions are defined in Table 4.

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. In each case, latency remains stable over a wide range of traffic intensity before finally increasing rapidly. This zone is unstable and should be avoided.

In summary, WiseMAC-HA provides a scalable MAC protocol optimized for ultra low power, reliable, medical BAN applications. Multiple modes of operation are possible dependent on traffic and channel conditions. An IEEE802.15.4 compatible TDMA mode is also possible.

## 4.  Prototype Test and Measurement

### 4.1  Bit Error Rate and Packet Error Rate

The results of BER measurements made on four different receiver prototypes are shown in Fig. 8. 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 $4 \times 60 \times 50,000 = 12$ million transmitted bits.

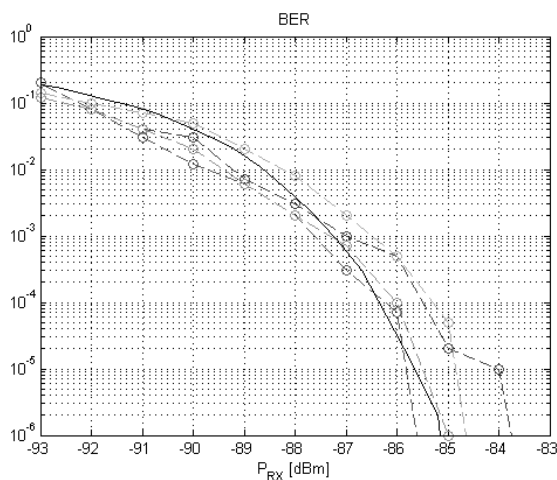From these results it can be concluded that the FM-



**Fig. 8**    BER measurements made on 4 receivers.

UWB receiver sensitivity is about $-85$ dBm (BER $\leq 10^{-6}$), 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. Receiver sensitivity can be further increased, e.g., by increasing the LNA gain.

### 4.2  Transmission Range

Next, the transceivers were equipped with antennas. Propagation experiments were carried out in a laboratory environment of size $12 \times 5$ meters and an indoor environment (cafeteria) of size $20 \times 10$ meters. Propagation in these environments is predominantly line of sight (LOS); however, the laboratory has many metallic objects that create multipath fading, while the cafeteria is more of an open indoor space. A first transceiver board was used as transmitter and a second one as receiver. The range that could be covered in the indoor environment was almost 20 meters. The laboratory wasn't big enough to reach the system's limits.

## 5.  Hybrid FSK/FM-UWB

FM-UWB may be used alone or integrated with narrowband Frequency Shift Keying (FSK) based radio solutions to form a hybrid narrowband FSK/FM-UWB radio that combines the advantages of the FM-UWB (low radiated power, good coexistence, robustness to multipath and interference) with those of narrowband FSK solutions (higher radiated power, better propagation around body, longer range, higher data rate) at a minimal increase in die size. As can be seen from

**Table 5**    Comparison of short range radio solutions and potential for an FSK/FM-UWB hybrid.

| Parameter | Bluetooth[2] (ISM 2.4-2.4835 GHz) | ZigBee[2] (2.4 – 2.483 GHz) | ISM 433/860 MHz[2] | FM-UWB[1] (4.2-4.8 GHz/7.25-8.5 GHz) | IR-UWB[2] (4.2-4.8 GHz/7.25-8.5 GHz) |
|---|---|---|---|---|---|
| **Power consumption** | Tx = 25-40 mW, 100 mW Rx = 30-50 mW, 100 mW | Tx = 20-30 mW Rx = 25-40 mW | Tx = 80 mW Rx = 30 mW | Tx = 1-2 mW (1GHz BW) Rx = 3-4 mW | Tx = 3.5 mW Rx = 150 mW |
| **Radiated power** | 1 mW (Power class 3) 2.5 mW (Power class 2) 100 mW (Power class 1) | 1-100 mW (Europe) 1 W (USA) | 10-30 mW | <100 μW (1GHz bandwidth) | <100 μW (1GHz bandwidth) |
| **Data rate** | 723.2 kbps | 250 kbps | Up to 62.5 kbps | 250 kbps | 256 kbps |
| **Multiple users** | 8 active users | Up to 255 devices per network, 16 RF channels | 2 in FDMA mode, others in TDMA mode | 15 @ 100 kbps 150 @ 1 kbps | Up to 255 devices per network based on the IEEE802.15.4 MAC |
| **Modulation** | FSK | FSK, MSK, O-QPSK | Analogue FSK/FM | Analog FSK/FM | PPM |
| **Medium access** | FHMA (Frequency Hopping Multiple Access) TDMA/FH combination | CSMA-CA with TDMA-based beaconing | FDMA or TDMA | FDMA subcarrier w/TDMA IEEE802.15.4, WiseMAC FDMA-like (e.g. 4-6) | IEEE802.15.4 |
| **Robustness to interference** | Slow frequency hopping, Block code | Symbol-to-chip mapping (32-chip PN sequence), FEC | Possible frequency or band change | Analogue spread spectrum PG = 27 dB (@1GHz BW) | Limited PG |
| **Robustness to multipath** | N/A | FEC | Implementation depedent | Wideband Diversity in freq. selective fading (~ 20 dB @ 99% availability) | Wideband Diversity in freq. selective fading (~ 20 dB @ 99% availability) |
| **Range** | 10 m, 20 m, 100 m | 10-100 m | 10-30m indoors 1-2km outdoors | 1-10 m | 10 m  indoors 100 m  outdoors |
| **Sensitivity** | -95 dBm | -90 dBm to -95 dBm | –95t to -115 dBm | -90 dBm | -95 dBm |
| **Capacity** | 80 MHz | 80 MHz | MHz | 600 MHz (low band) | 600 MHz (low band) |

1.    Continuous power   @ 250 kbps based and 100 μW. Lower power possible dependent on duty cycle, Tx power and BW.
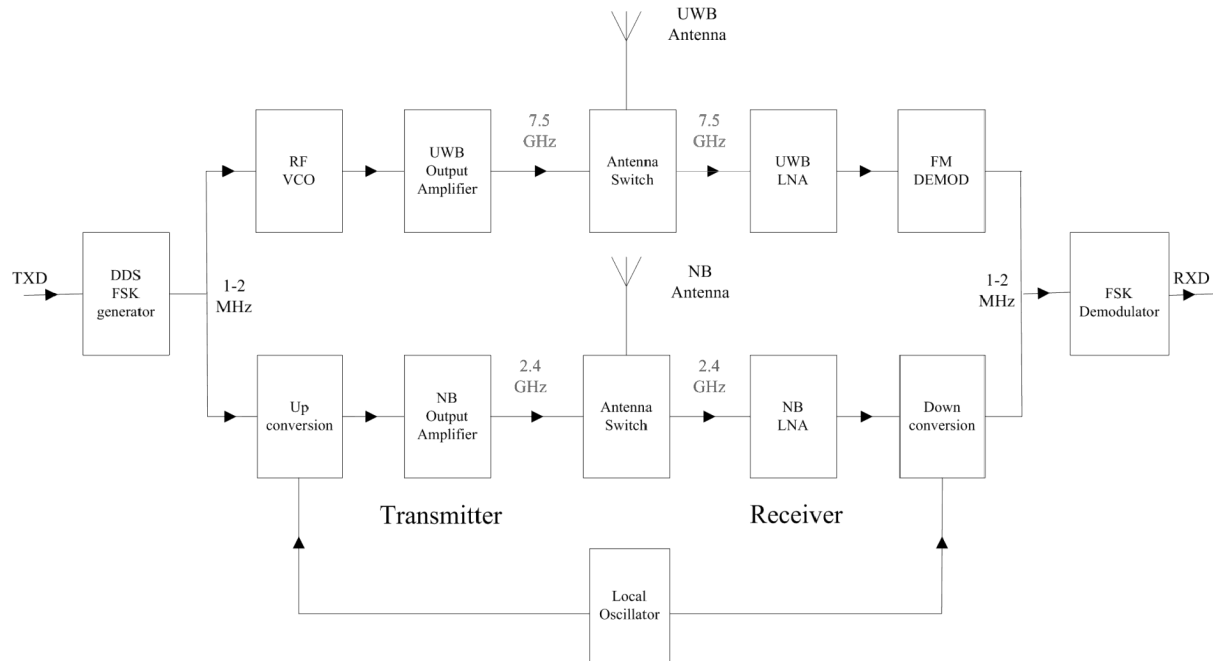
2.    Nominal values

**Fig. 9** Hybrid FSK/FM-UWB transceiver block diagram.

Table 5, a hybrid is possible with potential BAN solutions from narrowband 868 MHz to Bluetooth and IEEE802.15.4 operating at 2.4 GHz.

An illustration of the hybrid radio architecture is provided by Fig. 9. In the FSK mode, the analog FM (see Fig. 1) is replaced by direct up-conversion of the FSK subcarrier to RF and the wideband FM demodulator (see Fig. 3) is replaced by down-conversion from RF to FSK baseband. In this way, it is possible to communicate with a narrowband FSK based transceiver (e.g. 868 MHz, 2.4 GHz), reusing all of the baseband. It takes only an additional RF front-end and a multi-band antenna to turn a narrowband radio into a hybrid FSK/FM-UWB radio that uses narrowband FSK in one or several bands and FM-UWB in another band.

Initial analysis suggests that the additional RF-front-end would only marginally impact die area and cost (e.g. about 5%). Further, the same basic MAC protocol can be employed for both radios (i.e., narrowband FSK and FM-UWB).

## 6. 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 [19] defined for LDR applications, such as health and medical applications and meets or exceeds the targets identified in the TG6 Proposal Comparison Criteria [20].

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,
- robustness in BAN propagation environments.

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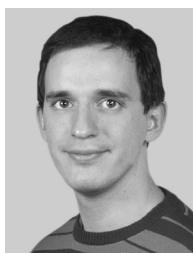
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