Benchmarking of WSN Solutions and IEEE 802.15.4-2006 PSSS based Solutions

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Abstract—**PSSS (Parallel Sequence Spread Spectrum) [1] technology is the basis for the PHY of the new IEEE802.15.4-2006 standard with the enhancement of the data rate from 20 kbps to 250 kbps for the European area. Robustness against multipath fading and interference is also enhanced and makes the sub 1 GHz PHY highly attractive. Compared to 2.4GHz solutions there is lower attenuation in the transmission path.**

I. Introduction

The sub 1 GHz PHYs of the IEEE 802.15.4-2003 standard offer only 20 kbps for Europe/ETSI (European Telecommunications Standards Institute) and 40 kbps for the FCC region. Compared to the 250 kbps possible at 2.4GHz, the data rate was unattractive, especially for WSN (Wireless Sensor Networks) with many nodes. For the ETSI region it has to be taken into account that there is a duty cycle limitation of 1%. That causes average data rates of not more than 200 bps for the IEEE 802.15.4-2003 PHY. The peak data rate for the sub 1 GHz IEEE820.15.4-2006 PHYs (ETIS/FCC) is 250 kbps as with the 2.4 GHz PHY.

The coverage is for sub 1GHz bands better than for the 2.4 GHz band. Simulations with a ray tracing tool underline this fact. Figure 1 shows the received power for a 2.4 GHz transmission for a LOS (Line of Sight) and a NLOS (No Line of Sight) area.

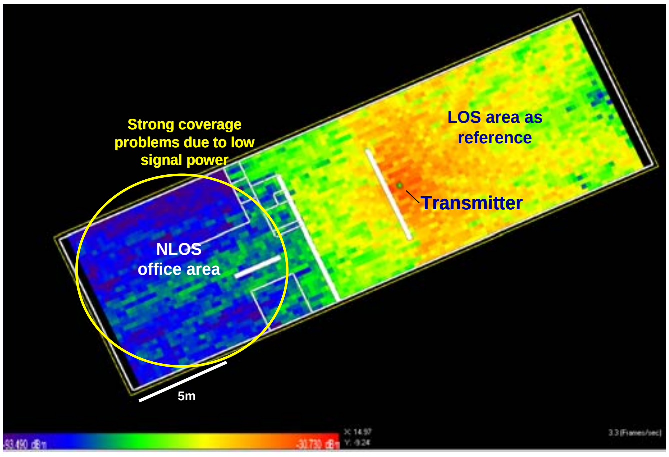

Figure 1. Coverage at 2.4 GHz in LOS and NLOS areas. Received power: blue -93,5 dBm, red -30 dBm

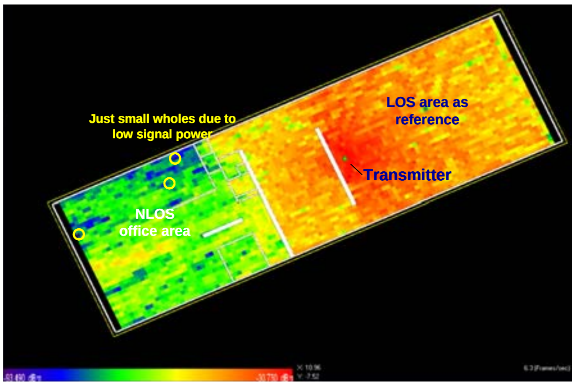

Figure 2. Coverage at 868 MHz in LOS and NLOS areas. Received power: blue -93,5 dBm, red -30 dBm

The 868 MHz example in figure 2 shows that the received power is significantly higher. Also the expected interference is in the sub 1 GHz better than in the 2.4 GHz band, because WLAN and Bluetooth are occupying the 2.4 GHz band.

The motivation for enhancing the data rate for the sub 1 GHz PHY in the IEEE 802.15.4-2006 standard was to combine the attractive coverage of the sub 1 GHz band and the low interference with the high data rate of the 2.4 GHz PHY. Especially for the ETSI area with the 1 % duty cycle limitation the increased data rate was necessary.

II. PSSS Technology

A. Basics

PSSS uses for the encoding m-sequences in parallel. Equation (1) describes the base m-sequence ms_1.

$$ms_1 = (m_{11}, m_{21}, ..., m_{M1}) \tag{1}$$

The coding table is given by EN and contains cyclic shifted m-sequences of ms_1.

$$EN = \begin{bmatrix} m_{11} & \dots & m_{1N} \\ m_{21} & \dots & m_{2N} \\ m_{M1} & \dots & m_{MN} \end{bmatrix} \quad (2)$$

For the encoding the data D (3) is multiplied with EN (2).

$$D^T = (d_1, d_2, ..., d_N) \quad (3)$$

$$S = EN \cdot D \quad (4)$$

Each data bit of D is spread with a cyclic shifted m-sequence. The spreaded bit are added column wise. The decoding can be reached by cyclic cross correlating the PSSS-Symbol S with the base m-sequence ms_1. This operation is similar to using a matrix DE for decoding.

$$DE = EN^T \quad (5)$$

$$CCF = S \cdot DE \quad (6)$$

CCF presents the cyclic cross correlation between the PSSS symbol S and the decoder matrix DE. The reconstruction is done by threshold decision as described in (7).

$$d'_n(ccf_n) = \begin{cases} d'_n = 0;\ ccf_n \le (Max\{CCF\} + Min\{CCF\} \div 2) \\ d'_n = 1; ccf_n > (Max\{CCF\} + Min\{CCF\} \div 2) \end{cases} \quad (7)$$

$d'_n(ccf_n)$ is the reconstructed data word. Depending on implementation targets of PSSS different threshold algorithms are available.

For reducing the PAPR (Peak to Average Power Ratio) and the DC component of the PSSS symbol S precoding could be used. The precoding of one symbol is executed independent of the precoding of any other symbol with the two steps described mathematically as follows:

$$S'(m) = S(m) + \frac{(Max + Min)}{2} \quad (8)$$

where S(m) is the current PSSS symbol and S'(m) is the aligned symmetric to zero PSSS symbol and Max and Min are the maximum and minimum chip amplitudes within the symbol respectively and

$$p''(m) = \frac{p'(m)}{A} \quad (9)$$

where A = (Max' – Min') and Max' and Min' are the maximum and minimum chip amplitudes within the aligned symmetric to zero PSSS symbol p'(m) respectively.

Precoding reduces the PAPR and therefore the required linearity of the power amplifier.

B. PSSS for the IEEE 802.15.4-2006 sub 1 GHz PHYs

Target for the new standard [2] was to reach 250 kbps for the sub 1 GHz PHY. For the PHY a 31 chip long sequence was selected as base m-sequence. From the resulting encoding matrix only a subset has been selected. Available are 31 cyclic shifted sequences. For FCC only five and for ETSI twenty sequences have been selected. This ensures that for the given chip rate a data rate of 250 kbps is realized, for both the FCC and ETSI versions of the PHY.

Selecting a subset of EN (4) causes the distance between the correlation peaks of CCF (6) to increase, which can be used for enhanced multipath fading robustness. The delayed multipath fading parts of the received signal are between the correlation peaks and don't cause ISI (Inter Symbol Interference), if the delay spread is shorter than the distance between the CCF peaks.

To avoid that the cyclic correlation of the decoder is hurt by multipath fading, the PSSS symbol S is cyclicly extended, similar to the cyclic extension of OFDM symbols. The extended PSSS symbol contains 32 chips.

III. Performance of PHY Implementations and Available Platform

For the ETSI and FCC PHYs of IEEE802.15.4-2006 discrete FPGA based implementations are available that have a sensitivity of better than -100dBm for 1% PER. The discrete module is shown in figure 3. The available link budget is about 120 dB or even more. Nguyen et al. [3] describe a single-chip implementation in CMOS.

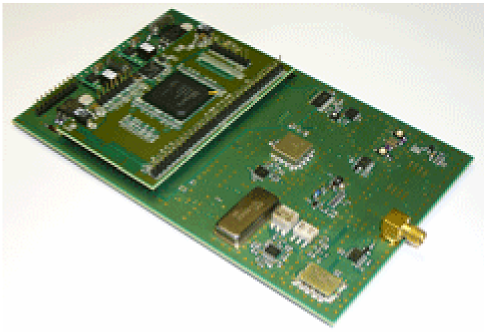

Figure 3. DWW IEEE802.15.4-2006 PSSS 868MHz "TRx154b_Eval" with Spartan 6

To evaluate the performance of the PSSS based solution a real word test was made. Figure 4 shows the urban test environment. The red dot marks the position of the transmitter in the basement of the building. The building has reinforced concrete ceilings, 50cm solid walls and the basement windows are with bars. The Tx position was 75 cm from the ground. The receiver test points are marked in yellow.

The tested modules are:

- **DWW IEEE802.15.4-2006 PSSS 868MHz "TRx154b_Eval" module** Transmit Power 0 dBm and +10 dBm. Even meets ETSI mask @+15dBm. 250 kbps data rate. Real PER testing.

- **868MHz Wireless M-Bus module** Transmit Power 0 dBm. Data rate 16.38 kbps. Real PER testing.

- **IEEE802.15.4-2003 868MHz module** Transmit Power +16 dBm. 20 kbps data rate. Real PER testing.

- **IEEE802.15.4-2006 2.4GHz module** Transmit Power +5 dBm. Data rate250 kbps. Only connection loss could be tested. Real testing was not implemented.

Test condition for successful coverage was PER < 1% for same packet lengths as defined in IEEE802.15.4-2006.

Figure 4 shows the tested coverage for the 868MHz Wireless M-Bus module, figure 5 the IEEE802.15.4-2003 868MHz module, figure 6 the IEEE802.15.4-2006 2.4GHz module, figure 7 the DWW IEEE802.15.4-2006 PSSS 868MHz module TRx154b_Eval with 0 dBm transmit power and figure 8 the same with 10 dBm transmit power.

Figure 4. Coverage of the 868MHz Wireless M-Bus module, dBm transmit power, 16.38 kbps. Map source Google Earth.

Figure 5. Coverage of the IEEE802.15.4-2003 868MHz module with +16 dBm transmit power and 20 kbps. Map source Google Earth.

Figure 6. Coverage of the IEEE802.15.4-2006 2.4GHz module with 5 dBm transmit power and 250 kbps. Map source Google Earth.

Figure 7. Coverage IEEE802.15.4-2006 PSSS 868MHz "TRx154b_Eval" module 0 dBm Tx power and 250 kbps data rate. Map source Google Earth.

Figure 8. Figure 8. Coverage IEEE802.15.4-2006 PSSS 868MHz "TRx154b_Eval" module 10 dBm Tx power and 250 kbps data rate. Map source Google Earth.

The conclusion of the benchmarking is, that the PSSS based module has at the same transmit power and at much higher data rate than the competitors a unique coverage. All other modules were not able to communicate across the street. A usage for metering applications seems to be difficult.

The coverage advantage of the PSSS based module can also be used to further reduce the Tx power for reducing the power consumption. The PSSS advantage is mainly caused by the enhanced PSSS robustness against multipath fading. That robustness was the selection criterion for the PHY selection at the IEEE standardization process of IEEE802.15.4-2006 .

IV. FUTURE STEPS

The PSSS solution will soon be available as a single chip based module. The chip partner is IHP GmbH in Germany. The PSSS technology is advantageous for WSN due to low power consumption and low cost of implementation, combined with unique data rates of 250 kbps for the ETSI region of the IEEE 802.15.4-2006 standard in the sub 1GHz band.

The low complexity of PSSS implementations is opening the path to high data rate solutions, where OFDM implementations are limited in the reachable data rate. PSSS can be combined with well known technologies like deconvolution and MIMO for enhancing the multipath fading robustness. Also a combination of PSSS and OFDM seems to be promising [4]. Actual R&D activities are for 100 Gbps wireless implementations of PSSS with deconvolution.

Using PSSS with deconvolution can compensate multipath fading nearly perfectly. In strong multipath fading environments decreases the PSSS performance only slightly (about 0.5dB for BER <1e-6) when using deconvolution compared to the performance in non multipath fading environment. The decrease was caused in that simulation due to the non ideal channel estimation with noise limitation.

That underlines that PSSS with deconvolution offers high performance combined with low implementation complexity. First real world tests show that the simulated performance can be realized in hardware implementations.

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