Coverage Range Analysis of Wireless Technologies for Industrial Automation

System Overview and Performance Evaluation

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Abstract: Reliable wireless communication is crucial to current and future industrial applications, but is however not yet applicable in many scenarios. Thus novel approaches are being investigated at the moment, from which three physical (PHY) layer technologies are depicted for detailed evaluation in this paper. Preceding the performance analysis, industrial application requirements and constraints as spatial extent, number of nodes, cycle time, PER and user data length are summarized. Error rates and coverage ranges are calculated and presented for Ultra Wide Band (UWB), Frequency Hopping Spread Spectrum (FHSS) and Parallel Sequence Spread Spectrum (PSSS) assuming an AWGN channel.

1 INTRODUCTION

Currently wired fieldbus systems are employed in industrial applications due to their deterministic performance, although they entail high installation and maintenance efforts. Thus wireless communication is desirable, since it offers advantages regarding flexibility, mobility and retrofitting. Nevertheless, most wireless communication systems do not yet meet the applications' requirements in determinism and quality of service. In order to overcome these challenges, novel wireless solutions are being developed at the moment. The applications are often categorized by field of operation and major requirements like number of nodes, cycle time, Packet Error Rate (PER) and user data length. Based on the resulting categories, wireless systems have to be scaled for each field of application, and the choice of the physical layer technology is an important consideration in this context.

Though the definition of application categories is of vital significance for a successful system design, it is not consistent in industry, research and standardization resulting in diverse specifications. Moreover, currently no de facto standard is established. Thus industrial requirements are investigated and aggregated in section 2. UWB, FHSS and PSSS are shortly introduced as promising wireless approaches in section 3 and discussed regarding their suitability in terms of error rates and coverage range in section 4. Summary and prospect on further work are given in section 5.

2 INDUSTRIAL ENVIRONMENT

Summarizing industrial application categories, a survey on their requirements is given in this section. These requirements comprise network size, environment and topology, safety as well as timing limitations. Moreover, possible frequency ranges are presented and reviewed regarding regulatory aspects.

The summary reveals challenging conditions for wireless industrial communication in all application categories. As a result physical layer concepts must be chosen carefully regarding reliability and coexistence aspects.

2.1 Application Requirements

The requirements of industrial applications vary broadly and are commonly classified into three categories to ease considerations: Factory Automation (FA), Process Automation (PA) and Condition Monitoring (CM). In a factory environment the spatial extent as well as the number of nodes are evidently small, whereas the reliability and safety requirements are very strong. Typically closed-loop communication systems with soft or hard real time requirements are employed here. In contrast to this, CM has a wide spatial extent and lower safety and timing requirements in its sensor network, which has no control but only monitoring purposes. PA is typically associated with chemical processing plants, which have an

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Table 1: Application requirements overview. (ETSI, 2011), (ZVEI, 2009), (VDI/VDE, 2007), (Güngör, 2013) (Frotzscher et al., 2014).

Property	FA	PA	CM
Maximum spatial extent	10 m × 10 m × 3 m	100 m × 100 m × 10 m	1000 m × 1000 m × 50 m
Nodes per system	30	100	1000
Nodes per m^2	0.3	0.01	0.001
Number of coexistent systems	10	5	5
Number of locally parallel nodes	300	500	250
Network topology	Star	Star/Mesh	Mesh
Cycle time	<1 ms	>10 ms	>100 ms
PER	$<10^{-9}$	$<10^{-4}$	$<10^{-3}$
Battery lifetime	<1 year	5 – 10 years	>10 years
User data length	<30 Byte	30 – 1500 Byte	<1500 Byte
System data rate	>7.2 Mb/s	<2.4 – <120 Mb/s	<120 Mb/s

intermediate spatial dimension and also intermediate safety and timing requirements. Often PA comprises mostly monitoring tasks with few control processes. Depending on the very deployment, the topology is typically either a star or a mesh network as shown in figure 1.

In FA, a star topology provides a good basis for the small spatial extent combined with shortest cycle times and high data rate. A typical industrial scenario is a production cell, in which sensors and actuators both interact on a real time basis. In a CM application, sensors mostly collect data, which need to be transmitted over long distances due to the big spatial dimension, whereas timing requirements are low.

Thus here a mesh topology with multi-hop transmissions is employed. In case of a star topology, the coexistence of multiple communication structures is required, which both means the coexistence of different systems (inter-system-coexistence) and the coexistence of different star topologies employing the same technology (intra-system-coexistence).

Table 1 shows major properties of these three categories compiled from various publications. (ETSI, 2011) lists requirements of communication in manufacturing cells, factory halls and on plant level. Typically FA is employed in manufacturing cells, whereas communication on factory hall scale is congruent with PA properties. Communication on plant level is a subset of CM, but is generally matching CM requirements. Spatial extent, nodes per system, number of

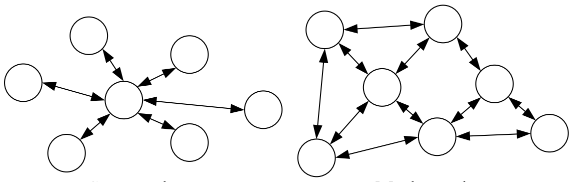

Figure 1: Typical topologies in industrial environments.

coexistent systems, number of locally parallel nodes and the network topologies are taken from this report. Nodes per m^2 is calculated based on these values.

Similar categories are investigated in (VDI/VDE, 2007), from where cycle time and user data lengths values are taken. They are congruent with requirements specified in (Frotzscher et al., 2014), where three closed-loop systems (machine tools, printing and packaging machines) are listed with their requirements in number of nodes, packet size, cycle time and jitter. Limits for packet error rates are defined in (ZVEI, 2009), which discusses primarily coexistence issues regarding wireless industrial communication. The system data rate is calculated based on number of nodes and user data lengths.

Today in the fields of FA and PA established wired fieldbus systems based on Ethernet are employed due to the strict deterministic performance of these wired communication systems. In contrast to that, CM recently emerged in terms of machine-to-machine communication and the Internet of Things (IoT), because wired systems cannot yield the required flexibility. For all three categories wireless communication is desirable and enables a raise of efficiency while reducing installation and maintenance efforts.

2.2 Frequency Ranges for Industrial Communication

At this time there are no dedicated frequency ranges for wireless industrial communication, thus Industrial, Scientific, and Medical (ISM) bands have to be used, which offer three relevant frequency bands: Sub-1 GHz (868 MHz in Europe and Africa and 900 MHz in America respectively), 2.4 GHz and 5.8 GHz (ETSI, 2010) (FCC, 2016). Especially the 2.4 GHz band is broadly employed posing a challenge to each technology's coexistence techniques. Since coexistence of wireless communication systems is crucial for wide usability, there are regulations in each ISM band, which enable the inter-system-coexistence of different technologies. Either the allowed transmission power is small or users have to apply “listen before talk” (LBT). LBT is inappropriate for FA and partially for PA as well, since the transmission delay is not predictable.

Due to the great interest, ETSI initiative TG41, who aims at a regulation guaranteeing exclusive use of 5.725 GHz to 5.875 GHz for wireless industrial communication systems, was formed. Here the transmit power is planned to be increased from 14 dBm to 26 dBm EIRP (ETSI, 2010). An exclusive use of a dedicated frequency band leads to less interference between different technologies, but reinforces the importance of intra-system-coexistence.

A different approach is the use of large frequency ranges as in UWB (IEEE, 2011) technologies. Here the employed bandwidth is equal to or larger than 499.2 MHz, which provides high interference resistance owed to its spreading concept. There are three operating bands defined: sub-gigahertz band from 249.6 MHz to 749.6 MHz, low band from 3.1 GHz to 4.8 GHz, and high band from 5.8 GHz to 10.6 GHz.

3 WIRELESS TECHNOLOGIES

Since the PHY layer technology vigorously affects the overall system performance, it must be carefully chosen for a certain field of operation. The range of available technologies from wireless standards and recent research projects is wide. It reaches from UWB technologies, that promise coexistence with existing wireless systems, to 5G cellular machine to machine (M2M) solutions, which can cover large areas and huge numbers of devices. With its Orthogonal Frequency Division Multiple Access (OFDMA) and Single Carrier Frequency Division Multiple Access (SC-FDMA) schemes for downlink and uplink and the enhancements from LTE Rel-11, 5G seems to be a promising approach for PA and CM, but its latencies are not capable of meeting the FA requirements. Another promising technology for PA applications is Sub-1 GHz-WLAN in IEEE 802.11ah, which shall achieve low-cost long range connectivity (Aust et al., 2015).

Technologies like ZigBee (ZigBee Alliance, 2012) with its star, mesh and cluster tree topologies are rather suitable for CM purposes. A recent approach that is also based on the IEEE 802.15.4 standard and covers industrial applications in the fields of FA and PA is WirelessHART (IEC, 2010). Another choice, based on the IEEE 802.15.1 standard, is Wireless Sensor Actuator Network (WSAN), which is designed for FA and coexistence with common technologies in the 2.4 GHz ISM band (PNO, 2012). Nevertheless, these standards cover the FA requirements insufficiently, so that wireless communication technologies, which meet the FA requirements, are current research topics.

Among others, UWB, FHSS and PSSS are subject of FA standard PHYs and recent research projects. These three promising wireless technologies are depicted for further analysis.

3.1 UWB Overview

In order to realize short-haul links for data communication for low power and low rate devices in a Wireless Personal Area Network (WPAN) the IEEE 802.15.4a standard offers several PHY transmission modes (IEEE, 2011). The investigated Impulse Radio (IR)-UWB PHY specification supports data rates from 0.11 Mb/s to 27.24 Mb/s with different Modulation and Coding Schemes (MCS). The IR-UWB impulses are modulated using burst position modulation (BPM) and binary phase shift keying (BPSK). In the BPM-BPSK modulation scheme two bits of information are carried in each UWB symbol. The first bit is determined by the burst’s temporal position and the burst’s polarity indicates the second bit. A complete burst is specified by a spreading sequence defining the polarity of it’s impulses (IEEE, 2011).

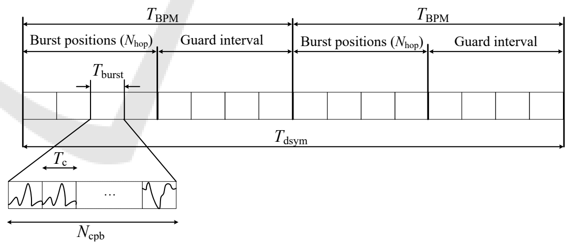

Figure 2: IEEE 802.15.4a IR-UWB PHY symbol structure (IEEE, 2011).

The structure of an IR-UWB PHY symbol is shown in figure 2. T_{dsym} is referred to as total symbol duration, T_c as chip duration and N_{cpb} as number of chips per burst. T_{BPM} is the duration of a BPM interval and T_{burst} corresponds to the burst duration.

In table 2 the significant parameters of selected IR-UWB MCSs are listed including the FEC rates of convolutional coding (CC) and Reed-Solomon (RS) coding.

Table 2: IR-UWB PHY Parameters.

MCS	Rate CC	Rate RS	N_{cpb}	T_{dsym} [ns]	Data rate [Mb/s]
1	0.5	0.87	128	8205.13	0.11
2	0.5	0.87	16	1025.64	0.85
3	0.5	0.87	2	128.21	6.81
4	1	0.87	1	64.10	27.24

With the large number of adjustable parameters, the IR-UWB PHY is adaptable to different communication scenarios from FA, PA and CM. In order to suit best for FA scenarios, delay requirements have to be met, and therefore MCS 4 is investigated in this paper. MCS 4 has a symbol duration T_{dsym} of 64.10 ns and reaches a data rate of 27.24 Mb/s with coherent reception (Reinhold, 2016).

Due to regulatory aspects such as duty cycle and power restrictions the high band with a mandatory channel at 7.9872 GHz is depicted for performance evaluation in section 4.3.2.

3.2 FHSS Overview

FHSS is one of the most common transmission techniques for automation and sensor networks. In order to achieve coexistence between multiple connections and to enhance the transmissions' robustness, the transmission channel is changed frequently, whereby the hopping frequency can vary among the technologies from 1600 Hz up to static channel usage. For most frequency bands this type of frequency usage is covered by regulations (FCC, 2016).

An established standard using FHSS spectrum access is Bluetooth LE (Bluetooth SIG, 2014). It is primarily designed for IoT tasks, but there are also variations for FA available. WSAN (PNO, 2012) has a PHY layer based on the IEEE 802.15.1 standard (IEEE, 2005), which also serves as a basis for Bluetooth up to version 1.2. The system operates within the 2.4 GHz ISM band and uses a FHSS mechanism with 79 channels, each occupying a nominal bandwidth of 1 MHz. WSAN additionally uses a hopping scheme allowing the parallel usage of multiple base stations and supports channel blacklisting as a coexistence feature.

In this work we consider a FHSS system with a Gaussian Minimum Shift Keying (GMSK) modulation scheme adopted from Bluetooth LE and WSAN operating in the 5.8 GHz ISM band. The 150 MHz of available system bandwidth are divided into 75 channels resulting in a channel center frequency distance of 2 MHz (Bluetooth SIG, 2014) (FCC, 2016) (ETSI, 2010). The channel center frequencies result as

$$f_{\text{c}} = 5726\,\text{MHz} + (i-1)\cdot 2\,\text{MHz}, \quad i = 1\ldots 75 \tag{1}$$

with the channel number i.

3.3 PSSS Overview

In order to enhance response times due to parallel access, spread spectrum techniques offer promising properties. In contrast to Direct Sequence Spread Spectrum (DSSS)-techniques, where each bit is spread with an appropriate pseudo noise (PN)-sequence, PSSS is an approach based on spreading with a m-sequence. It was firstly presented in (Wolf, 2004; Schwetlick and Wolf, 2004) and is, based on an m-sequence of length 31 chips, part of IEEE 802.15.4-2011 (IEEE, 2011), but in general any m-sequence is applicable. A detailed description of PSSS en- and decoding is given in (KrishneGowda et al., 2015), whereas a short overview is given in this paper.

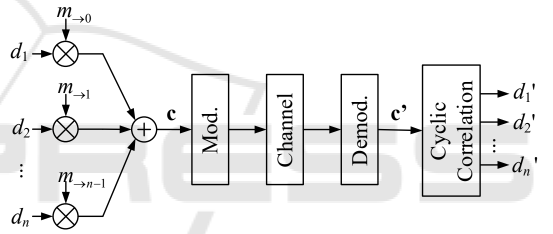

Figure 3: PSSS coding and decoding process.

The bits of the data vector $\mathbf{d}$ are spread each with the same, but cyclically shifted, m-sequence of length n as shown in Figure 3, where $m_{\to 0}$ denotes the basic m-sequence. Correspondingly, $m_{\to i}$ denotes the same sequence cyclically shifted by i chips. Thus up to n bit can be transferred in parallel in one PSSS symbol. The transmitted PSSS symbol $\mathbf{c}$ is multivalent due to the chipwise addition of the spread bits of $\mathbf{d}$. An arbitrary modulation scheme can be used for transmission. For the analysis in section 4.3 a Amplitude Shift Keying (ASK) is utilized.

The PSSS decoding is performed by cyclic correlation of the received multivalent PSSS sequence $\mathbf{c}'$ with the basic m-sequence. A longer m-sequence leads to a more reliable result of the cyclic correlation assuming a uniform distribution of data bits. This effect is shown in section 4.3.

3.4 Technology Comparison

Though all three described technologies are promising in terms of wireless industrial communication, their properties diverge. An overview of relevant properties is shown in figure 4 based on the assumptions made in table 3 in section 4.3.2. UWB uses a bandwidth of 499.2 MHz with one channel per system, and achieves a total data rate of 31.2 Mb/s.

FHSS employs 75 channels with 1 Mb/s data rate each resulting in a system data rate of 75 Mb/s. The depicted configuration utilizes all available channels for a single system. For cellular coverage of the factory floor, the system can also be rescaled by reducing the number of utilized channels, making a coexistence of parallel systems possible. For a 3×3 pattern eight channels can be utilized per system in average, when inter-system interference is avoided.

Here, PSSS is exemplarily assumed to be employed based on a m-sequence with a length of 255 chips, which is further denoted as PSSS 255. Up- and downlink provide a number of 255 channel occupying a bandwidth of 20 MHz each. Accordingly the total system bandwidth is 40 MHz. The link data rate amounts to 78 kb/s resulting is a total system data rate of 40 Mb/s. If the link data rate of a single link is too small, multiple links can be grouped and thus a larger data rate is achieved, but concomitantly the number of simultaneous nodes in service is reduced. In PSSS, the system data rate can be shared at any desired fragmentation.

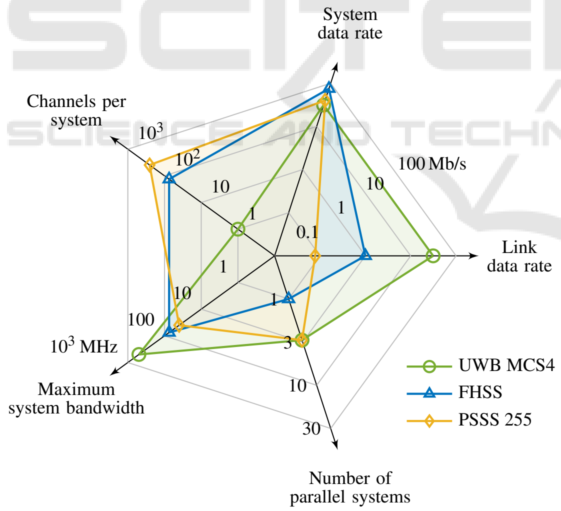

Figure 4: System capacities.

4 SYSTEM EVALUATION

The proposed PHY technologies are investigated in the subsequent sections regarding their applicability for FA. Based on the Bit Error Rate (BER) analysis, the coverage ranges are considered for typical packet sizes based on an AWGN channel model. The technologies' feasibility is validated as given in table 1.

4.1 Theoretical Analysis

For the purpose of the subsequent error rate and coverage range analysis, the performance of the three proposed systems in AWGN is analysed in this section. For simplicity reasons, we assume that the systems are perfectly synchronised and have the correct symbol clock and phase.

4.1.1 UWB Analysis

In order to evaluate the system's performance, typical receivers have to be analyzed. Coherent UWB receivers are often implemented as correlation receivers. Here the detection is performed by cross-correlation between the received signal and a local reference signal. Assuming pulse-position modulation (PPM), perfect synchronization and binary symbols with AWGN, the mean value u_{b_k} of the received signal results as derived from (Ge et al., 2002) in two separable cases:

1. for a transmitted bit $b_k = 0$

$$\begin{aligned} u_0 &= \mathrm{E}\{g_k | b_k = 0\} \\ &= E_\mathrm{b} \cdot [\mathrm{AKF}(\tau_0) - \mathrm{AKF}(\tau_0 - \Delta)] \end{aligned} \tag{2}$$

2. for a transmitted bit $b_k = 1$

$$\begin{aligned} u_1 &= \mathrm{E}\{g_k | b_k = 1\} \\ &= E_\mathrm{b} \cdot [\mathrm{AKF}(\tau_0 + \Delta) - \mathrm{AKF}(\tau_0)] \end{aligned} \tag{3}$$

where g_k is the decision variable resulting from correlation of received signal $r(t)$ and local reference template as given in (4).

$$g_k = \int_0^{T_\mathrm{dsym}} r(t) \cdot \underbrace{[v(t) - v(t-\Delta)]}_{\text{template}} \, \mathrm{d}t. \tag{4}$$

With AWGN, the BER results as

$$\begin{aligned} \mathrm{BER} &= \frac{1}{2} \cdot [\Pr(\mathrm{err}|0) + \Pr(\mathrm{err}|1)] \\ &= \frac{1}{4} \cdot \left[\mathrm{erfc}\left(\frac{u_0}{\sqrt{2}\sigma}\right) + \mathrm{erfc}\left(\frac{u_1}{\sqrt{2}\sigma}\right) \right], \end{aligned} \tag{5}$$

with σ^2 being the two-sided noise density (Reinhold, 2016). Equation (5) can be simplified for MCS 4 assuming equal transmission probabilities for each of the binary symbols to

$$\mathrm{BER} = \frac{1}{2} \, \mathrm{erfc}\left(\sqrt{\frac{E_\mathrm{b}}{N_0}}\right), \tag{6}$$

which is equivalent to BER of antipodal signaling.

4.1.2 FHSS Analysis

While a FHSS system with Frequency Shift Keying (FSK) was chosen for analysis in (Reinhold et al., 2013), a more realistic approach is chosen in this paper. For the later analysis GFSK with modulation index $\eta = 0.5$ and a bandwidth time product $BT = 0.5$ is assumed.

For the coverage analysis, we consider limiter-discriminator reception (LD), which is incoherent and thus does not need phase recovery to operate. This makes it suitable for fast FHSS systems and allows packet communication without syncwords (Bluetooth SIG, 2014). The receiver filter h_r is chosen to be a Gaussian filter and is given by its impulse response in (7). For the following investigations this filter's bandwidth time product $BT = 1$ is assumed.

$$h_\mathrm{r}(t) = \sqrt{2} \cdot BT \cdot \exp\left(-2\pi (BT)^2 \cdot t^2\right) \tag{7}$$

The performance of the limiter-discriminator depends on the width of the receiver filter's frequency response and the modulation index. The authors in (Cartier, 1977), (Simon and Wang, 1983) and (Pawula, 1988) have evaluated its performance for FSK in AWGN. The bit error probability sums up from two components.

$$\mathrm{BER} = P_\mathrm{cont} + P_\mathrm{click} \tag{8}$$

The error probability resulting from clicks P_click dominates for low SNR figures, whereas the continuous error probability P_cont dominates for high SNR. Since the receiver's filter leads to inter symbol interference, the error probabilities must be averaged over all possible bit sequences $\mathbf{d}$. When the receiver filter's BT is larger than or equal to one, a bit sequence length of three is sufficient. Assuming that every click leads to an error, the error probability resulting from clicks P_click is equal to the average number of clicks $\bar{N}$ averaged over all possible bit sequences $\mathbf{d}$ (Simon and Wang, 1983). When Gaussian impulse shaping is applied with a $BT = 0.5$ the length of the sequences $\mathbf{d}$ has to be increased. For the investigated filter chain, a overall sequence length of six symbols is sufficient.

$$P_\mathrm{click} = \overline{\bar{N}}^{\mathbf{d}} \tag{9}$$

P_cont can be calculated semi-analytically with (10), where $\Delta\varphi$ is the phase difference between two symbols and Ψ is the modulo 2π phase difference between the two symbols that are superposed with correlated complex Gaussian noise (Pawula, 2001).

$$P_\mathrm{cont} = \overline{\Pr\{\Delta\varphi - \pi \leqslant \Psi \leqslant 0\}}^{\mathbf{d}} \tag{10}$$

Equation (10) can be solved with the help of (20) in (Pawula, 2001).

For extended comparison in the system evaluation in section 4.3 we also take FSK with coherent reception (CR) into consideration. As given in (Proakis and Salehi, 2008) in this case the BER is calculated as

$$\mathrm{BER} = \frac{1}{2}\,\mathrm{erfc}\left(\sqrt{\frac{E_\mathrm{b}\,(1 - \Re\{\rho\})}{2N_0}}\right), \tag{11}$$

where ρ is the correlation coefficient. For orthogonal signaling, which is given in case of MSK, the correlation coefficient qualifies as $\rho = 0$.

$$\mathrm{BER} = \frac{1}{2}\,\mathrm{erfc}\left(\sqrt{\frac{E_\mathrm{b}}{2N_0}}\right) \tag{12}$$

4.1.3 PSSS Analysis

The simulative base band evaluation given in (Schwetlick and Wolf, 2004) for 31 chips is calculated semi-analytically in this work and extended to a general description for arbitrary m-sequences, on which this paper's evaluation is based. In the following, the derivation is explained shortly. Employing a spreading technique with orthogonal PN-sequences, the BER is calculated by (6), which is equivalent to BER of a BPSK (Proakis and Salehi, 2008). Since m-sequences are not orthogonal, a penalty coefficient $\gamma(n, p)$ is defined to adapt the BPSK calculation for PSSS. The cyclic autocorrelation φ of an arbitrary m-sequence is given by

$$\begin{aligned} \varphi(\tau) &= \mathbf{m}_{\to 0} \tilde{\otimes}\, \mathbf{m}_{\to 0} \\ &= \begin{cases} n, & \tau \bmod n = 0 \\ -1, & \text{otherwise} \end{cases}, \tau \in \mathbb{Z} \end{aligned} \tag{13}$$

The cross correlation yields the maximum at $\tau = i$ respectively, where i denotes the cyclic shift. Thus superposed cyclically shifted m-sequences influence each other in their maximum value depending on the bit values carried. The effective correlation amplitude in the relevant shift after superposition is further defined as

$$\varphi(\tau = i) = \epsilon(p) \tag{14}$$

and can be calculated with respect to the number of used sequences and the value of all other values in $\mathbf{d}$. Especially the superposition of equal bits in $\mathbf{d}$ is critical, since the correlations' result is degraded due to lacking orthogonality. Assuming a uniform distribution of the bit values in $\mathbf{d}$, a binomial distribution of the number of equal bits p results as shown in figure 5.

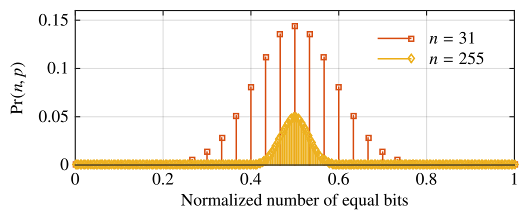

Figure 5: Distribution of equal data bits in **d**.

Taking this into account the penalty coefficient can be calculated as

$$\gamma(n,p) = \frac{\epsilon^2(p)}{\overline{\Pr(n,p)\cdot\epsilon^2(p)}^{p}} \,. \tag{15}$$

The effective correlation amplitude $\epsilon(p)$ is squared since it influences E_b/N_0 and is normalized by the probability of p equal bits since E_b/N_0 is defined as mean over all bit combinations in **d**. BER of PSSS is thus calculated as a function of n as

$$\mathrm{BER} = \overline{\Pr(n,p)\cdot\frac{1}{2}\,\mathrm{erfc}\left(\sqrt{\gamma(n,p)\cdot\frac{E_b}{N_0}}\right)}^{p} \,. \tag{16}$$

Caused by the averaging, the slope of the BER curve is not falling monotonically.

4.2 Evaluation Methodology

The presented technologies UWB, FHSS and PSSS are further compared in BER, coverage range and PLR. In this section the evaluation principles are explained shortly.

The BER calculation based on E_b/N_0 is given for each technology in (6), (8) and (16) respectively. The relation between SNR and E_b/N_0 is given as

$$\frac{E_b}{N_0} = \frac{P_{RX}}{P_N}\,\frac{1}{B\cdot T} = \mathrm{SNR}\cdot\frac{1}{B\cdot T}\,, \tag{17}$$

where B is the effective bandwidth, T the bit duration, P_{RX} denotes the reception power and P_N the effective noise power. Considering PSSS and UWB, additionally the spreading gain has to be taken into account.

Moreover, P_{RX} is the difference between transmission power P_{TX} and path loss a_{dB}:

$$P_{RX} = P_{TX} - a_{dB} = P_N + \mathrm{SNR}_{dB} \tag{18}$$

Assuming free-space propagation, a_{dB} results as

$$\begin{aligned} a_{dB} = &- G_{TX} - G_{RX} + F + I \\ &+ 20\log_{10}\left(\frac{4\pi\cdot d\cdot f_c}{c_0}\right)\,, \end{aligned} \tag{19}$$

where G_{TX} and G_{TX} denote the antenna gains of transmitter and receiver respectively. F defines the noise figure, and I describes implementation losses. f_c is the carrier frequency and d the distance between transmitter and receiver, which is equivalent to the coverage range.

Finally, (19) can be solved for d, and a_{dB} can be substituted with (18). The coverage range $d_{dB} = 10\log_{10}\left(\frac{d}{1\,\mathrm{m}}\right)$ results as

$$\begin{aligned} d_{dB} = &\frac{1}{2}\Big[G_{TX} + G_{RX} - F - I + P_{TX} - \mathrm{SNR}_{dB} \\ &- P_N - 20\log_{10}\left(\frac{f_c}{1\,\mathrm{GHz}}\right) - 32.44\Big]\,. \end{aligned} \tag{20}$$

For an reasonable system comparison in terms of Packet Loss Rate (PLR), Forward Error Correction (FEC) and physical layer overhead have been neglected for this analysis. The PLR thus is calculated by

$$\mathrm{PLR} = 1 - (1 - \mathrm{BER})^{N_{bit}}\,. \tag{21}$$

where N_{bit} denotes the number of bits per packet.

4.3 Evaluation Results and Discussion

In the subsequent section the three suggested systems are compared with each other considering the key requirements for FA resulting from section 2.1. Initially a bit error evaluation is performed based on section 4.1, before the systems are collated in a coverage range comparison for the AWGN channel model. Afterwards the results are discussed regarding their suitability for FA.

4.3.1 BER versus SNR

Figure 6 illustrates the BER performance versus E_b/N_0 of the described PHY layer technologies in AWGN. Under the described preliminaries, the IR-UWB performance is congruent with the performance of binary antipodal signaling. In the scope of FHSS we observe the expected performance difference between MSK with coherent reception (CR) and GMSK with limiter discriminator reception (LD). While the performance of the FSK reference with CR is congruent with binary orthogonal signaling, the LD reception loses around 4 dB in the range of practically relevant BERs. Regarding PSSS demodulation, we observe the influence of the length of the utilized PN-sequence. The PSSS 31 system loses about 5 dB compared to antipodal signaling. By increasing the sequence length by a factor of approximately 8 to

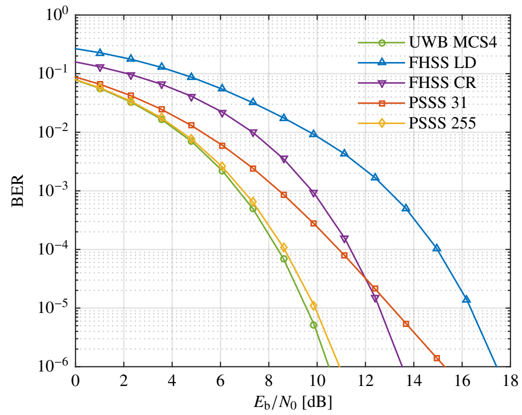

Figure 6: Bit error rate versus E_b/N_0.

PSSS 255 this performance loss reduces to less than 0.5 dB.

As presented in figure 7, by changing the scale to BER versus SNR, the effect of the different concepts of frequency spreading are clarified. While FHSS spectrum spread effect arises from frequency changes, UWB and PSSS originate their wideband characteristics from impulse or sequential spreading. Here, for PSSS the signal power refers to only one of the utilized sequences, while all sequences are in use.

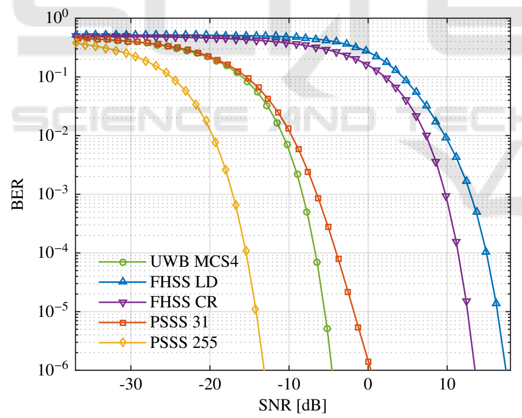

Figure 7: Bit error rate versus SNR.

4.3.2 Coverage Range Analysis

In order to determine realistic coverage ranges, a set of reasonable values describing the transmission characteristics has to been chosen. Table 3 summarizes the parameters that are used in (18) for reasonable coverage range estimation in AWGN for the three depicted technologies.

Due to interoperability with existing communication systems in the 2.4 GHz ISM band, for the FHSS and the PSSS system the 5.8 GHz ISM band is chosen for coverage range analysis. For UWB, the 7.9872 GHz channel is selected as defined in section 3.1. While the parameters f_c, B and P_{TX} differ among the three technologies, the system parameters, which include antenna gains G_{TX} and G_{RX}, noise figure F and implementation losses I, are chosen identically for a reasonable system comparison.

Table 3: Parameters for Range Calculation.

Parameter	UWB	FHSS	PSSS
f_c [GHz]	7.9872	5.825	5.825
B [MHz]	499.2	1	20
P_{TX} [dBm]	10	14	14
P_N [dBm]	-86.99	-113.98	-100.97
N_{bit}	$8 \cdot 60$ Byte		
G_{TX}	0 dBi		
G_{RX}	0 dBi		
F	5 dB		
I	10 dB		

As a result, figure 8 is obtained from (20). Obviously the sequential spreading concepts are able to stand harsher SNRs as depicted in figure 7, but certainly suffer from higher P_N (see table 3). The absolute EIRP transmission power is the same for FHSS and PSSS, but IR-UWB is subject to a regulatory limitation of 0 dBm per 50 MHz bandwidth in the 6 GHz to 8.5 GHz range (ETSI, 2013).

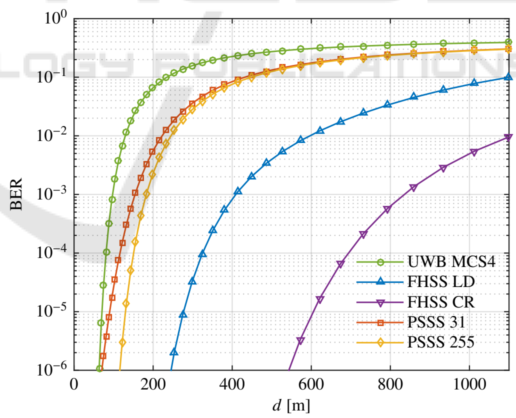

Figure 8: Bit error rate versus coverage range.

Next, the evaluation results in terms of PER versus coverage range are shown in figure 9. The PLR considerations are calculated with (21) and 60 Byte packet size. The proposed 60 Bytes include user data, which is up to 30 Byte for FA (see table 3), packet overhead and FEC overhead. In order to attain an reasonable system comparison without MAC layer evaluation, the packet size is kept the same for all three PHY technologies.

4.3.3 Discussion

As displayed in figure 9, the PSSS 31 system does not meet the FA coverage range requirement and turns out as impractical for this application field. The inhomogeneity in the PLR curve's slope for low error rates from about 10^{-7} to 10^{-8} results from the averaging over binomially distributed bits per PSSS symbol as indicated in section 4.1.3. The UWB system and the PSSS 255 system are comparatively low range, but both match the range requirements for FA under ideal free-space conditions. Other communication scenarios are only applicable using FHSS leading to its higher flexibility.

While the UWB PHY reaches a coverage range of 43 m for PLR of 10^{-9}, the PSSS 255 system covers up to 75 m and the FHSS LD system up to 156 m. For the PSSS coverage range it is assumed that the maximum data rate is utilized, thus all codes are in use. When the number of utilized codes is reduced, the coverage range for the remaining codes is increased depending on the coding gain factor, which is up to 255 for PSSS 255. Furthermore, the BER degradation coefficient γ is influenced by less concurrent codes (see section 4.1.3).

As depicted in section 3.4 the considered systems vary in their parameters and so does the link data rate. Regarding the latency requirements, the achieved data rate is vital. While FHSS and UWB have a fixed channel data rate, which is equal to the link data rate, the PSSS system can adapt the channel data rate dependant on the specific application data rate. In case of FHSS the fixed channel data rate can only be adapted within restricted limits by parallel reception on multiple FHSS frequencies as realized for WSAN (PNO, 2012). For serving multiple clients in a star topology the UWB system is dependent on Time Division Multiple Access (TDMA), thus cycle times for scenarios with large numbers of connected nodes are high (Reinhold, 2016). For FHSS, besides TDMA, a Frequency Division Multiple Access (FDMA) channel access scheme is possible with advanced transceiver concepts, but on the other hand abrogates the advantage of simple transceivers. With PSSS a combination with Code Division Multiple Access (CDMA) is possible, allowing very low latencies and novel and flexible resource management strategies, which are currently being investigated.

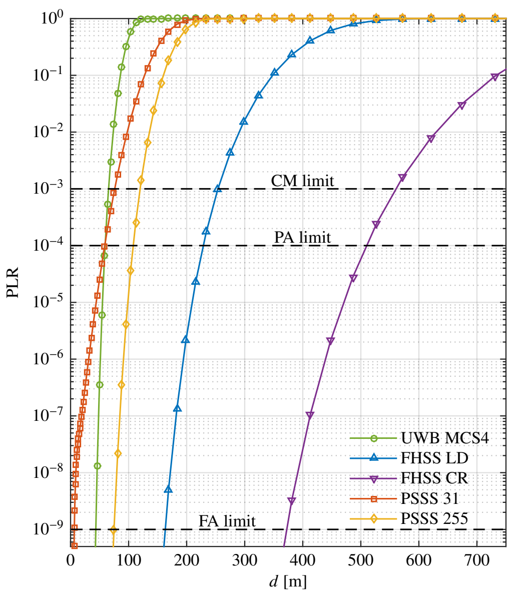

Figure 9: Packet loss rate versus coverage range.

5 CONCLUSION

In this paper, requirements for industrial applications have been discussed. These requirements are critical for realization with wireless technologies in at least the one of the application categories. Focusing on FA, the performances of IR-UWB, FHSS and PSSS physical layers have been analyzed. The system analysis and comparison have been performed under regulatory aspects and assuming realistic reception concepts in AWGN. The systems have been discussed considering the delay requirements for FA and the systems' potential with respect to appropriate medium access strategies is assessed.

Since the presented evaluation bases on an AWGN channel model, future work focuses on advanced performance evaluation with more realistic channel models for industrial environments like presented in (Molisch et al., 2004). Consecutively, a delay analysis with appropriate MAC layer concepts for each technology is possible and reasonable. Apart from that, a coexistence analysis, including both inter- and intra-system-coexistence, contributes a vital piece on the feasibility of the presented PHY concepts.

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