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Improved Usage of Time Slots of the IEEE 802.15.4a UWB System Model

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Abstract—**The fundamental idea of a technology currently known as ultra wideband (UWB), can be tracked at the end of the 19th century to the spark-gap tests of Guglielmo Marconi. Producing and transmitting short – in UWB on a nanosecond scale - impulses in time domain, potentially offers high signal bandwidth and low complexity for a communication system. Despite the simplicity and other advantages, it was not until in the 21st century when the first global regulation concerning UWB was revealed, not to mention the first global standard relating to the impulse based UWB. In this paper, the first completed impulse radio UWB standard, IEEE 802.15.4a published in 2007, is investigated and few improvements are suggested together with simulation results to support the stated enhancements and the effects of them. The enhancement can be, for example, increased data rate or number of users and improved detection performance.**

Keywords; UWB; IEEE 802.15.4a; modulaton methods;binary phase-shift keying

I. INTRODUCTION

Ultra wideband (UWB) technology can roughly be divided in two categories; multiband and singleband UWB. Multiband is a corresponding technology to the traditional multi-carrier or orthogonal frequency division multiplexing systems as singleband is considered as a carrier-free technology. Singleband UWB is based on sending very short impulses in time and often referred as impulse radio UWB (IR-UWB). It is by basis, a low complexity and a low power transmission system due to the baseband nature of the signal transmission. On the contrary to the multiband-UWB, in the IR-UWB it is not required to have the mixing stage to modulate the baseband signal into a carrier frequency. This feature enables low power consuming transceivers but yet with high signal bandwidth. Due to the large spectrum of a UWB signal, it appears in a noise-like signal which is resistant to severe multipath and jamming. It also has very good time domain resolution which can be used in location and tracking applications. [1]

Even though impulse radio technology has been known for long time and the fundamental idea of the technology currently known as ultra wideband can be tracked all the way back to Guglielmo Marconi's experiments, it was not until in the 1990s when the UWB studies started to gain more attention in data communication sector. One of the major changes in the development of UWB for communications occurred in 2002. Federal Communications Commission (FCC), being first in the world, issued a decision where the usage of UWB was defined [2]. The first attempt for impulse radio UWB standard, IEEE 802.15.3a, was withdrawn as unanimous decision was not reached [3]. However, IEEE 802.15.4a [4] defining UWB physical layer for low data rate communications was published in 2007. [1] [5] [6]

Despite of the standard, UWB is still facing challenges, such as the lack of international convergent regulations. At the moment, the FCC has the most liberal regulation on UWB by allowing the usage of 3.1-10.6 GHz band for unlicensed indoor communications with -41.3 dBm/MHz of maximum average power spectral density [2]. In Europe, the power limitation is the same but the unlicensed band is narrower, from 6 to 8.5 GHz. With detect and avoid technology the band can be extended to 3.1-4.8 GHz and 8.5-9 GHz [7]. Japan applied the same power limit too, but the band for UWB is different. For unlicensed use a band from 7.25 to 10.25 GHz can be used and with detect and avoid from 3.4 to 4.8 GHz [8].

In this paper, we are suggesting an enhancement how to use the existing IEEE 802.15.4a standard's system model for ultra wideband. By utilizing the suggested method, improved usage of time slots within a symbol is achieved together with better performance in terms of bit error rate (BER). The price for the enhancement is that coherent receivers only are able to detect the modulated signal. Generally, coherent receivers are more complex in real implementation, thus requiring more processing power than non-coherent ones. Another counter-argument is that in the original idea of the standard, both coherent and non-coherent receivers are able to receive and detect the same signal and the same information.

The results of the suggested method are presented by simulation model which is modified version from the standard following model presented and used in [9], [10] and [11]. The used channel model is based on the measurements in real hospital environment [12] and it is the same channel model which used in the previous work as well.

II. IEEE 802.15.4A UWB PHYSICAL LAYER

The IEEE 802.15.4a [4] standard was published in 2007 and it is an amendment to the IEEE 802.15.4 published in the previous year. There are two alternate physical layers defined in the IEEE 802.15.4a, in addition to the base standard. These are IR-UWB and chirp spread spectrum. In this paper, we concentrate only on the IR-UWB and present the UWB symbol structure with related modulation methods as these are the most important information for the novel ideas of ours. For more detailed information about the standard, reader is referred to [4]. From [13] and [14] can be found comprehensive overviews with analysis of the IEEE 802.15.4a.

A. Modulation methods and symbol structure

There are two modulation methods defined for the UWB in the IEEE 802.15.4a standard. These are burst (pulse) position modulation (BPM) and phase-shift keying (PSK), both binary methods. The modulation methods are consecutive in the sense that PSK cannot be used alone but it can be used additionally with BPM. In other words, a burst is always position modulated and an additional bit can be sent in the same burst by modulating the polarity of the burst. Generally, information bit is position modulated and the additional phase modulated bit is redundant convolutional channel coded bit. In some options though, the phase modulated bit can be an information bit as well, i.e., two information bits are transmitted in one symbol. Benefit of this type of modulation is that receiving and demodulating a burst can be done in both coherent and non-coherent methods yet retaining exactly same information (unless the phase modulated bit is another information bit too). In such way coherent receivers can improve their performance by decoding the convolutional coding or non-coherent receivers can gain in simplicity.

Figure 1, a redrawn version of the one in the standard, presents the symbol structure of a UWB signal. The symbol is divided into four quarters; first quarter is for position modulated bit zero and third quarter for position modulated bit one. Second and fourth quarters are guard intervals in order to “limit the amount of inter-symbol interference caused by multipath” [4]. Each quarter are then divided into 2, 8 or 32 time-hopping slots. Figure 1 is presented with eight time-slots, i.e., possible burst positions. [4]

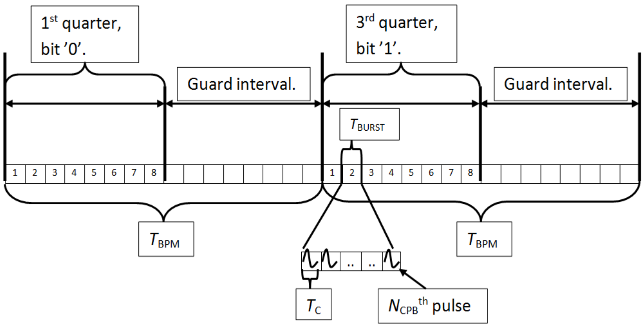

Figure 1. Symbol structure in the IEEE 802.15.4a

In the UWB transmission based on the IEEE 802.15.4a standard, a user or, for example, a sensor has a dedicated time slot inside a symbol quarter (which place inside the quarter is varying according to a predefined pseudo random hopping code). If the transmitted bit is zero, the transmission is occurring in the first quarter and if it is one, in the third quarter. If there is another bit to be transmitted in the same symbol, the phase of the same burst is modulated accordingly, multiplied with either 1 or -1. [4]

This type of modulation method has also drawbacks. First one is caused by the nature of position modulation. Having different instants for binary transmissions inevitable means that 50% of the transmission time is unused. The burst is sent either in the first quarter or in the third quarter. A second drawback is the combination of BPM and PSK. Since a burst can also be phase modulated, the position demodulation has to be done in a non-coherent manner. In generally, coherent detection has better performance metrics than non-coherent detection. Demodulating the burst position first, being necessary, causes dependency between the two demodulation methods. In such way, generally worse method is done first for defining the burst position in time and then using a better method for the detection of another bit is executed. If the position of the burst is detected wrong, the probability for detecting the second bit correctly is 1/2.

The next section presents an alternative way to modulate a signal yet retaining the same symbol structure as defined in the IEEE 802.15.4a and still using a demodulation method defined in the standard. Modulating a UWB signal another way provides few advantages.

B. Suggested enhancements

The key idea of improving the performance of a system build according to the IEEE 802.15.4a standard can be summarized in one sentence; bypassing the position modulation. Bypassing the position modulation and utilizing only the PSK opens a whole new perspective yet retaining compatibility with the existing standard. As explained earlier, in position modulation half of the possible transmission time is “unused”. Bypassing the position modulation, the unused time can be taken in use. The freed transmission time can either hand out to additional user within the same sensor network potentially doubling the number of possible users or by doubling the burst positions provides more multiuser interference rejection. Another option is to let the same user transmit during the two time slots within a single symbol. The latter one has additional sub-options as well. The additional time slot can be used either for transmitting the same bit twice in order to improve the detection performance (smarter option would be to send the same bit twice in different symbols) or sending twice as many bits within a symbol which would double the data rate. A third sub-option is to send channel coded bits together with information bits in order to achieve coding gain. Sending channel coded bits can be done in a traditional way by interleaving the bits or by using the standard’s definitions and send one information bit and one channel coded bit within the same symbol. The convolutional channel coding is already defined in the standard and can therefore be used in the suggested method as well.

Even though the suggested model is modified from the original, it is still retaining backward compatibility with the existing standard. The symbol structure remains the same, transmitted signal is constructed in similar way but transmitted twice within a symbol and one of the defined demodulation methods is used also. Additional to this, both of the defined channel decoding methods can be utilized too. In the defined decoding methods, Reed-Solomon and convolutional, the transmitted coded bits are systematic redundant bits, i.e., additional bits added on top of the information bit stream.

III. SYSTEM MODEL

The transmitted UWB waveform during the k^{th} symbol interval is expressed as [4]

$$x^{(k)}(t) = \left[1 - 2g_1^{(k)}\right] \sum_{n=1}^{N_{\text{cpb}}} \left[1 - 2s_{n+kN_{\text{cpb}}}\right] \times p\big(t - g_0^{(k)} T_{\text{BPM}} - h^{(k)} T_{\text{burst}} - nT_{\text{c}}\big), \qquad (1)$$

where $g_0^{(k)}$, in the standard, is a position modulated bit and $g_1^{(k)}$ is a phase modulated bit. Sequence $s_{n+kN_{\text{cpb}}} \in \{0,1\}$, $n = 0, 1, \ldots, N_{\text{cpb}} - 1$ is the scrambling code used in the k^{th} interval and $h^{(k)}$ is the k^{th} burst hopping position defined also by the scrambler. $p(t)$ is the transmitted pulse waveform at the antenna input, T_{BPM} is the half length of a symbol defining the position of the burst in the symbol, T_{burst} is the length of a burst and T_{c} is the length of a pulse. The symbol structure is presented in Figure 1. [4]

If the position modulation is bypassed as suggested, the transmission of two bursts is occurring in both symbol quarters, in the first and in the third one, according to the time varying hopping code, $h^{(k)}$. This leads to two separate transmissions during one symbol and that $g_0^{(k)}$ gets both binary values within a symbol. However, either value does not mark a position modulated bit anymore, even though the value remains the same, zero or one. Therefore, $g_0^{(k)}$ in (1) is replaced by $g_{0_{i+1}}^{(k)}$ as

$$g_{0_{i+1}}^{(k)} = \begin{cases} 0, i = 0, \\ 1, i = 1, \end{cases} \qquad (2)$$

where $i + 1$ presents either the first or the second transmitted bit, depending on the value of i, within the k^{th} symbol interval.

The k^{th} received symbol can be written as [15]

$$r^{(k)}(t) = x^{(k)}(t) * h(t) + n(t), \qquad (3)$$

where $x^{(k)}(t)$ is the transmitted signal as in (1), $h(t)$ is the channel impulse response, '*' states convolution and $n(t)$ is a white Gaussian noise.

Since the position modulation is bypassed, only the coherent detection is investigated in this paper. However, receivers, such as energy detector and a binary orthogonal non-coherent receiver, have been studied earlier, i.e., in [9], [10] and [11]. In [11] it is provided six different receiver types, i.e, different combinations of receivers detecting either BPM or both the BPM and BPSK demodulations.

Coherent detection can be expressed as

$$v_i^{(k)} = \int_s^{s+T_w} r(t-\tau) w(t)\, d\tau, \; i=0,1, \qquad (4)$$

where

$$w(t) = \left(\sum_{n=1}^{N_{\text{cpb}}} \left[1 - 2s_{n+kN_{\text{cpb}}}\right] \times p(t - nT_{\text{c}})\right) * h(t) \qquad (5)$$

is a locally generated reference, T_{w} is the length of the locally generated reference, T_{c} is the length of single pulse and $s = k2T_{\text{BPM}} + iT_{\text{BPM}} + h^{(k)}T_{\text{burst}}$. Generating $w(t)$ in this way performs an all-rake receiver collecting all multipath components of the propagated signal. This requires good a priori channel information, and in reality, is extremely complex to build. Therefore, in practice, simpler selective and partial rake receivers are normally used.

After the correlator, the decision variable is compared to zero in order to make a decision of the received bit

$$v_0^{(k)}, v_1^{(k)} \underset{\text{"0"}}{\overset{\text{"1"}}{\gtrless}} 0. \qquad (6)$$

After the decision, the received bit stream is fed into channel decoders, if any or either one of the decoding methods is used or if both are used at the same time.

The channel model used in the simulations is based on a measurement campaign in a real hospital environment introduced in [12]. In [16] it was concluded that it provides more accurate channel information of the hospital environment than the IEEE 802.15.6 channel model.

IV. RESULTS

Table 1 provides a comparison of the standard definitions and the suggested options.

Table 1. Improvements based on the suggested method.

Parameter defined by the standard:	**According to the standard**	***Suggested option***
Number of possible burst positions (time-hopping slots) inside a symbol	2	*4*
	8	*16*
	32	*64*
Data rates in Mbit/s	0.110	*0.220*
	0.850	*1.700*
	1.700	*3.400*
	27.24	*54.48*
Data rate with 2 information bits per symbol, Mbit/s	6.810	*6.810*
	27.240	*27.240*

As can be seen from Table 1 and as explained earlier, bypassing the position modulation and using PSK only, potentially doubles either the data rate or the number of time hopping slots when compared to the model defined in the IEEE 802.15.4a standard. When compared to the standard defined option where two information bits are transmitted in the same symbol with the BPM-PSK combination, the data rate remains the same but advantages come from another way. Firstly, achieving the same data rate but with use of only one demodulation method simplifies the receiver structure; the demodulation of signal is done only once as in the original model two different demodulations are used. Secondly, the detection of the second bit within the same symbol is not dependent on the first detected bit which improves the performance of detection (PSK as a method is also better than the position modulation [1]).

Figure 2 presents performance comparisons of different receivers with the mandatory mode of the standard, 16 pulses per burst. The resulting bit error rate curves are presented as a function of energy per bit over noise (E_b/N_0). These performance curves and the related receiver structures have already been studied, concluded and published earlier in [9] [10] and [11].

As comparison purposes and a conclusion of the previous work, the solid lines in Figure 2 present the performances of different receivers, i.e., energy detector and combinations of position and phase demodulator, capable of detecting the IEEE 802.15.4a standard's signal model. The dark blue solid line presents the performance of a simple non-coherent receiver, an energy detector. As can be assumed, it has the worst performance. The next solid line, the light blue, approximately 8 dB better in BER level of 10^{-3}, have been executed with position demodulation together with convolutional decoding which is coherently detected. The best solid line in black presents the best performance that can be achieved with BPM-PSK combination. It is approximately 1 dB better than the one with convolutional channel decoding. The reason for having the best performance is that there are two information bits transmitted in the same burst. Therefore in the results which are presented as a function of bit energy vs. noise, the advantage is 3 dB.

The dashed lines in Figure 2, on the other hand, present performance curves obtained according to the suggested enhancement explained in the previous section. A circle as a marker indicates that convolutional channel decoding has been utilized and a cross as a marker means that Reed-Solomon decoding only has been used. The curve without markers indicates that no channel decoding method is employed.

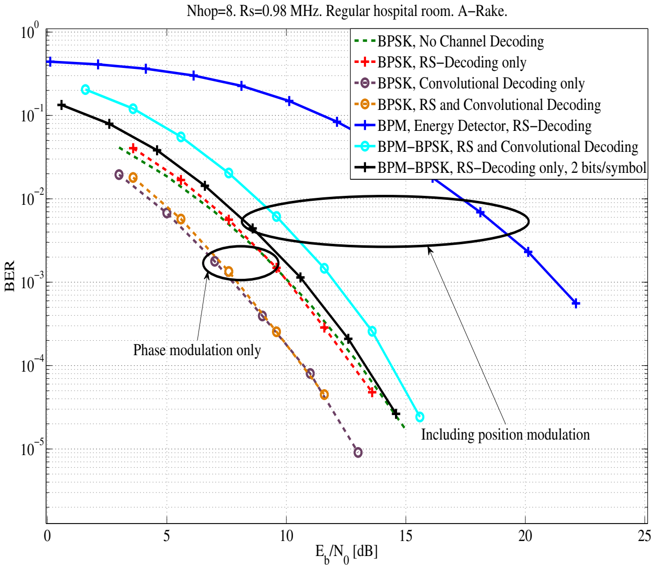

Figure 2. Performance comparison of different receivers.

In the dashed performance curves there are only one bit transmitted in each burst, but within the same symbol there can be two information bits (i.e., two bursts as well) transmitted. These curves present the receiver structures implemented according to the suggested method where the position modulation is bypassed and therefore coherent detection only is used. The performance curve without any channel decoding is slightly better than with the receiver from the original model using two different demodulation methods and Reed-Solomon decoding. The red dashed curve presents the coherent detection only with RS-decoding. As can be seen, the RS-decoding is rather inefficient and not improving the performance in the inspected BER levels, 10^{-4} or higher. The same effect can be seen in the two best curves. Both receivers use the convolutional channel decoding and only in the other one the RS-decoding is utilized but without any improvement in the performance. The convolutional channel coding on the other hand provides approximately 2 dB benefit.

Figure 3 provides similar comparisons as Figure 2 for the suggested method but the used burst is shorter, two pulses, providing higher data rate. However, the results and conclusions remain the same. PSK as a method offers better performance metric than using position modulation and the advantage of convolutional channel decoding is around 2 dB when the Reed-Solomon decoding is inefficient.

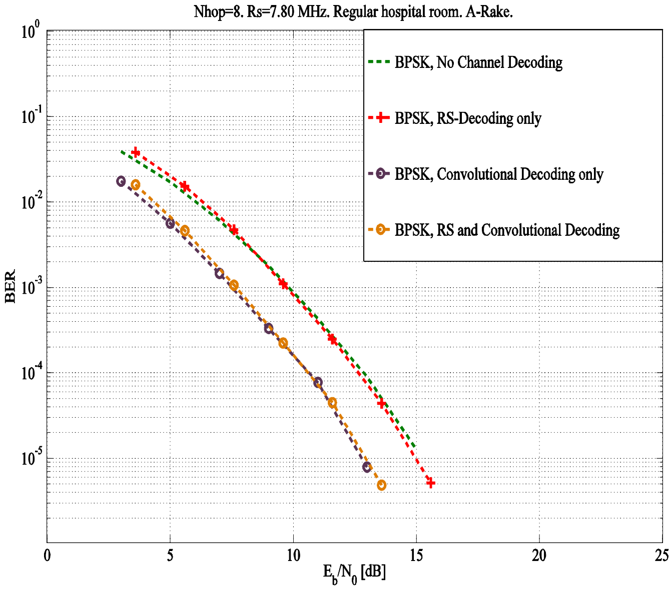

Figure 3. Performance comparison with shorter burst.

V. CONCLUSIONS

In this paper we have presented an idea for improving the usage of time slots of a UWB symbol defined in the IEEE 802.15.4a standard. Bypassing the burst position modulation and utilizing only the phase-shift keying, defined in the standard, offers higher data rates, more reliable data transmission or an option for adding more users in the same network. We recognize the fact that the IEEE 802.15.4a was originally intended for "devices using low-data-rate and low-complexity transmissions" and from this point of view doubling the data rate and using coherent receivers only might not be justified. The proposed method is also in contrast to the original idea of detecting exactly the same information by both coherent and non-coherent receivers. But for some applications, especially in transmissions between network coordinators these options might be meaningful and offer valuable advantages and freedom. Additionally, the idea of bypassing the position modulation and using phase modulation can be extended to usage of other known modulation methods as well. Using, for example, on-off keying (OOK) or pulse shape modulation (PSM) instead of PSK is possible and offers similar benefits as the PSK. Utilizing OOK offers a possibility to use non-coherent receivers too and at the same time reaches towards the upcoming UWB standard IEEE 802.15.6 since OOK is defined in the draft version [17] as one option for modulating the signal. In this occasion though, studying the effects of using other modulations is left for future work.

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