On the Energy Detector, P- and S-Rake Receivers in a Measured UWB Channel Inside a Hospital

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Abstract—**Medical industry is potentially a big market for the wireless applications in the coming years. As the number of elder people is increasing, the need for various wireless body monitoring and measurement equipment is increasing as well. However, having any kind of electronic device next to the human body, or even inside of a body, faces challenges. For wireless body area network (WBAN) solutions, the battery life needs to be long, the equipment has to be safe to use and un-harmful also for other electronic devices. From power usage point of view, the most complex high performance receivers are not the best option since they tend to have high power consumption, thus short battery life. In this paper, the performances of receiver types suitable for low cost WBAN solutions are compared in a real hospital environment. The ultra wideband (UWB) transceiver system has been implemented by following the IEEE 802.15.4a standard requirements. The WBAN channel model is based on the measurements carried out in a regular hospital room in Oulu University Hospital, Finland.**

Keywords; energy detector; partial and selective rake receivers; hospital environment; IEEE 802.15.4a; WBAN; UWB;

I. INTRODUCTION

In wireless applications, generally, important features of devices are reliability of transmission, good coexistence capability with other devices, low cost, easy to use and low power usage, thus long battery life. In medical applications, the reliability and interference issues are highlighted due to sensitive information and challenging environment. For wireless sensor networks (WSN), low power consumption is an important feature due to the typical lack of an external power source. Combining a WSN into a medical application, i.e., a WSN measuring physiological parameters of a human body, the challenges are increasing as the body impacts on the propagation of a signal [1].

There are different receiver types available for various purposes. Generally, the most complex receiver types have the best performance, and also the highest power consumption. Coherent receivers are the most complex ones and non-coherent receivers are the simplest ones. The IEEE 802.15.4a standard [2] allows a possibility to implement both coherent and non-coherent receivers. An energy detector (ED) is an example of a low power and low complex receiver [3]. On the other hand, coherent receiver implementation can include different levels of complexity. In rake receivers, different multipath propagated components of the same transmitted signal are coherently combined. In such a way, the detection is improved as more energy of the signal can be captured. The rake receivers can be divided into all-rake (a-rake), selective rake (s-rake) and partial rake (p-rake) receivers.

In theory, an a-rake receiver combines all the multipath components, and thus, collects all the signal energy. This requires a perfect knowledge of the radio channel and lot of calculation, and hence receiving fingers. In practice, it is very difficult and complex, thus expensive and power consuming way to implement such a receiver in realistic channels.

A significantly simpler way to implement a coherent rake receiver is to combine *n* strongest multipath components. This is called as an s-rake receiver. It requires the channel information and calculation algorithms to decide which multipath components are the strongest ones. [4]

The simplest rake receiver is a p-rake which combines the *n* first arriving multipath components. P-rake does not require synchronization and estimation of all the multipath components. Most of the energy is usually in a line-of-sight cluster, including the couple of tens of the first arriving signal components. In a line-of-sight channel, this type of a receiver can be almost as good as an s-rake, but being less complex and requiring less calculation, and thus consumes less power.

Various studies, such as [4 - 7], concerning low complexity ultra wideband (UWB) rake receivers and energy detectors, have been published during the past years. In this paper, the performance of different complexity rake receivers and optimized energy detector is evaluated in a real hospital environment. This is done in a transceiver system implemented according to the IEEE 802.15.4a UWB requirements [2]. Therefore the results continue and extend the results presented in [8, 9]. The UWB wireless body area network (WBAN) channel model used in the simulations is based on the measurements carried out in a real hospital environment at the Oulu University Hospital, Finland [10]. IEEE 802.15.6 for WBAN [11] is still in its finalizing process and therefore the IEEE 802.15.4a model for wireless personal area network is used. The channel model of IEEE 802.15.6 [12] was published in 2009 but it does not cover the hospital environment as precise as the used UWB channel model [13].

II. SYSTEM MODEL

A. Transmitted waveform

Matlab® simulation tool was used to implement a time domain presentation of an UWB WBAN simulator. The simulator follows the IEEE 802.15.4a standard requirements

[2] and performs an impulse radio signaling based UWB transceiver. The transmitted UWB waveform during the k^{th} symbol interval is expressed as [2]

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

where $g_0^{(k)}$ is a position modulated bit and $g_1^{(k)}$ is a phase modulated bit. N_{cpb}, depending on the data rate, defines the number of pulses per burst. 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, T_{burst} is the length of a burst and T_{c} is the length of a pulse.

The k^{th} received symbol can be written as [14]

$$r^{(k)}(t) = x^{(k)}(t) * h(t) + n(t) \qquad (2)$$

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

Both binary burst position modulation (BPM) and binary phase-shift keying (BPSK) are enabled for the modulation of the signal. However, for modulating information bits the BPM is used as the BPSK is used for redundant convolutional parity bits only. With this modulation structure, the information bits can be received by both coherent and non-coherent receivers. Difference is that the coherent receiver can utilize the redundant bits to improve its performance. Reed-Solomon (RS) channel coding is another method enabled by the standard, and it can be utilized by both receiver types. RS encoded parity check bits are always position modulated, therefore visible for both types of receivers. The encoding methods are systematic, thus the information bits are transmitted also unchanged. Therefore, a receiver can either decode the parity bits to improve the performance or discard the additional bits, either RS or convolutionally encoded, in order to achieve more simplicity. [2]

For detailed information of the standard requirements and definitions, such as symbol structure, number of users and data rate, the reader is referred to [2], for a comprehensive overview to [15] and for a brief presentation to [8] or [9].

B. Receiver types

A coherent receiver represents a reference receiver of the best possible performance. In the simulations with the coherent receiver, the system model's position modulated bits are assumed to be known and only the phase modulated bits are being detected, thus giving a good reference point for comparison. Exact synchronization is also assumed. A coherent detection and good channel estimation are required when implementing rake receivers. In reality, this might be too complex and computationally expensive to obtain in WBAN solutions.

A binary orthogonal non-coherent receiver, both with and without convolutional channel decoding, is the second studied receiver structure. This means that the detection of the position modulated bit is done in a non-coherent manner.

An energy detector (ED) is a simple way to implement a low-power consuming receiver. The performance is not as good as with coherent receivers but the simplicity is an important feature.

Coherent detection is expressed as

$$v_i^{(k)} = \int_q^{q+T_w} r(t-\tau) w(t)\, d\tau, \; i = 0,1 \qquad (3)$$

where $w(t) = \left(\sum_{n=1}^{N_{\text{cpb}}} \left[1 - 2s_{n+kN_{\text{cpb}}}\right] \times p(t - nT_{\text{c}})\right) * h(t)$ is a locally generated reference, T_{w} being the length of the $w(t)$, T_{c} is the length of one pulse and $q = k2T_{\text{BPM}} + iT_{\text{BPM}} + h^{(k)} T_{\text{burst}}$.

In s-rake receiver, the n strongest components (taps) of the channel impulse response $h(t)$ are being used by the receiver when implementing the locally generated reference $w(t)$. In p-rake, the n first taps are used for the same purpose. The a-rake receiver utilizes all the measured taps from the channel impulse response to implement the reference burst $w(t)$, thus T_{w} is much longer than the ones of s- or p-rake receivers.

In non-coherent receiver, the position modulated bit is defined by the comparison of the absolute values

$$\left|v_0^{(k)}\right| \underset{\text{"1"}}{\overset{\text{"0"}}{\gtrless}} \left|v_1^{(k)}\right|, \qquad (4)$$

i.e., if $v_0^{(k)}$ is bigger than $v_1^{(k)}$, the received bit is "0". Otherwise it is "1".

As an input for the detection of convolutional coding, the Viterbi decoder gets the sequence of bits obtained by both position and phase modulated bits. The phase modulated bits are detected by taking the correlation output described in (3) according to the burst position detected by (4). For the larger decision variable v_{i} (i = 0 or 1) from (4), the phase detection is expressed as

$$v_i^{(k)} \underset{\text{"0"}}{\overset{\text{"1"}}{\gtrless}} 0. \qquad (5)$$

If the correlation output is bigger than zero, the phase detected bit is "1", otherwise it's "0".

The position modulated bit is assumed to be known in the reference coherent receiver, and only the phase modulated bit is detected according to (3) and (5). In non-coherent receiver without convolutional coding, only the position modulated bits are detected as presented in (3) and (4). Convolutional coded bits are always phase modulated. In case the coding is used in non-coherent receiver, the phase detection is done according to (3) and (5), based on the information provided by (4).

The received signal in ED receiver is first passed through a band-pass filter (BPF) for noise reduction. Assuming that the BPF does not cause distortion to the received signal, the decision variable for the position modulation can be written as

$$w_i^{(k)} = \int_q^{q+T_{\text{burst}}+T_{\text{opt}}} r(t)^2\, dt,\ i = 0, 1. \qquad (6)$$

In the ED, the integration times are optimized for the channel. T_{burst} is the minimum integration time used by the energy detector. T_{opt} defines the optimized extension of integration time for each burst caused by the channel effect.

The decision on the received bit is based on the comparison between the decision variables and it is expressed as

$$w_0^{(k)} \underset{\text{"1"}}{\overset{\text{"0"}}{\gtrless}} w_1^{(k)} \,. \qquad (7)$$

Note that, due to the ED receiver structure (6), as the burst length increases, the longer integration time increases also the impact of noise. For various lengths of bursts, an optimized, burst length specific integration time for can be found.

C. Hospital channel model

An UWB WBAN channel model used in the simulations is based on the measurement campaign in a real hospital surrounding at the Oulu University Hospital, Finland [10]. The link in the channel model used is a line-of-sight link. The distance between the transmitter and the receiver is less than one meter from the center of the body to a left wrist. The channel was measured in a regular hospital room when a person was lying down on a hospital bed [10]. This scenario is thought as a "general" situation when being in a hospital as a patient and is therefore used in this study. Examples of the models are shown in [9].

D. Simulations and verifications

In the simulations 1.155×10^6 bits per each signal-to-noise ratio, E_b/N_0, have been executed. E_b is energy of a bit, i.e., energy over one burst and N_0 is a zero mean Gaussian noise. Different symbol rates and number of users (N_{hop}) were covered with different lengths of bursts. The standard defined symbol rates and N_{hop} values are presented in [2], [8], [9] and [15].

The results are presented in bit error rates (BER) as a function of E_b/N_0. Verification of the simulation model was done by comparing the reference BER curve in AWGN channel without channel coding with the theoretical antipodal bit error probability curve. The curves were identical. In binary orthogonal non-coherent detection without channel coding, the difference to the theoretical antipodal bit error probability curve is 4 dB in theory. In the simulations, using decision variables from (4) gave the same result.

III. RESULTS

Figure 1 presents a BER comparison as a function of the number of rake fingers between s-rake and p-rake receivers with the mandatory mode of the IEEE 802.15.4a, i.e., N_{hop}=8, R_s=0.98 MHz and 16 pulses per burst [2]. For E_b/N_0 to be studied, three different fixed values have been chosen; 8 dB, 13 dB and 18 dB. In the simulations, maximum number for the rake fingers is limited to 40, as in the hospital channel over 400 multipath components, on average, were detected by the measurements [10]. Limited number of fingers in rake receivers can be considered as low complexity receivers despite that the power consumption may be too high for WBAN applications. From Figure 1, the impact of the number of fingers between s- and p-rake receivers on BER can be seen. For example in the radio channel used in the simulations, the s-rake needs 6 – 8 fingers less than p-rake to have the same performance in BER level 10^{-3}. S-rake utilizes the strongest signal components and p-rake only the first ones.

Figure 2 shows the effect of optimization of the integration times of ED receiver. The curves present two different data rates, the mandatory mode and a shorter burst of 2 pulses. With the short burst, following parameters are used: N_{hop}=8 and R_s=7.80 MHz. For fixed E_b/N_0, two values based on the previous figure have been chosen: 13 dB and 18 dB. Due to the ED receiver structure presented in (6), as the burst length increases, the integrated noise increases as well. This can be seen in the figure where the ED receiver with short burst has better BER than with the mandatory mode. Another important feature is that as the integration times are being extended from the duration of a time slot, the performance of ED is improved only with the short burst. Therefore, extended optimized integration time can be found. However, the difference in BER is rather small. With the long burst, the integration time is already long enough and extending it is not improving the performance.

Figures 3 and 4 present performance comparisons of a reference coherent receiver, a binary orthogonal non-coherent receiver with and without convolutional channel coding and an energy detector in a real hospital environment. ED is the only receiver type in which the coherent rake detection is not utilized. On the comparison of performance order with a-rake types, the reference coherent receiver, in which only the phase modulated bit is detected and the position bit is assumed to be known, has the best performance. Binary orthogonal non-coherent with convolutional coding is the second, having approximately 2 dB lower performance in BER than the reference coherent receiver. Without convolutional coding, the binary orthogonal non-coherent receiver is the third, detecting only the position modulated bit. Exploiting the convolutional coding improves the detection around 2 dB. ED has the worst performance, about 7 dB worse than the binary orthogonal non-coherent without convolutional coding.

The number of s-rake or p-rake fingers is selected in such a way that the performance level would be as close as possible of the performance of ED with different BER values. With BER level of 10^{-3} in Figure 3, different s-rake receivers need to have 4 fingers in order to have approximately the same performance than ED. In Figure 4 with similar comparison, the required number of fingers with different p-rake receivers is 12. These crossing points of the curves are achieved when E_b/N_0 is approximately 22 dB. The used data rate is the mandatory mode of the IEEE 802.15.4a, symbol rate being 0.98 MHz. A burst has 16 pulses, each of 2 ns.

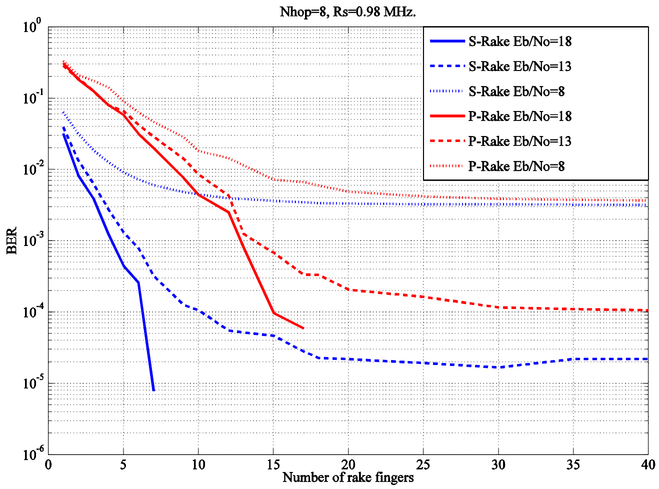

Figure 1. S- and p-rake comparison as the number of fingers increase.

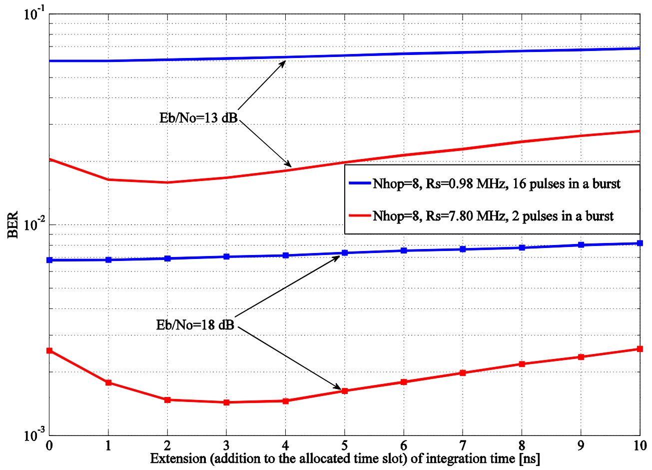

Figure 2. Optimization of integration times in energy detector.

With higher E_b/N_0 values than 22 dB in Figures 3 and 4, ED is performing better than the s- and p-rake receivers with the 4 and 12 number of rake fingers, respectively. This is due to the fact that in coherent detection, a proportion of the energy in the channel is lost when having limited number of rake fingers. If E_b/N_0 is lower, for example 15 dB, the fore mentioned rake receivers are having better performance than the ED unless the number of fingers is reduced. In Figures 3 and 4 with 15 dB, s-rake needs only 2 fingers and p-rake 7 fingers to have approximately the same BER level than the ED. With reduced fingers, the complexity in computation is reduced as well. On the opposite, with higher E_b/N_0 values, more rake fingers is needed to achieve the performance of the energy detector.

A general conclusion between s- and p-rake receivers can also be seen in Figures 3 and 4. For the same performance level, the number of fingers required in s-rake is obviously less than in p-rake (4 vs. 12 in this simulated scenario). The strongest arriving signal components are not necessary the first ones, despite the line-of-sight.

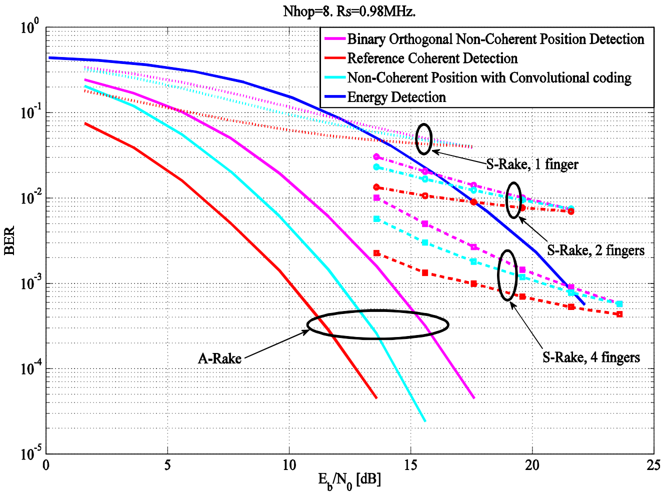

Figure 3. The performance of a-rake, s-rake and ED with a long burst.

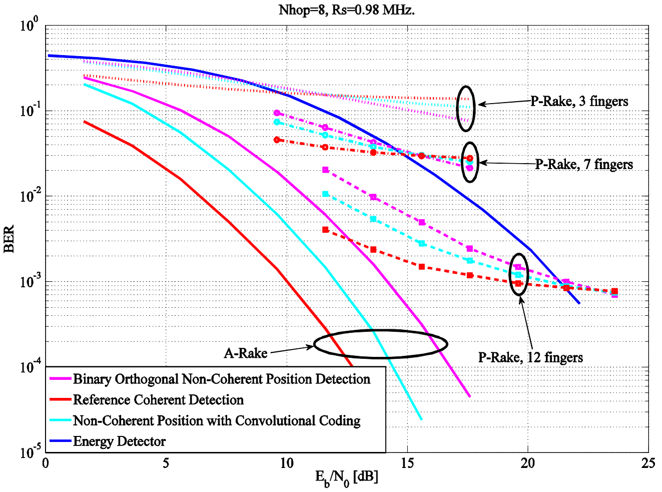

Figure 4. The performance of a-rake, p-rake and ED with a long burst.

IV. CONCLUSIONS

As the results show, a-rake, in theory detecting all the possible multipath components, gives the best performance in terms of bit error rate. In practice though, the a-rake is very complex and expensive in computing to implement. More practical solution is s-rake where the *n* strongest multipath components are summed together at the receiver. This too, requires the channel estimation of the multipath propagated signal components and most likely is too power consuming for many WBAN solutions.

P-rake receiver on the other hand is the simplest of the coherent receivers. It only needs to sum up the *n* first arriving signal components at the receiver and make the decision of the received bit. This is less power consuming way than the other two rake receivers and probably suitable for some WBAN applications. As the number of fingers in p-rake receiver is increasing, the performance level is closing to the level of s-rake receiver. Increasing the number of fingers in p-rake receiver (and in s-rake also) offers a trade-off between complexity and performance.

ED is the simplest and less power consuming of the receivers studied here and, in general, has also the worst performance. With fairly high E_b/N_0 ratio though, the ED has quite good performance. Comparing the ED receiver to different rake receivers with low number of fingers and BER level of 10^{-3}, the required number of s-rake and p-rake fingers is 4 and 12, respectively. However, with lower E_b/N_0, the performance of the mentioned rake receivers is better than the performance of ED. To have equal performance with lower E_b/N_0, the number of fingers can be reduced, thus benefitting in complexity.

With low data rates, thus long burst lengths, the ED collects more noise as the coherent receivers benefit from the higher number of pulses in a burst. For the optimization of the integration times in ED, only with short burst, thus high data rates, some minor improved is achieved. With the long burst, there is no improvement in the performance of the ED receiver.

As for the future work, one potential option is to study the performance of s- and p-rake receivers in different hospital environments. In the case of a-rake, the effect of the environment inside the hospital was insignificant [9].

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