Interference-Free OFDM Embedding of Wake-up Signals for Low-power Wake-up Receivers

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***Abstract*—The use of ultra-low power wake-up receivers (WuRx) can significantly reduce idle listening energy cost. To tailor a WuRx scheme to orthogonal frequency division multiplexing (OFDM) based systems, such as LTE-MTC or IEEE 802.11, the wake-up signal (WUS) also needs to follow OFDM principles to avoid interfering with other transmissions in the same shared bandwidth. Here, we address this particular issue and propose an approach where the OFDM transmitter is modified to also transmit WUSs designed for non-coherent low-power WuRxs, on a subset of the carriers, thus embedding the WUS correctly and ensuring orthogonality. The approach is evaluated for different system parameters and its applicability across a wide range of OFDM-based systems is verified.**

I. Introduction

The success of internet of things (IoT) has led to an increasing demand on wireless sensor network (WSN) type applications, through which more devices are intelligently connected to each other. Recent standard wireless protocols such as 3GPP LTE-MTC/NB-IoT, IEEE 802.11ba, and LoRa address connectivity for these types of applications. Energy efficiency is one of the key design requirements for IoT type applications since many devices have limited energy resources both due to their small size and their possible locations. In these applications, idle channel monitoring is one of the major sources of energy waste for a device, particularly in networks with low traffic intensity. Duty-cycling techniques where the main receiver of the devices periodically listen for a certain time period is a common approach to reduce energy associated to idle channel listening [1]–[5]. In this technique, there is however a trade-off between power saving, delay and device availability[1]. While long duty-cycles help conserve device energy resources the associated drawback is increased latency (or reduced reachability), especially if the main receiver is used for this periodic listening.

Using an extra duty-cycled ultra-low power receiver, typically referred to as a wake-up receiver (WuRx), dedicated for channel listening is accounted as a practical solution to reduce the idle listening energy cost and make shorter delays more affordable, e.g., as shown in [6]. In this scheme, the low-power WuRx monitors the wireless channel periodically for a wake-up signal (WUS) while the main receiver is switched off. The main receiver is powered up only if the device detects a WUS carrying certain information related to it. In the WuRx scheme, both low-power operation of the WuRx and the WUS design are of great importance. To allow for the use of low-power low-complexity WuRx designs, a simple non-coherent modulation scheme like on-off keying (OOK), frequency shift keying (FSK), or pulse width modulation (PPM), are often used [7]–[16]. To tailor the WuRx scheme to standard protocols, the WUS also needs to be compliant with the transmission principles of the standard in which it is embedded. For instance, in systems such as IEEE 802.11 or 3GPP LTE the transmission is based on orthogonal frequency division multiplexing (OFDM). To avoid interfering with the OFDM transmission, the WUS needs to be orthogonal in the same way as OFDM sub-carriers are, despite being based on different modulation principles. In this study, we address how to design efficient WUSs for extreme low-power IoT devices fulfilling all above properties.

Recently, different approaches to WUS design and WuRxs are introduced both in 3GPP-MTC/NB-IoT and IEEE 802.11ba. In 3GPP a new WUS is introduced for both MTC and NB-IoT devices. The WUS is designed based on OFDM modulation principles which ensures its orthogonality to other signals transmitted in the same OFDM symbol. However, for its detection, the WUS needs to be received by the same power hungry fast Fourier transform (FFT) based receivers used to decode the control and data channels. To be able to detect the WUS with such a design, the MTC device also needs to perform a costly synchronization before detection, unless it continuously stays synchronized with the network by keeping certain parts of its circuit on, e.g., the channel estimator. Both the use of a power hungry receiver and performing a costly synchronization makes the resulting energy savings from this wake-up signalling scheme rather limited, especially in scenarios where there is a tight requirement on device availability. The ongoing work in IEEE 802.11 addresses WUS designs suitable for low-power WuRxs [17]–[20]. Using an inverse FFT (IFFT) based solution [17] an OOK-modulated WUS is directly mapped to the OFDM symbols. While fulfilling the orthogonality requirement, this solution limits the WUS design to the specified carrier spacing and the corresponding OFDM symbol rate. A frequency division multiple access (FDMA) solution is presented in [18] to break the dependency on the OFDM symbol rate. However, in this approach the WUS is not completely orthogonal to the OFDM signal, resulting in interference. The authors of [20] present a different solution where the orthogonality to other sub-carriers is guaranteed. The influence of the cyclic prefix (CP) on WUS detection

[1]This is sometimes also refer to as reachability. In this work, we use these two terms interchangeably and both refer to the time aspect of reaching a device.

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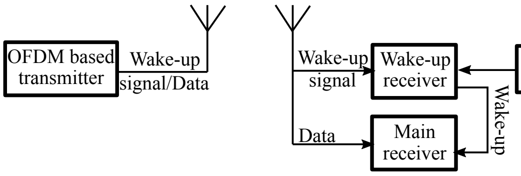

Fig. 1. Simplified block diagram of the reference system consisting of an OFDM-based transmitter, a low-power duty-cycled wake-up receiver (WuRx), and a main receiver.

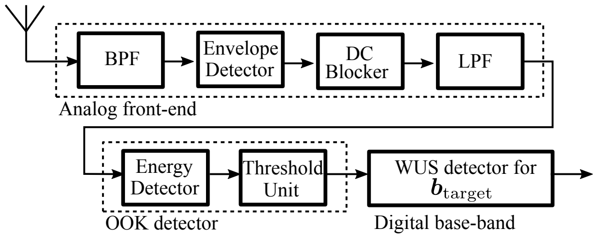

Fig. 2. Simplified block diagram of the reference WuRx consisting of an analog front-end (AFE), an on-off keying (OOK) detector, and a digital base-band.

is, however, not addressed and the WuRx needs to be fully synchronized to the OFDM transmission. A recent contribution [19] presents a solution where both the orthogonality of the WUS to other sub-carriers and the influence of the CP on WUS detection are addressed. This WUS is, however, specifically designed for IEEE 802.11 systems.

In this work, we address the above limitations and propose a new approach for interference-free OFDM embedding of a non-OFDM based WUS. With our proposed solution, we create a WUS which

- has all the properties that allows it to be decoded/detected by an ultra-low power WuRx,
- is orthogonal to the rest of the OFDM signal and do not cause interference, and
- is neither limited to a single OFDM symbol in length, nor tied to the OFDM symbol rate.

The orthogonality also opens up possibilities for boosting the WUS power without introducing interference to other sub-carriers in the OFDM signal. Through this we can, at least partly, compensate for the low-power WuRx performance loss and obtain better coverage, without spending more WuRx power.

In Section II, we describe the overall operation of our reference system and some of its important properties. We discuss general WUS design characteristics for low-power reception in Section III. In Section IV we propose a specific signal design for the WUS and show how a modified OFDM transmitter can be used for its transmission. We discuss and evaluate the performance of the proposed scheme in Section V. Conclusions and remarks are discussed in Section VI.

II. System Description

Our reference system, as shown in Fig. 1, consists of an OFDM-based transmitter, a duty-cycled wake-up receiver/WuRx and a main receiver. At the transmit side, a WUS compatible to OFDM transmission is transmitted. The operation at the receive side is based on the duty-cycled WRx scheme, described in the introduction, where a WuRx is switched on periodically by the sleep/listen timer and listens to the channel for any potential communication, i.e., a WUS. A main receiver is switched on by the WuRx only after it detects a WUS carrying correct identity.

To save power, WuRxs need to have a power consumption significantly lower than the one of the main receiver. By lowering requirements on time and frequency precision we can save on synchronization energy costs and by choosing not to use coherent modulation types we can further reduce power consumption at the receiver. With these restrictions we can also expect reduced WuRx performance. To get good detection performance combined with low-power reception, we therefore need a WUS design that takes this into account. With concurrent OFDM transmission, we also need to maintain orthogonality with data transmitted on other sub-carriers to avoid causing interference. In the following, we discuss more precisely how to design a WUS which allows low-power WuRx designs to be used on the receive side while at the same time it is orthogonal to other data transmission.

III. Signal design for low-power reception

In this section, we focus on the WUS design aspects allowing for WuRx low-power reception. For low-power reception, as indicated earlier, the signal needs to be both simple to detect and insensitive to time and frequency drift. We therefore select non-coherent modulation type based on our discussion in the introduction. Extreme low-power design of such receivers, however, leads to higher noise figures and degraded sensitivity. By relaxing the requirement on raw BER and using spreading (lowering the practical data rate), as we describe in [21], [22], we can compensate for the receiver performance loss and improve on its practical sensitivity. With longer WUSs using spreading, the associated processing gain compensates for the WuRx performance loss. The auto-correlation properties of the spreading signal also allows for self synchronization. A side-effect of this is that the WUSs can become longer than one OFDM symbol. In a typical OFDM based transmission, CPs are inserted to guarantee orthogonality between OFDM symbols. When mapping a WUS into an OFDM system, it is important to take into account the influence of CP on low-power reception. An intuitive solution would be to break a long WUS in parts and place it only within the main OFDM symbols. If the length of the main part of the OFDM symbol is an integer multiple of the CP length, we have an opportunity to adjust the WUS symbol time so that it can stay constant without slipping relative to the OFDM symbol structure. This is, however, not the case in all OFDM based systems. LTE is an example where this is not the case, since the fraction is $2048/144 \approx 14.22$, and IEEE 802.11 is an example where it is the case, since the fraction there is $64/16 = 4$. The latter is to some extent exploited in [19], but cannot be carried over directly to LTE where a non-trivial uneven distance between WUS symbols would result in more complicated and power hungry detection in the WuRx. We are primarily targeting

LTE-type systems and therefore address this issue in the next section. We propose an approach which allows for even WUS symbol spacing and thereby low-power detection in the WuRx, independently of the CP length, as long as it is a small-enough fraction of the total OFDM symbol length.

In this paper we have chosen to illustrate the concept using a simple non-coherent OOK modulation for the WUS transmission and thereby to avoid the use of power hungry WuRx components. The analysis is, however, not limited to this particular architecture. A simple block diagram of our reference WuRx is shown in Fig. 2. The received signal is down-converted to base-band by a band-pass filter (BPF) and an envelope detector. To reduce power consumption a large BPF bandwidth, compared to the WUS bandwidth, is typically chosen as it allows for relaxed requirements on local oscillator stability [14]. However, for a WUS embedded in an OFDM signal, increasing the BPF bandwidth also increases interference from other sub-carriers. The bandwidth of the BPF is therefore an important parameter and is addressed specifically in Section V, where we evaluate performance. A DC blocker and a low-pass filter follow the envelope detector to filter out the DC component and components at multiples of the carrier frequency, generated by the non-linear characteristics of the envelope detector. A simple non-coherent energy detector measures the energy content of the incoming signal during one symbol interval and converts the base-band signal to sequence of bits which is then fed to the digital base-band (DBB). The task of the DBB is to look for the target WUS, i.e. $\mathbf{b}^{\text{target}}$, in this bit-sequence by simple correlation[2]. In [6], [22] we show the DBB can handle high raw BERs in the tens of percent and still achieve low WUS miss and false-alarm probabilities by using this type of low-complex/low-power DBB processing. In this work, we therefore only look at raw BERs when we analyze the performance of the WUS design. The type of signals described here are, however, not orthogonal to the rest of the OFDM signal. Next, we describe how to maintain the above properties of our WUS and make it orthogonal to other signals at the same time.

IV. Signal Design for OFDM systems

To transmit a non-coherently modulated WUS suitable for extremely-low power reception, as described above, in a multi-carrier based system, the WUS needs to fit the structure of OFDM to avoid interfering with simultaneous OFDM transmission on other sub-carriers. A simple way to achieve this is to use the OFDM modulator for its transmission. As mentioned above, the time-duration of a WUS depends on several factors, such as detection requirements, overall system characteristics and the available bandwidth for WUS transmission. This means that a target WUS can span multiple, M, OFDM symbols. Further, CPs inserted to guarantee orthogonality within and between OFDM symbols can influence WUS low-power reception. In this section, we address this issue and propose a signal design which is orthogonal to other sub-carriers in an OFDM symbol and can be received by a low-power WuRx. Before that, let us introduce some of the key parameters and notations used for WUS signal design and its analysis.

In our reference system, an N-point IFFT is selected as the OFDM modulator and L is the number of samples in the CP. From the total number of sub-carriers N, K consecutive sub-carriers are used for WUS transmission while the remaining ones are used for other purposes than WUS transmission. The K WUS sub-carriers are from a set $\mathcal{K} = \{k_0, k_1, ..., k_0 + K - 1\}$ where k_0 is the WUS sub-carrier offset. To simplify expressions we use vector notations for our signals, with signal samples as vector elements.

Our aim is to create a base-band signal, at the OFDM transmitter, as close as possible to the target WUS. By close we mean that the resulting signal gives a detection performance close to the target WUS detection performance when detected by a low-power WuRx. With a target WUS spanning M OFDM symbols, we also want to create the WUS at the OFDM transmitter so that we can maintain the regular bit period of the target WUS even after CPs are inserted. This allows for simple low-power detection without a need for adjusting sampling times around CPs, making the required DBB processing very simple, similar to that in [6]. To create a signal design with such properties, we propose to add two blocks, a "sectioning" block and a "signal shaping" block before the OFDM modulator. Fig. 3 illustrates a simplified block diagram of the OFDM transmitter including these two additional blocks. The input/output signals of each block in the transmitter are illustrated, using a simple example, in Fig. 4. Since the transmitter has full control over the OFDM transmitter, a natural place to start the WUS transmission is at the beginning of the main part of an OFDM symbol. This is illustrated in Fig.4 (A) by the positioning of the WUS in relation to the OFDM symbol structure. With a WUS target $\mathbf{b}^{\text{target}}$, with P samples at the OFDM sampling rate, spanning M consecutive OFDM symbols

$$\mathbf{b}^{\text{target}} = [b_0, b_1, \ldots, b_{P-1}]^T, \quad P \geq N + L, \tag{1}$$

we propose to create M sections of the target WUS where the length of each section is one OFDM symbol, including CP, as shown in Fig.4 (B). For each of these sections we remove the parts of the target WUS that coincide with the CPs. This results in M vectors

$$\mathbf{b}_m = [b_{m(N+L)}, b_{m(N+L)+1}, \ldots, b_{m(N+L)+N-1}]^T, \tag{2}$$

of respective lengths N, for $m \in [0, M-1]$ where $M = \lceil \frac{P}{N+L} \rceil$. We then shape each section $\mathbf{b}_m$ by using the signal shaping block followed by an OFDM modulator, respectively. The shaping block is an important component here since this is the part which makes the WUS embedding in OFDM interference-free. As described earlier, our aim is to create a base-band signal (in time-domain) as close as possible to the target WUS. The signal shaping block therefore calculates the necessary input to the OFDM modulator (on the

[2]Performing hard-bit detection and correlation instead of using a more advanced analog-to-digital converter leads to a worse bit error rate (BER), but the advantage is a simple design of the corresponding circuitry and a low-power consumption. Manchester coding and a low oversampling are used to make the detection more robust to time and frequency errors, as well as changes in received power.

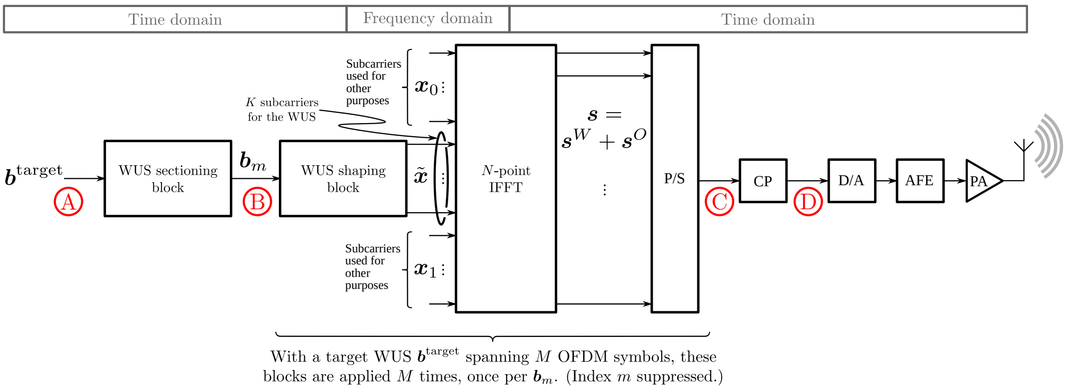

Fig. 3. Block diagram of the modified OFDM transmitter, including the two blocks used to create the embedded WUS. First a WUS sectioning block creates M sections of the target WUS. A WUS shaping block then shapes each of these sections so that the resulting signal at output of the OFDM modulator becomes as close to the target WUS as possible, using only the K designated sub-carriers.

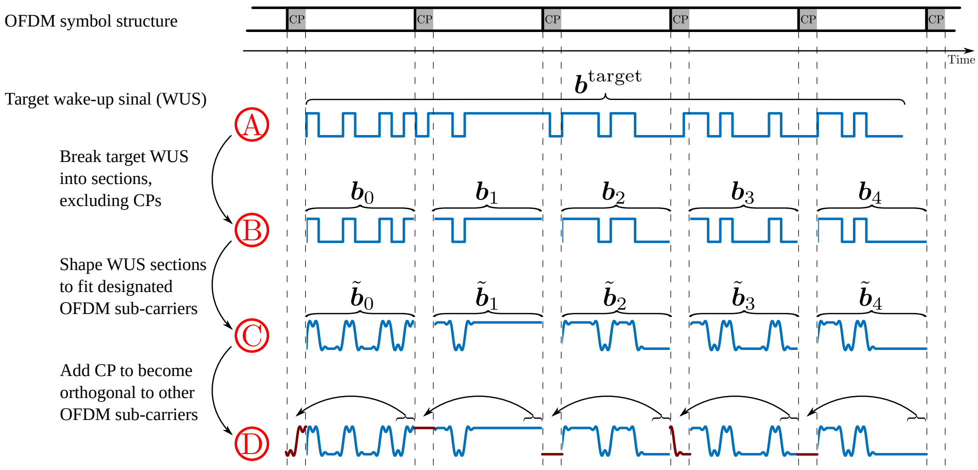

Fig. 4. Illustration of input/output signals of each block in the transmitter of Fig. 3, using a simple example. Step (A) to (B) creates $M = 4$ sections of the target WUS, excluding CPs. Step (B) to (C) shapes each section to fit designated sub-carriers while making the output of the OFDM modulator as close to the target WUS sections as possible. Step (C) to (D) adds CPs to maintain orthogonality in channels with time dispersion.

K sub-carriers designated for the WUS) giving the desired approximation of the target WUS when processed by the OFDM modulator. Any suitable metrics can be considered for the approximation. For the analysis in this study we have selected the least squares solution, as it leads to, closed form expressions.

Let us now describe the shaping process as applied individually to each of the WUS sections. For notational convenience, we suppress the section index m. Now, assuming an input $\mathbf{x}$ to the OFDM modulator, partitioned in three parts as

$$\mathbf{x} = [\overbrace{x_0, ..., x_{k_0-1}}^{\mathbf{x}_0^T}, \overbrace{x_{k_0}, ..., x_{k_0+K-1}}^{\tilde{\mathbf{x}}^T}, \overbrace{x_{k_0+K}, ..., x_{N-1}}^{\mathbf{x}_1^T}]^T, \quad (3)$$

where the middle part $\tilde{\mathbf{x}}$ is the input on the K designated WUS sub-carriers and the other two, $\mathbf{x}_0$ and $\mathbf{x}_1$, relate to other transmissions in the OFDM symbol. The resulting signal $\mathbf{s}$ after OFDM modulation becomes

$$\begin{aligned} \mathbf{s} &= \text{IFFT}_N(\mathbf{x}) = \mathbf{F}\mathbf{x} \\ &= \mathbf{s}^W + \mathbf{s}^O, \end{aligned} \quad (4)$$

with

$$\mathbf{s}^W = \mathbf{F} \begin{bmatrix} \mathbf{0} \\ \tilde{\mathbf{x}} \\ \mathbf{0} \end{bmatrix}, \text{ and } \mathbf{s}^O = \mathbf{F} \begin{bmatrix} \mathbf{x}_0 \\ \mathbf{0} \\ \mathbf{x}_1 \end{bmatrix}, \quad (5)$$

being the resulting output WUS and signal on other sub-carriers, respectively, and

$$\mathbf{F} = \frac{1}{N}[\omega^{nm}]_{m,n}, \quad (6)$$

for $\omega = e^{j2\pi/N}$ and $0 \leq m, n \leq N-1$, is the $N \times N$ IFFT matrix. Expressing the output $\mathbf{s}^W$ in terms of a WUS base-band signal approximation $\tilde{\mathbf{b}}_\mathbf{m}$ gives

$$\mathbf{s}^W = \text{diag}\left(\omega^{k_c 0}, ..., \omega^{k_c(N-1)}\right)\tilde{\mathbf{b}}_m, \quad (7)$$

where k_c is the center carrier frequency index of the subset $\mathcal{K}$. Using the least-squares approach, we find the input $\tilde{\mathbf{x}} = \tilde{\mathbf{x}}_{\text{LS}}$ on sub-carriers K so that the base-band representation $\tilde{\mathbf{b}}_\mathbf{m}$ of the resulting WUS $\mathbf{s}^W$ is as close as possible to the target base-band WUS $\mathbf{b}_m$, i.e.

$$\begin{aligned} \tilde{\mathbf{x}}_{\text{LS}} &= \underset{\tilde{\mathbf{x}}}{\text{argmin}}||\tilde{\mathbf{F}}\tilde{\mathbf{x}} - \mathbf{b}_m||^2 \\ &= (\tilde{\mathbf{F}}^H\tilde{\mathbf{F}})^{-1}\tilde{\mathbf{F}}^H\mathbf{b}_m, \end{aligned} \quad (8)$$

where $\tilde{\mathbf{F}}$ is the $N \times K$ sub-matrix containing columns $l = k - k_c \mod N$ from $\mathbf{F}$ for $k \in \mathcal{K}$, and $[.]^H$ and $[.]^{-1}$ denote Hermitian transpose and inverse of a matrix, respectively. After OFDM modulation, the CP is added to the signal $\tilde{\mathbf{b}}_m$. The result of this entire process is illustrated in Fig. 4 where signal (C) contains the shaped WUS inside the main parts of the OFDM symbols, and in (D) the CP is added to maintain orthogonality in channels with time dispersion.

By creating the WUS in this manner, not only the total length of the resulting signal remains the same as the original target WUS, but we also maintain the regular WUS bit period. This allows for simple low-power detection, without complex DBB processing or synchronization with the OFDM structure. The transmitted WUS is entirely orthogonal to the other signals transmitted in the same OFDM symbols and does not create any interference.

V. Design parameters and Performance Evaluation

In this section, we analyze and evaluate WUS BER performance when using the proposed approach, i.e., embedding a WUS, designed for low-power WuRxs, in OFDM systems. We do this by simulation where we study the influence of different parameter choices when transmitting over an Additive White Gaussian Noise (AWGN) channel. WUS and data have the same transmit power level per sub-carrier.

For the OFDM transmission we use LTE-MTC parameters, i.e., an $N = 2048$-point IFFT with 1200 active 15 kHz sub-carriers resulting in a 20 MHz total bandwidth. Of these, $K = 72$ sub-carriers are available for embedding the WUS, constituting a 1.08 MHz gap in the OFDM signal at our disposal. To allow for guard bands, against interference from the OFDM signal, our WUS is designed to have a bandwidth smaller than that gap. We restrict the bandwidth by using only 64 of the 72 available sub-carriers.

Given the above, we simulate the WuRx design shown in Fig. 2 for an LTE band in the 2 GHz range and a 240 kbps Manchester coded OOK WUS, occupying a 480 kHz bandwidth. We model the envelope detector by a component that outputs the squared input signal and set the bandwidth of the LPF following it to the 480 kHz bandwidth of the WUS.

A WuRx with a large bandwith on the first BPF can be implemented with higher frequency uncertainty without missing the WUS as indicated in, e.g., [14]. This allows for reducing WuRx power consumption at the cost of more noise and interference entering the receiver. It is therefore important to study how the bandwidth of the BPF influences BER performance. Furthermore, with the distortion introduced at CP locations in the WUS transmission, the BER performance becomes limited. For this reason, we also investigate how different CP lengths influence BER. In particular, we are interested in finding out how large bandwidth we can have on the first BPF, and how long the CP can be, without degrading BER beyond what is required on the input to the DBB processing.

Fig. 5 shows the simulated raw BER performance of the WuRx AFE and OOK detector, containing the components

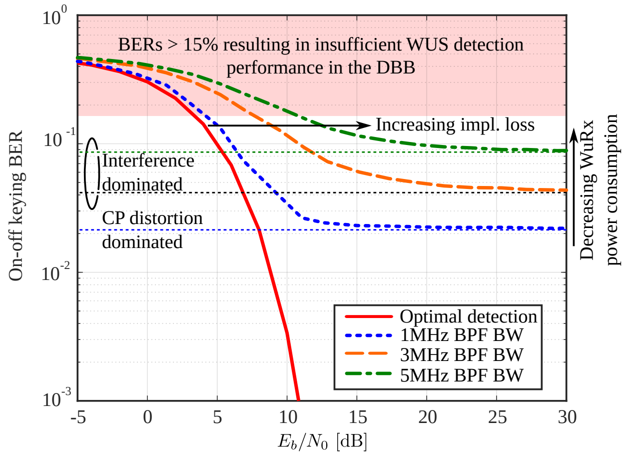

Fig. 5. BER performance of the WuRx analog front-end and OOK detector shown in Fig. 2, for an Additive White Gaussian Noise (AWGN) channel, when receiving a WUS created using the proposed OFDM-based transmission scheme. Transmit power per sub-carrier of WUS and data are at the same level. The CP length is set to $L = 144$ as in LTE-MTC. The bandwidth of the first WuRx BPF is varied from 1 MHz to 5 MHz.

above. In this simulation, aligned with LTE-MTC we use a CP length of $L = 144$, i.e., an $L/N \approx 0.07$ CP ratio, and vary the bandwidth of the first BPF from 1 MHz to 5 MHz. As a reference we show the BER performance of an optimal OOK detector (solid red). Based on investigations in, e.g., [6] and [23], a raw BER of 0.15 on the channel is quite adequate to achieve high detection and low false alarm probabilities[3]. The region of the BER above 0.15 is shaded light red. Using a 1 MHz bandwidth, we can limit noise and interference from other sub-carriers entering the WUS detector. At low E_b/N_0 we observe only 1 to 2 dB performance loss compared to optimal detection. When E_b/N_0 increases, as indicated in the figure, there is an error floor dominated by the CP distortion, as we will see below. By increasing the bandwidth of the first BPF, here by a factor of 3 and 5, we can save WuRx power consumption by lowering requirements on frequency accuracy. With a larger bandwidth, there will be more interference from other sub-carriers and more noise entering the WuRx, leading to reduced performance. This can be seen as a higher BER or a larger E_b/N_0 required to obtain the same BER. The latter we call implementation loss and it is indicated with an arrow in the figure. For the higher bandwidths the error floor is, as we will see below, no longer dominated by the CP distortion but by the interference from other sub-carriers. All three error floors are well below the required 0.15 BER, making all three designs functioning WuRxs. The one with the 5 MHz bandwidth would, however, result in the lowest power consumption, at the cost of a higher WUS transmit energy.

Above we saw the general behavior of the BER and can conclude that error floors at high E_b/N_0s play an important role. To investigate how these error floors depend on system parameters we perform BER simulations at high E_b/N_0s for

[3]According to investigations in the cited degree project, supervised by the paper authors, using a 63-bit Kasami sequence and unsynchronized reception with 0.15 BER results in 99% detection and 0.7% false-alarm probabilities.

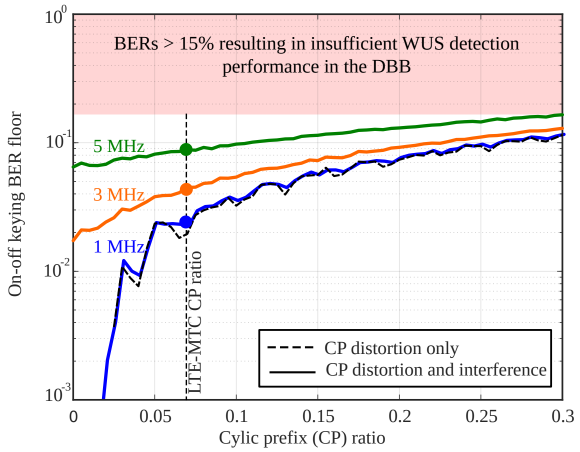

Fig. 6. WuRx BER floors when receiving a WUS based on our proposed OFDM-based transmission scheme, for different CP ratios and WuRx BPF bandwidths.

different CP ratios and different bandwidths of the first WuRx BPF. This will also reveal for which OFDM systems/CP ratios our proposed solution is appropriate. As a reference and lower bound we simulate the case where there is no interference present and only CP distortion limits performance. The results are shown in Fig. 6 for different CP ratios, with one solid error floor curve for each bandwidth and the interference-free lower limit dashed. The 0.07 LTE-MTC CP ratio is indicated by a vertical dashed line with the error floors appearing in Fig. 5 as dots. We see that for lower CP ratios, the error floors are comfortably below the 0.15 BER requirement. At higher CP ratios the CP distortion dominates and the error floors move closer to the 0.15 BER requirement. This shows that there is a limit to the applicability of the proposed WUS approach. For IEEE 802.11 systems with a CP ratio of 0.25, we may have to use more spreading to relax the BER requirement, if we want to use the presented approach.

VI. Conclusions

This paper presents a new approach for orthogonal frequency division multiplexing (OFDM) embedding of wake-up signals (WUSs) designed for low-power wake-up receivers (WuRxs). With the proposed approach the WUS does not interfere with transmission on other sub-carriers and has all necessary properties to be detected by an ultra-low power WuRx. We have shown that the approach works well for OFDM systems with relatively short cyclic prefixes, and in particular for an LTE-MTC-like system. The analysis is of course done under simplified channel assumption and more detailed studies are needed to fully establish performance in real conditions. Using this scheme in low-traffic IoT-type scenarios, with high demands on device reachability, the potential for power savings is large, compared to only operating with a traditional high-power OFDM based receiver.

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