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Quasi-Real-Time Wireless Communication Based on Wake-Up Receivers with a Latency Below 5 ms

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Abstract

Wake-up receivers (WuRxs) enable wireless sensor nodes to operate on battery power while maintaining efficient low-latency communication. Passive envelope detectors and low-frequency pattern matchers (LFPMs) are combined to design WuRxs working in the RF ranges. Recent publications have consistently demonstrated the effectiveness and reliability of this combination. Due to the modulation scheme employed, the wake-up packets (WuPts) used to activate the WuRxs are resistant to interference but tend to be complex and lengthy. None of the existing publications in this field have achieved a WuPt duration below 5 ms while retaining decent addressing capabilities. This article conducts a detailed analysis of the LFPMs' behavior and evaluates the performance of various WuPts. As a result, we propose two distinct solutions to reduce the WuPt duration to less than 5 ms, marking a 2.5-fold improvement compared to the current state of research.

Keywords

Low-frequency receiver, Manchester code, multicast, packet error rate, reliable, ultra-low power, univocal, wireless sensor network.

1 Introduction

Long-lasting battery life in wireless sensor nodes is essential for the establishment of modern wireless sensor networks. It is a well-known fact that the reception mode of the sensor node exhibits the highest overall power consumption. While continuous data reception is desirable, it is incompatible with achieving a battery life spanning several years. Even modern RF transceivers consume more than

10 mW during continuous reception, making it necessary to adopt a duty-cycling approach to significantly reduce power consumption. However, this approach comes at the cost of increased latency in event-driven communication. These high latencies render such systems unsuitable for many real-time applications. [Kan+21]

Several recent publications suggest the use of wake-up receivers (WuRxs), which are specialized RF receivers integrated into the sensor node and exhibit a power consumption in the range of 10 µW. Such a low power consumption allows for continuous and energy-efficient reception. Typically, WuRxs are designed to receive specific RF packets referred to as wake-up packets (WuPts) and are integrated into the sensor node alongside the main radio. [Gam+10]

Recent publications introduce various WuRx prototypes. This article specifically examines a subset: WuRx based on commercial off-the-shelf (COTS) components and low-frequency pattern matchers (LFPMs). LFPM-based WuRxs stand out for their simplicity, demanding minimal components and ensuring interference-safe communication [FKD23; Hmi+24; Sá+12].

A crucial element is the RF envelope detector, which passively converts the incoming signal from RF to LF. The LFPM serves as the final component in the WuRx block, designed for the reception of the LF signal. The WuPt contains a distinct pattern demodulated and matched by the LFPM. The output of the WuRx block is the digital wake signal. [FKD23]

In all WuRx solutions, there is a trade-off involving three key parameters: minimum detectable signal (MDS), power consumption, and latency. Most articles prioritize optimizing MDS, as an improved MDS extends the reception range of the WuRx communication. To maximize the battery life of the sensor node, minimizing the power consumption of the WuRx is essential. Our article, however, places primary emphasis on reducing the latency of WuRx communication. In the case of an always-on WuRxs, latency is approximately equivalent to the duration of the WuPt. The reaction time of the LFPM is generally significantly shorter than the WuPt duration and can be disregarded. Reducing the WuPt duration offers several advantages, enhancing the time- and power-effectiveness of the entire communication process. Numerous applications, such as localization, industrial automation, and control loops, require response times below 5 ms [GD15; BKK15]. Particularly when the wake-up transmitter (WuTx) is battery-powered, a shorter WuPt duration translates to reduced WuTx power consumption.

In our previous work, a detailed investigation into the addressing pattern of LFPMs was conducted [FKD24]. In that study, we delved into the significance of a univocal and reliable address space. Especially, patterns with a high run

Table 1: Summary of the State of Research

Proposals / Ref.	Sec. 4.2	Sec. 4.1	[FKD24]A	[FKD24]D	[Sut12]	[Gam+10]	[BDK18]	[BDK16]	[Gav+18]	[Sae+17]
NDR (kbit/s)	1.64	1.42	0.94	0.89	0.65	0.62	0.60	0.53	0.44	0.28
MDS (dBm)	−60.1	−59.9	−61.9	−61.6	−43	−52	−61	−60	−47.8	−61
t_{WuPt} (ms)	4.89	4.93	15.9	9.02	10.8	13	25	15	18	29
Consumption (µW)	10.2	10.2	5.71	5.71	8.52	7.8	7.2	7.5	18.5	70.2
LFPM [1]	x33	x33	x33	x33	x30	x32	x33	x33	x33	x33
LF (kHz)	36.0	30.0	25.7	25.7	125	125	17	18	11.36	20
Pattern (sym.)	16	16	32	16	16	16	32	16	16	16
URAS (bit)	8	7	15	8	7 [2]	8 [2]	15 [2]	8 [2]	8 [2]	7 [2]
β_{LF}	8	4	8	8	45	42	4	4	8	16
Coding [3]	direct	Look-up	Manch.	3S2B	Manch.	direct	Manch.	direct	direct	Manch.

[1] AS3930, AS3932, or AS3933
[2] estimated based on our investigation of [FKD24]
[3] direct bit to symbol conversion, coding based on look-up tables, 3S2B (3 symbols correspond to 2 bit, see [FKD24]), Manchester coding
Abbreviations: low-frequency pattern matcher (LFPM), minimum detectable signal (MDS), net data rate (NDR), wake-up packet (WuPt), univocal and reliable address space (URAS)

length limit (RLL) suffer from random packet loss. High RLL translates to multiple identical symbols following each other, resulting in the saturation of the data slicer and therefore random packet loss. To mitigate this, we ensured that RLL = 2 for all address combinations, effectively avoiding packet loss. Given that LFPMs cannot distinguish between the preamble and the pattern of the WuPt, addressing schemes are typically non-univocal. Transmitting WuPts with a single address results in wake-ups of unwanted WuRxs. To address this issue, we introduced special separation sequences to guarantee that the address spaces are univocal. While these separation sequences reduce the usable address space of the LFPM, ensuring a univocal and reliable address space is crucial for real-world scenarios. The number of address combinations, that allow for univocal and reliable address combinations is converted to the number of address bits (binary logarithm). In this article, we refer to these true freely usable address bits as univocal and reliable address space (URAS).
The primary objective of this article is to attain a WuPt duration below 5 ms, a goal not previously accomplished by any other LFPM-based implementation. Additionally, we ensured that our address space is univocal and reliable. We took measures to ensure that the MDS was not degraded by more than 2 dB despite the increased data rate. To measure our accomplishments in comparison to the existing state of research, we calculated the net data rate (NDR) using the formula presented in Equation 1, where t_{WuPt} represents the WuPt duration.

$$\mathrm{NDR} = \mathrm{URAS}/t_{\mathrm{WuPt}} \tag{1}$$

Our two proposed solutions achieved NDR values of 1.41 kbit/s and 1.64 kbit/s. This signifies an improvement of over 51 % compared to our latest publication [FKD24] and a factor 2 improvement when compared to independent articles [Sut12].

The remaining sections of the article are organized as follows: In section 2, we provide an overview of the state of research. section 3 outlines the working principle of LFPMs in WuRx, our measurement setup, and the conducted measurements. section 4 details our two proposals. Lastly, we summarize and discuss our results in section 5.

2 State of Research

Table 1 provides a summary of the current state of research along with the two proposals 4.1 and 4.2 introduced in this article. The columns in this table are sorted by NDR. The calculation of the LF modulation ratio β_{LF} is illustrated in Equation 2 and represents the ratio between the LF and symbol rate f_{sym}.

$$\beta_{LF} = f_{LF}/f_{sym} \tag{2}$$

A higher β_{LF} leads to a more robust modulation, but it necessitates longer WuPts to transmit the same information. In the following, we will describe the state of research in chronological order.

Gamm et al. [Gam+10] were the first to incorporate an LFPM in conjunction with an RF envelope detector. A high LF of 125 kHz was employed. However, such a high LF poses challenges, including a very high bandwidth and a high β_{LF}. Moreover, a high β_{LF} makes it difficult to use a commercial RF transceiver as WuTx due to their limited buffer size. The pattern size in this implementation is 16 symbols. Whether the address space is univocal or not was not discussed in the article. Based on our investigations in [FKD24], we estimate a URAS of 8 bit for this implementation. Through our proposed solutions, we achieved a 2.6-fold increase in NDR.

Sutton [Sut12] employed Manchester coding. According to our findings in [FKD24], Manchester coding is reliable but the address space is not univocal. To address this, we introduced the separation sequence LH in [FKD24]. Consequently, we estimate that the URAS of this article is reduced to 7 bit. Due to the high LF value in this work, both bandwidth and modulation effort are increased. Through our proposed solutions, we achieved a 2.5-fold increase in NDR.

Bdiri et al. [BDK16] are among the first to employ a lower LF value. This implementation exhibits an improved MDS due to the incorporation of an LF amplifier. However, no coding scheme is introduced. Whether the address space is univocal and reliable was not discussed in the article. Therefore, we estimate an URAS of 8 bit based on our investigations. With the lower LF, the β_{LF} is decreased to a value

of 4. Comparing this to our proposal 4.1, which also utilizes $\beta_{LF} = 4$, we achieved a 2.6-fold increase in NDR without significantly degrading the MDS.
Saez et al. [Sae+17] showed the lowest NDR value among the analyzed state of research. They accomplished a very robust modulation with $\beta_{LF} = 16$, resulting in an MDS of −61 dBm. Due to the use of Manchester coding, we estimated a URAS of 7 bit.
In our proposals, we employed a β_{LF} of only 4 and 8, achieving a 5.7-fold increase in NDR.
Bdiri et al. [BDK18] employed a hardware design nearly identical to their previous article [BDK16]. However, they utilized a 32-symbol pattern and incorporated Manchester coding. Given Manchester coding, only a separation sequence would be needed to achieve univocal and reliable address space. Therefore, we estimated an URAS of 15 bit. Due to the utilization of the LF amplifier, the MDS is −61 dBm. We achieved an MDS degraded by only 1 dB. However, our NDR is increased by a factor of 2.7.
Gavrikov et al. [Gav+18] employed a very low LF and could not achieve a low MDS value. We estimated a URAS of 8 bit. With our proposals, we increased the NDR by a factor of 3.6.
In [FKD24], we extensively discussed the significance and methods to achieve a univocal and reliable addressing scheme. Two our of four proposals are presented in Table 1. Proposal A utilizes a pattern length of 32 symbols with Manchester coding, achieving the highest NDR in the state of research thus far. Proposal D uses the 16-symbol mode with a dedicated coding scheme called 3S2B (3 symbols, 2 bits) and achieves the shortest WuPt. However, through the improvements investigated in this article, we were able to further increase the NDR by 74 %.

3 Investigation of Pattern Matchers

3.1 Low-Frequency Pattern Matchers in Wake-Up Receivers

LFPMs are specialized receivers designed for operation in the LF range, typically below 150 kHz. They facilitate the detection of on-off keying (OOK)-modulated packets in the LF range. Certain LFPMs are equipped with an integrated pattern correlator, offering a digital wake output.
The use of LF signal transmission within a wireless sensor network presents several challenges. These challenges are overcome by modulating the LF WuPt to RF. In most COTS WuRx implementations, a passive RF envelope detector is employed for demodulation. OOK, as a simplified amplitude modulation, is commonly uti-

lized. Given that the LFPM employs an internal LF envelope detector, there are two envelope detectors in total in the reception path of an LFPM-based WuRx. This reception path is illustrated in Figure 1a. Additionally, Figure 1b shows the typical WuPt for an LFPM-based WuRx, comprising a carrier burst, separation symbol, preamble, separation sequence, and pattern.

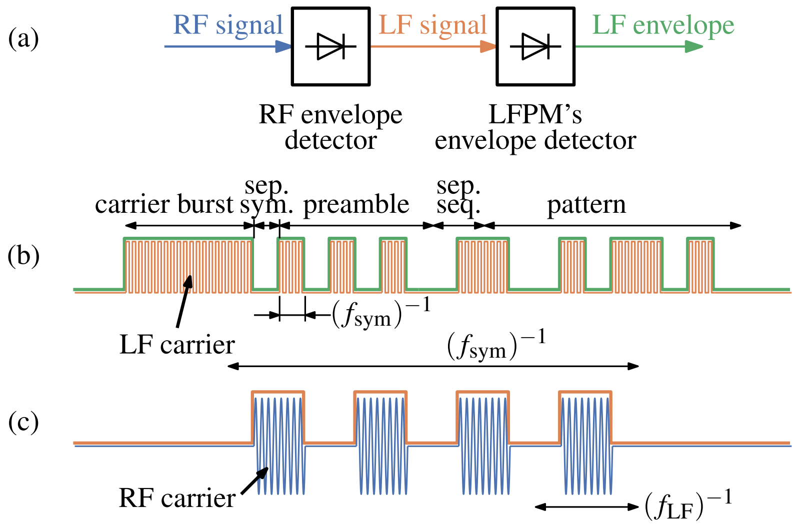

Figure 1: Generation of the wake-up packet (WuPt) for low-frequency pattern matchers. (a) Simplified reception path containing two different envelope detectors working at different frequencies. (b) LF envelope and LF signal of the WuPt. Visualization of the components: carrier burst, separation symbol, preamble, separation sequence, and pattern. (c) LF signal generated by the envelope of the RF signal.

The carrier burst, separation symbol, and preamble play crucial roles in exciting the reception mode of the LFPM and calibrating the data slicer. The separation sequence is introduced to ensure that the address space is univocal and was implemented based on our investigations in [FKD24]. The pattern itself contains the address information and is matched by the pattern corrector. In Figure 1c, it is shown that the LF signal is generated by demodulating the OOK signal in the RF envelope detector. Please note that the entire figure is not plotted to scale to ensure visibility [Gam+10].

As presented in [FKD23], β_{LF} should be a multiple of four to ensure simplified WuPt generation in the WuTx. Four signal periods are generated by a single modulation byte 0xAA. When β_{LF} is not a multiple of four, the number of bit-shift operations inside the WuTx increases significantly. We will explore the performance of modulation schemes with $\beta_{\text{LF}} = 6$. Here, bit-shift operations increase only slightly. The symbol rate f_{sym} of an LFPM is defined as a fraction of the LFPM's clock frequency f_{clk}, as seen in Equation 3.

$$f_{sym} = f_{clk}/n_{sym} \tag{3}$$

The integer n_{sym} is typically programmed into one of the LFPM's registers.

3.2 Minimum Detectable Signal Measurement

We conducted a detailed analysis in [FKD23] on how other publications specified the performance of their WuRx prototypes. We discussed various definitions of sensitivity and the corresponding RF power definitions. For our articles, we define the MDS as the average signal power of the WuPt necessary to achieve a minimum packet error rate (PER) of 30 %. Figure 2 illustrates the measurement setup we used for the subsequent MDS measurements.

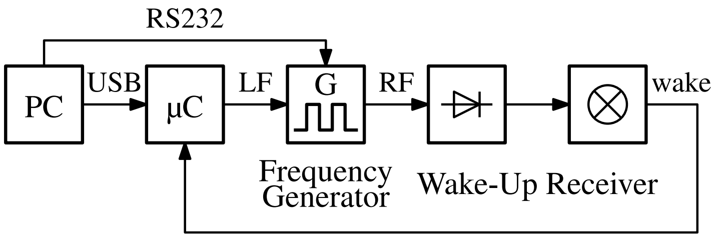

Figure 2: Building blocks of the MDS measurement system.

The PER is estimated by Equation 4.

$$\mathrm{PER} = 1 - \frac{n_{RX}}{n_{TX}} \tag{4}$$

The microcontroller commands the frequency generator to output exactly n_{TX} WuPts. Simultaneously, the microcontroller counts the number of received WuPts n_{RX} signaled by the WuRx through its wake output. The MDS is measured by finding the lowest RF power resulting in PER = 30 %. We varied the RF power of the frequency generator in steps of 0.1 dB and measured the PER for each step. Through regression, we calculated an exact value corresponding to our MDS definition.

3.3 Limitations of the Frequency Detector

Our measurements were based on the prototypes proposed in [FKD23], which consist of a voltage-doubler-based envelope detector matched to 868 MHz and the LFPM AS3933. Our results can be applied to other WuRx implementations and are nearly independent of the envelope detector used. However, our results are limited to the AS3930, AS3931, AS3932, and AS3933 series LFPMs. For all measurements, we utilized the highest specified clock frequency of 45 kHz. According to the datasheet [AS3933], the center frequency of band 5 is defined by Equation 5.

$$f_{LF} = f_{clk} \cdot 8/14 \tag{5}$$

For a clock frequency $f_{clk} = 45$ kHz, this results in 25.7 kHz.
In [FKD23], we defined the LFPM's operation within the LF range and removed the RF envelope detector from the WuRx's reception path. This allowed us more flexibility in generating the WuPt. We examined how the LFPM responds to changes in the LF while keeping the pattern and symbol rate constant. The results from these measurements indicated that LFPMs operate effectively over a broad frequency range. We observed only a slight degradation over the range from 16 kHz to 45 kHz. This suggests that we are not restricted to the fixed value of 25.7 kHz as specified in Equation 5. A higher LF, on the one hand, increases the bandwidth of the WuPt. On the other hand, shortening the WuPt duration is possible while maintaining the same level of redundancy.
We explored this behavior in the RF domain through measurements with our prototypes. We prepared different WuPts designed for various divider values n_{sym}. As the symbol rate increases while keeping β_{LF} fixed, the LF increases, leading to a decreased WuPt duration. For the subsequent measurements, we utilized a 16-symbol Manchester pattern. For each value of n_{sym}, we calculated the WuPt duration and measured the MDS of our WuRx. We repeated the measurements for β_{LF} values of 4, 6, and 8. The results are presented in Figure 3 as the relationship between WuPt duration and MDS.

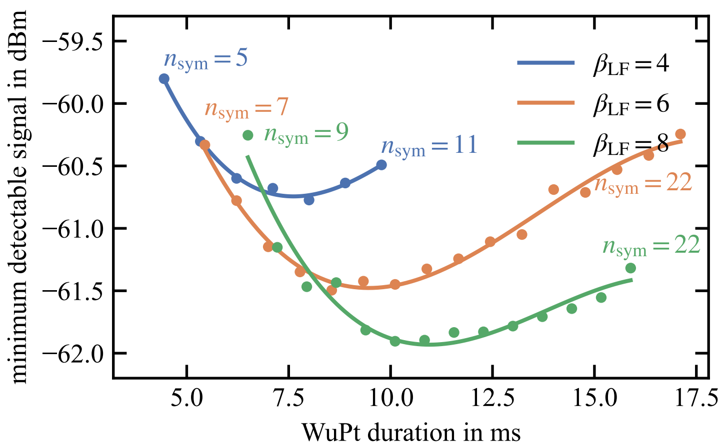

Figure 3: Measurements of different modulation ratios and symbol rates. Results are presented as the relationship between WuPt duration and MDS.

The measurement results exhibit a typical band-pass behavior of the LFPM. The results indicate that $\beta_{LF} = 8$ provides the best MDS values. However, due to the increased modulation effort, the WuPt duration is high. With a divider value of $n_{sym} = 10$, the WuPt duration was 7.2 ms. Lowering β_{LF} results in degraded MDS values, which is expected as there is less redundancy in the WuPt.

3.4 Run-Length Limitations of Patterns

In our work [FKD24], we investigated how the RLL of the pattern affected the reliability of pattern detection. Patterns with RLL = 2 exhibited no random packet loss. However, not a single pattern with RLL ≥ 4 was detected by the LFPM. Patterns with RLL = 3 proved extremely unreliable and exhibited pattern-depended packet loss (PDPL). Some of these patterns showed no packet loss, while others showed up to 90 % packet loss.

Subsequently, we explored the reasons behind the occurrence of PDPL with RLL ≥ 3 packets. We examined various configurations of the LFPM, including its automatic gain control, data slicer reference, time constants, and symbol rates. Unfortunately, none of these adjustments proved effective in resolving the PDPL problem. Further analysis, involving the probing of specific output signals from our LFPM, revealed that the reception mode is halted when the frequency detector is not excited for more than three symbol durations. This discovery explains why RLL = 3 exhibits PDPL and with RLL ≥ 4, no reception is possible at all.

Hence, we searched for ways to consistently excite the frequency detector while maintaining reliable symbol detection by the LFPM. The solution lies in employing different modulation words. When using $\beta_{LF} = 8$, the default modulation words 0xAAAA and 0x0000 were used to represent H-symbols and L-symbols, respectively [FKD23, p. 17]. Introducing and removing specific pulses within the modulation word ensures that the frequency detector remains excited during an L-reception, and the pattern detector stays synchronized. We measured the MDS for different combinations of modulation words. Subsequently, we tested the signal detection of 100 randomly selected patterns with RLLs ranging from 2–15. Table 2 presents the results of these measurements.

Different modulation words exhibited varying degrees of random packet loss. However, the only modulation words found to show nearly zero packet loss are (2AA8, 8002). It should be noted that this pair of modulation words comes with an MDS degradation of 2.2 dB compared to the default (AAAA, 0000). However, as we will discuss in the next section, it is worthwhile to use these modulation words because a substantial reduction of the WuPt duration is possible, thanks

Table 2: Measurements of Modulation Word Variation

H-word (hex.)	L-word (hex.)	MDS (dBm)	packet loss (%)
AAAA	0000	–61.5	90.5
AAA8	2000	–60.9	5.3
AAAA	C0C0	–60.7	91.5
AAAA	C003	–60.5	70.6
AAAA	F0F0	–60.0	85.7
2AA8	8002	–59.3	0.4
2AA8	8001	–59.2	11.2

to a larger address space without the RLL restriction. Figure 4 visually illustrates the difference between the two pairs of modulation words.

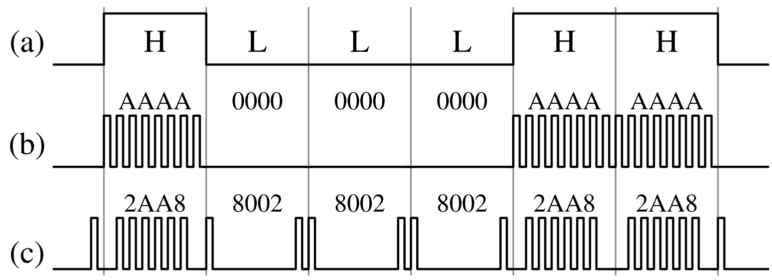

Figure 4: Visualization of different modulation sequences. (a) Symbol pattern. (b) Modulation words (AAAA, 0000). (c) Modulation words (2AA8, 8002).

In (b), a prolonged pause without any modulation is evident during the transmission of three consecutive L-symbols. This extended pause leads to the LFPM exiting the reception mode, rendering it unable to reliably receive this pattern. However, when employing the modulation words in (c), additional pulses prevent these effects from occurring. Because only single pulses are used, the LFPM can still clearly differentiate between L- and H-symbols. The removal of pulses from the H-symbol is crucial to ensure proper synchronization of the reception, as can be deduced from our measurement results presented in Table 2. The LFPM successfully received all 100 randomly selected patterns with RLL values ranging from 2–15 and exhibited a packet loss of only 0.4 %.

4 Proposed Wake-Up Packets

We proposed two distinct WuPts based on our earlier research findings. Proposal 1 utilizes the lower modulation ratio β_{LF} to achieve the highest possible data rate but relies on an RLL of 2. Proposal 2 utilizes β_{LF} = 8 and achieves a higher NDR by leveraging special modulation words, without the need to adhere to the RLL restriction.

4.1 Low Modulation Ratio

From the measurements presented in subsection 3.3, we selected the second-fastest configuration with $\beta_{LF} = 4$ and $n_{sym} = 6$ to ensure a sufficient MDS value. This configuration achieved a WuPt duration of 5.33 ms and an MDS of −60.3 dBm. To further reduce the WuPt duration, we optimized the coding of the entire WuPt. We minimized the carrier burst, introduced the separation sequence, and incorporated parts of the preamble inside the pattern. The inclusion of part of the preamble inside the pattern was already investigated and introduced in [FKD24]. Figure 5 illustrates the proposed addressing pattern.

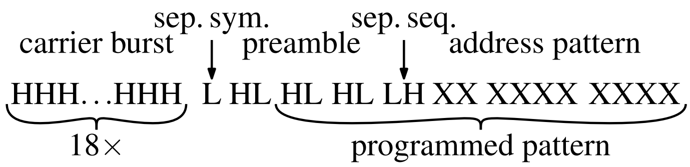

Figure 5: Visualization of proposal 1 wake-up packet with H = 0xAA, L = 0x00, and $f_{LF} = 30$ kHz.

The carrier burst requires 18 symbols. The preamble consists of three periods of the pattern HL. As seen in Figure 5, three preamble periods are situated inside the pattern to reduce the overall WuPt duration. The separation sequence LH is necessary to ensure that the address space is univocal, as discussed in [FKD24]. Ten symbols are left for the addressing information.

As specialized modulation words cannot be used with $\beta_{LF} = 4$, it is imperative to ensure RLL = 2 for all utilized patterns. To achieve the maximum address space, we employed look-up table addressing, as previously presented in [FKD24]. Through analysis, we determined that for ten address symbols, there are a total of 144 patterns satisfying RLL = 2. Consequently, we can affirm that more than 128 address combinations are available, allowing for the representation of a 7-bit address. All 144 address combinations were tested in hardware, revealing no instances of random packet loss.

With a WuPt duration of 4.93 ms, the NDR is 1.42 kbit/s. We measured an MDS of −59.9 dBm. No power-saving measures of the LFPM were utilized, as most of them demand an increase in the WuPt duration [FKD23]. We measured a supply current of 3.4 μA with a supply voltage of 3 V, resulting in a power consumption of 10.2 μW.

4.2 High Modulation Ratio

In subsection 3.4, we found that with specialized modulation words, the pattern is free from all RLL restrictions. Removing all RLL restrictions significantly increases the modulation efficiency compared to an RLL = 2 restricted pattern. However, when utilizing the specialized modulation words, we are constrained to $\beta_{LF} = 8$. The measurement results presented in Figure 3 show that we can achieve a 7.22 ms WuPt when allowing for a slight MDS degradation. We propose using the second fastest WuPt from Figure 3 with $\beta_{LF} = 8$ and $n_{sym} = 10$. It utilizes an LF of 36 kHz and reaches an MDS of −61.2 dBm. By optimizing the durations of the carrier burst and preamble and including parts of the preamble inside the pattern, we created the following proposal, visualized in Figure 6.

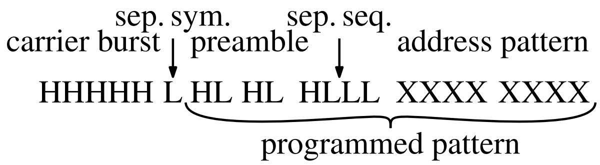

Figure 6: Visualization of proposal 2 wake-up packet with H = 0x2AA8, L = 0x8002, and $f_{LF} = 36$ kHz.

For the carrier burst, only 5 symbols are needed. The preamble consists of only two periods of the pattern HL. The separation sequence HLLL is needed to ensure that the address space is univocal. We determined this separation sequence by applying the methods we described in [FKD24]. To achieve the lowest possible latency, we decided to include the preamble and separation sequence completely into the programmed pattern. Therefore, eight symbols remain for addressing. Due to the specialized modulation words, there are no restrictions on the addressing patterns remaining to achieve a reliable and univocal addressing pattern. Therefore, 8-bit addressing is implemented.
We tested all 256 address combinations in hardware and found no random packet loss. With a WuPt duration of 4.88 ms, the NDR is 1.64 kbit/s. Additionally, we measured an MDS value of −60.1 dBm. No power-saving measures of the LFPM were utilized. Therefore, the power consumption stays constant at 10.2 µW.

5 Conclusions

This article focuses on minimizing the packet duration of the wake-up receiver (WuRx) communication to reduce latency and enhance the overall time-effectiveness of wireless sensor network communication. The reduction in wake-up packet

(WuPt) duration also contributes to lowering the power consumption of the battery-powered wake-up transmitter (WuTx).

In subsection 3.3, we conducted measurements to determine the minimum detectable signal (MDS) values for increased LF values and different β_{LF} values. The LF modulation ratio β_{LF} represents the ratio between the symbol rate and LF. Higher values of β_{LF} result in longer WuPts, but they also improve signal detection due to increased redundancy in the WuPt. The manipulation of LF values allows for a significant reduction in the WuPt duration.

In subsection 3.4, we explored methods to eliminate the run length limit (RLL) restriction of the WuPt. Our earlier analysis in [FKD24] highlighted the importance of maintaining RLL = 2 for reliable WuPt reception. By employing specialized modulation words containing additional pulses for enhanced synchronization in the low-frequency pattern matcher (LFPM), we successfully received patterns up to RLL = 15. The use of these modulation words eliminated the need for Manchester coding or other bit-stuffing techniques, resulting in a significant increase in modulation efficiency.

Based on these measurements, we proposed two addressing patterns for the given WuRx hardware, and their key parameters are outlined in the first two columns of Table 1. Proposal 1, discussed in subsection 4.1, utilizes a lower $\beta_{LF} = 4$. By introducing additional measures to decrease the WuPt duration, we achieved a duration of 4.93 ms. A total of 10 symbols are allocated in the pattern for addressing. With RLL = 2, 144 address combinations are available, allowing for 7 address bits. The calculated net data rate (NDR) for this proposal is 1.42. This represents a 51 % improvement compared to our best proposal in [FKD24] and an improvement of over a factor of 2 when compared to independent articles [Sut12].

Proposal 2, as discussed in subsection 4.2, utilizes the higher β_{LF} of 8 along with specialized modulation words. By implementing additional measures to reduce the WuPt duration, we achieved a duration of 4.89 ms. Eight symbols are allocated for addressing, allowing for the direct coding of 8 address bits. The calculated NDR for this proposal is 1.64. This represents a 74 % improvement compared to our previous article [FKD24] and a factor of 2.5 improvement compared to [Sut12].

Both proposals result in a degradation of the MDS by 1.7 dB and 1.5 dB, respectively. It is essential to note that this degradation corresponds to only a 17 % reduction in the wake-up range, as per Friis equation. Whether this loss in the range is acceptable and if the proposed address space of 7 bit and 8 bit is sufficient depends on the desired application field of the WuRxs.

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