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Univocal and Reliable Addressing Patterns for Wake-Up Receivers based on Low-Frequency Pattern Matchers

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Abstract

Wake-up receivers (WuRxs) allow wireless sensor nodes to run on battery power while maintaining asynchronous, low-latency communication. This article focuses on WuRxs based on low-frequency pattern matchers (LFPMs). Many recent studies either investigate physical WuRx implementations or simulate WuRx-based protocols. Our goal is to address the challenges that arise when realizing WuRx-based protocols in hardware. These challenges are, that a packet activates unwanted WuRxs, an unreliable address space, and missing cluster broadcast capabilities. The proposed separation sequences and run-length limited patterns ensure a reliable address space. WuRxs based on LFPMs use a fixed pattern matching. Cluster broadcasts are enabled by the proposed variable Manchester coding. Typically, LFPMs use Manchester coding with an efficiency of only 0.5 bit/symbol. We introduce two non-Manchester coding techniques with higher efficiency: lookup table-based coding with an efficiency of 0.71 and 3S2B coding with an efficiency of 0.67.

Keywords

Cluster broadcast, Manchester code, low-frequeny receiver, reliable, ultra-low power, univocal, wireless sensor network.

Table 1: Summary of the State of Research.

Proposal / Ref.	Pro. 4.1	Ref. [BDK18]	Pro. 4.2	Pro. 4.4	Ref. [Sut12]	Ref. [Gam+10]	Ref. [BDK16]	Ref. [Gav+18]	Ref. [Sae+17]
Pattern (symbol)	32	32	16	16	16	16	16	16	16
Address[1] (bit)	15	16	4–7	8	8	16	16	16	8
WuPt duration (ms)	15.9	25	7.15–9.02	9.02	10.8	13	15	18	29
Manchester	yes	yes	yes	no	yes	no	no	no	yes
PDPL[2]	no	no	no	no	no	yes	yes	yes	no
Univocal[2]	yes	no	yes	yes	no	no	no	no	no
RLL[3]	2	2	2	2	2	3	2	2	2
Cluster Broadcast	no	no	yes	no	no	no	no	no	no
LF (kHz)	25.7	17	25.7	25.7	125	125	18	11.36	20

4.1, 4.2, and 4.4 are the proposed addressing patterns of this article running on the WuRx hardware proposed in [FKD23] (see subsection 4.1, 4.2, 4.4, respectively)
The table is sorted by pattern and WuPt duration. Improvements are highlighted by a gray background.

[1] Address width claimed by the references. Our investigations show, that the usable address range is reduced by unreliable and non-univocal patterns.

[2] We estimated the rows PDPL and univocal by the patterns given in the references and the results of our investigations in section 3.

[3] RLL of the presented pattern.

Abbreviations: pattern-depended packet loss (PDPL), run-length limit (RLL), wake-up packet (WuPt)

1 Introduction

Long-living, battery-powered sensor nodes are critical to building dense and cost-effective wireless sensor networks (WSNs). When designing these sensor nodes, key considerations include power consumption, response time, communication range, and minimum detectable signal (MDS). Even today's RF transceivers require more than 10 mW to maintain continuous communication. To mitigate this, it is common practice to use duty cycling for the RF transceiver. However, this approach results in increased latency. [Piy+17]

Wake-up receivers (WuRxs), which serve as specialized RF receivers, are integrated into the sensor node to facilitate continuous reception mode. These WuRxs are realized to keep the power consumption in the range of 10 µW. WuRxs are installed alongside the primary RF transceiver in a wireless sensor node. These WuRx units are specifically designed to receive special RF packets known as wake-up packets (WuPts). The device responsible for transmitting the WuPts is referred to as the wake-up transmitter [Gam+10].

This article focuses on a particular set of WuRxs that are based on commercial off-the-shelf (COTS) components and low-frequency pattern matchers (LFPMs). There are other types of WuRxs, and our findings may help improve them as well. WuRx designs based on LFPMs excel in requiring very few components. Our proposal, described in [FKD23], used only eight surface-mounted components. The WuPts used in LFPM-based WuRxs ensure interference-safe communication and very few false wake-ups. [FKD23]

Many recent publications are devoted to exploring and improving the physical properties of WuRx prototypes. Their primary focus is on enhancing signal detection, reducing latency, and minimizing power consumption [Gom+18; BDK18; Sut12; Gam+10; BDK16; Gav+18; Sae+17; FKD23]. Conversely, another set of recent publications deals with the study and optimization of protocols built around

WuRxs. They mainly perform simulations of WSNs and compare different routing and communication strategies. [Web+22; Gun+18; Jel+14; SB19]
Based on our investigations in section 3, we claim that with the current state of research, it is nearly impossible to implement the WuRx protocols in hardware. Our findings revealed that recent WuRx prototypes lack certain properties and features that are considered standard in protocols-oriented articles. These properties are: reliability over all addresses, univocal address space, and support for cluster broadcasts. We describe these challenges and our solutions one by one in the following paragraphs.
Our research shows that certain WuRxs cannot reliably receive all addresses and have different packet error rate (PER) for different patterns. We named this phenomenon pattern-depended packet loss (PDPL). We found out that the PDPL depends on the maximum number of consecutive symbols in a pattern, or called run-length limit (RLL). When a WSN is plagued by PDPL, it experiences additional packet loss, additional wake-up transmitter activity, additional power, and time costs. We have mitigated the occurrence of PDPL with our patterns by reducing the RLL to 2.
Whenever proper separation sequences are missing in the WuPt, the address space is not univocal. In this case, a WuPt containing a single address will also activate other unwanted WuRxs. Activating unintended sensor nodes is an undesirable result. It also results in increased power consumption and potential collisions with subsequent RF packets. As detailed in section 4, the proposed separation sequences ensure that a WuPt containing a single address will only activate the desired WuRxs. Thus, the address space is univocal.
Recent LFPM-based WuRx prototypes are limited to performing a single address match. This means that they do not support cluster broadcasts. However, several protocols, including the ones presented in [Pet+14; Gun+18; SB19], require the use of cluster broadcasts. With the help of little additional microcontroller processing, one of our proposed addressing patterns will support cluster broadcasts.
Because the previous measures increased the size of the WuPt, we introduced two addressing patterns with improved efficiency. Current WuRx prototypes use Manchester coding in their addressing schemes, which has a code efficiency of 0.5 bit/symbol (see subsection 3.2). In contrast, we propose two alternative and reliable non-Manchester coding methods that provide superior code efficiencies and shorter WuPts.
This article is organized as follows: In section 2, we analyze the current state of research and highlight the existing research gap. In section 3, we explain the working principles of the LFPMs, provide details about our measurement systems and

present the outcomes of our measurements and theoretical investigations. section 4 outlines the proposed addressing patterns. In section 5, we discuss and summarize our results.

2 State of Research

This article focuses primarily on different addressing patterns. We do not examine the performance of specific WuRx prototypes with respect to aspects such as power consumption, MDS, and data rate. We have previously done a comprehensive investigation of WuRxs based on LFPMs in [FKD23]. According to the operational principle of LFPMs, MDS and power consumption remain unchanged when the addressing pattern is changed.

We did not find any articles dealing with the addressing schemes of LFPM-based WuRxs. We found no evidence that topics such as PDPL, univocal address space, and broadcast addressing were discussed. However, for another group of WuRxs: WuRxs based on a comparator with an adaptive reference generator, we found one article. Basagni et al. [Bas+19] found RLL = 5 for their used WuRxs. Whether the addressing scheme used by [Bas+19] is univocal or not is not clear. The parts of the WuPt were not presented, and whether the preamble detector provides a reliable separation between preamble and pattern is unclear. Since a microcontroller was used as the address decoder, support for cluster broadcasts is likely.

In Table 1, we provide a summary of the research discussed in this article. In addition, we present three of our four proposed addressing patterns (4.1, 4.2, and 4.4), which are detailed in their respective subsections of section 4. To populate the "PDPL" and "univocal" rows of this table, we used information from the references and the results of our investigations presented in section 3. The table is sorted by pattern width and WuPt duration. However, the following description of the state of research is presented in chronological order.

Gamm et al. [Gam+10] were the first to use a LFPM in combination with a RF envelope detector. The addressing pattern presented in that paper uses a RLL of 3. Our analysis in section 3 revealed that a significant portion of the 16-bit addresses in this pattern experience PDPL. We also demonstrated that the address space presented is not univocal.

In the article by Sutton [Sut12], they introduce a Manchester-coded pattern that results in an 8-bit address configuration. Our analysis showed that Manchester-coded patterns do not experience PDPL. However, we found that the address space is still not univocal.

Bdiri et al. [BDK16] are among the early adopters using a lower LF of 18 kHz. The addressing pattern shown in this article has a RLL of 2, but does not use Manchester coding. The minority of 16-bit addresses have an RLL of 2. Our results, as presented later, indicate that for non-Manchester coded patterns, the address space is not univocal and exhibits PDPL.

In the article by Saez et al. [Sae+17], they use an 8-bit addressing scheme using Manchester coding. It is important to note that Manchester-coded patterns, as shown in our analysis, are not univocal.

In the work of Bdiri et al. [BDK18], they use the 16-bit addressing mode with Manchester coding. Although the article does not provide a specific pattern example or delve into further discussion, the issue of a non-univocal address space remains.

In the research conducted by Gavrikov et al. [Gav+18], they use the 16-bit addressing mode without Manchester coding. The address pattern provided has a RLL of 2, although the article claims to support 16-bit addressing. Our measurements indicate that only a portion of the 16-bit address space is free of PDPL.

As highlighted in this brief review of existing research, the addressing patterns of LFPM-based WuRxs have often been overlooked. As our subsequent investigations will show, there are limitations associated with the use of non-Manchester-coded patterns. Our research will show that the address spaces presented in these publications are not univocal. Working with any non-univocal address space can lead to the activation of unwanted WuRxs when a single WuPt is transmitted. Both of these effects can significantly degrade the performance of a WSN, causing additional collisions and rendering some sensor nodes unaddressable. In this article, we identify these problems and propose solutions to achieve univocal and reliable addressing through our addressing schemes, which are detailed in section 4.

It is worth noting that none of the reviewed publications provide a solution for cluster broadcast, which is an essential feature for flooding-based routing protocols [Pet+14]. In Table 1, the proposal 4.4, shows the shortest WuPt duration, achieved by using efficient modulation and a fast WuRx prototype, as discussed in [FKD23].

3 Modelling of Pattern Matchers

3.1 Low-Frequency Pattern Matchers in Wake-Up Receivers

LFPMs are specialized receivers that operate in the LF range, typically below 150 kHz. They allow signal detection of an on-off keying (OOK) modulated LF packet. Some LFPMs have an integrated pattern correlator and provide a digital

wake output [Gam+10].
The use of LF signal transmission within a WSN presents several challenges: It requires the use of large transmitter and receiver coils, which can be impractical in terms of size and power consumption. In addition, LF signal transmission typically achieves only a limited transmission range. To address these issues, the transmission of the WuPt is shifted to the RF range. This approach helps overcome the challenges associated with LF signal transmission. To enable this transition, a passive RF–LF converter is introduced. This converter is an envelope detector using passive Schottky diodes.

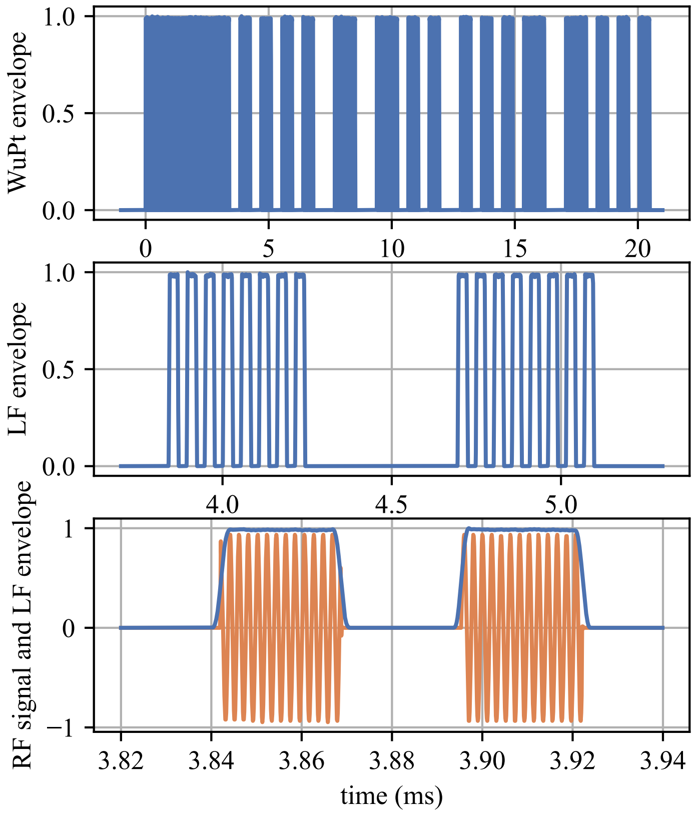

Figure 1: Typical wake-up packet (WuPt) of a low-frequency pattern matcher (LFPM) captured with software-defined radio. Complete WuPt envelope in the first plot, LF envelope in the second plot, and RF carrier together with LF envelope in the third plot.

The first plot of Figure 1 shows a typical LFPM WuPt. This WuPt is divided into three parts: The carrier burst part is from 0 ms to 3.42 ms. The carrier burst is essential for initializing the LFPMs receive mode. The preamble covers the time from 3.42 ms to 7.27 ms. During preamble reception, the data slicer of the LFPM is calibrated. The wake-up pattern starts at 7.27 ms. The second plot in Figure 1 zooms in on a segment of the preamble and visualizes the LF envelope of the signal. In the RF domain, these pulses are generated by turning the RF carrier on and off, as shown in the third plot.

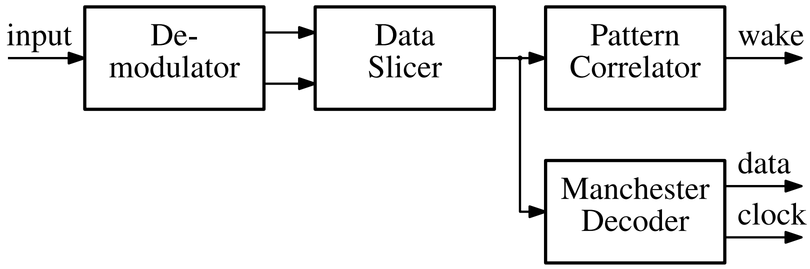

Figure 2: Simplified internal building blocks of a typical LFPM according to [AS3933].

Figure 2 provides a simplified representation of the internal components of a typical LFPM. The internal demodulator is responsible for performing demodulation based on the configured frequency band. In our experiments, the best MDS was achieved with an LF of 25.7 kHz [FKD23]. The demodulator produces two output signals: a slow envelope and a fast envelope. These two envelope signals are then compared by the data slicer, which then produces a digital bit stream. The addressing pattern is programmed into the LFPM's memory and contains the address information. The pattern correlator uses this information to generate the wake signal. If Manchester coding is used, the decoder is able to reconstruct the clock and data signals. These signals are available for output. [AS3933]

3.2 Manchester Coding

To avoid any confusion, we will use the term "bit" and the representations "0" and "1" when referring to the WuRx address. Conversely, when discussing the wake-up pattern, we will use the term "symbol" and the representations "L" (low) and "H" (high).

In Figure 3 we illustrate a typical implementation of Manchester coding. We define the ratio of address bits to pattern symbols as the code efficiency m. For Manchester coding, the code efficiency is always equal to 0.5 bit/symbol. Manchester coding ensures that there are never more than two consecutive H or L symbols in the pattern (RLL = 2). [Tao+18]

Address (Hex):	5				C			
Address (Bin):	0	1	0	1	1	1	0	0
Pattern:	LH	HL	LH	HL	HL	HL	LH	LH

Figure 3: A typical implementation of Manchester coding explained with the help of the example 8-bit address 0x5C.

3.3 Measurement System

To ensure the reliability of addressing patterns, it is critical to measure the PER of WuRx communication. This measurement is performed using the PER measurement system shown in Figure 4. Please refer to [FKD23] for additional information on this measurement system.

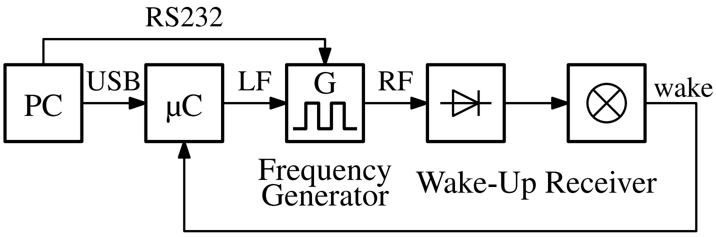

Figure 4: Block diagram of the packet error rate measurement system used for the following measurements.

The frequency generator by itself can only produce simple continuous-modulated signals. However, as shown in Figure 1, the LFPM WuPts are more complex in structure. A microcontroller was used to generate the LF component of the WuPt. This LF signal was then fed into the frequency generator via the external pulse modulation input. The RF signal generated by the frequency generator was then fed into the WuRx circuit. The wake signal from the WuRx is fed back to the microcontroller. Both the microcontroller and the frequency generator were controlled by a PC.
To measure the PER, a fixed number of WuPts n_{TX} were transmitted, and the number of received WuPts n_{RX} was counted. The PER is estimated using Equation 1.

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

The MDS curves, shown in Figure 5, were generated by adjusting the RF level of the frequency generator and then performing repeated PER measurements.
We also performed measurements to validate the reliability of the pattern. In doing so, we adjusted the RF level of the frequency generator to ensure that there would be no packet loss due to the MDS limit of the WuRx. Since our WuRx has an MDS threshold of −61 dBm, we chose an RF level of −55 dBm for these measurements. [FKD23]

3.4 Investigations of Manchester Coding

Our first hardware measurements should confirm the working principle of the pattern correlator of the LFPM. We wanted to show that it is not possible to distinguish between the WuPt's preamble and the addressing pattern. We have configured the LFPM to recognize the 16-symbol pattern HLHL HLHL HLHL HLHL. According to the specifications of our LFPM [AS3933], the WuPt consists of the following components: carrier burst (HHHH HHHH), preamble with separation symbol (LHLHLHLHL), and 16-symbol pattern (HLHL HLHL HLHL HLHL). In total, this WuPt contains 14 occurrences of the sequence HL. However, only eight repetitions are needed for pattern matching. Figure 5 shows the MDS curves for different WuPts, each containing a decreasing number of HL sequences. Importantly, the LFPM remained programmed with the same pattern throughout these measurements.

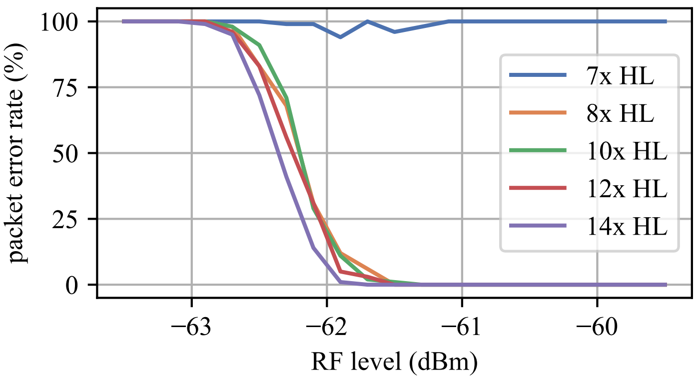

Figure 5: Measured minimum detectable signal (MDS) curves of the WuRx for WuPts with different numbers of HL sequences.

The number of HL sequences had little effect on MDS. The observed difference in MDS was within the margin of error for the frequency generator used, SML-02. In particular, we observed no degradation in MDS when reduced to only eight HL sequences. However, when reduced to only seven HL sequences, the PER remained consistently close to 100 %. In this measurement, the LFPM received some WuPts in the signal range between –62.3 dBm and –61.3 dBm, primarily due to noise induced bit errors. These observations lead to the conclusion that LFPMs do not distinguish between the preamble and the pattern. The preamble is recognized as part of the pattern without affecting the MDS.

We have theoretically analyzed packet reception by directly matching WuPt and receiver patterns. Figure 6 shows the results of our analysis. We systematically examined all possible combinations between the 8-bit transmitter and receiver addresses. In cases where we found a pattern match, a blue dot is plotted on the graph. This figure illustrates that the Manchester coding used is not univocal. Most WuPts with an address can activate multiple WuRxs. For example, a WuPt with address 0x44 can activate WuRxs with addresses 0x44, 0xA2, 0xD1, 0xE8, 0xF4, 0xFA, and 0xFD. We visualized this example in Figure 7.

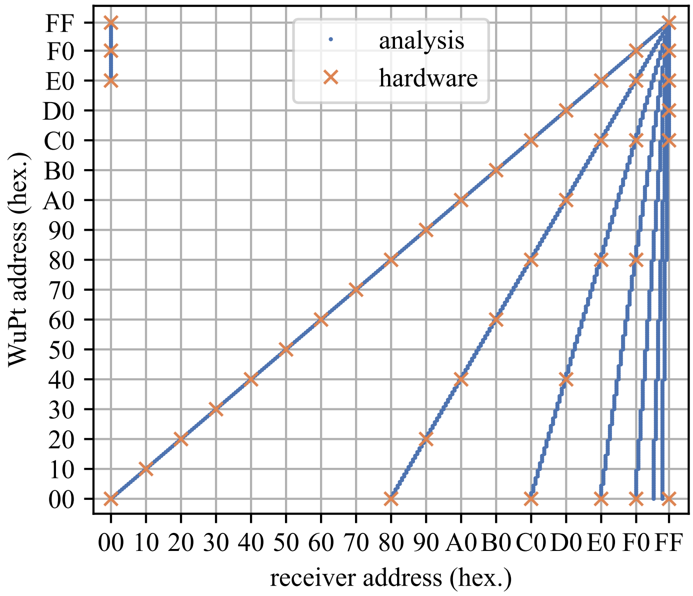

Figure 6: Analysis and hardware investigation of 8-bit Manchester coding. In hardware, only every 16th address was verified.

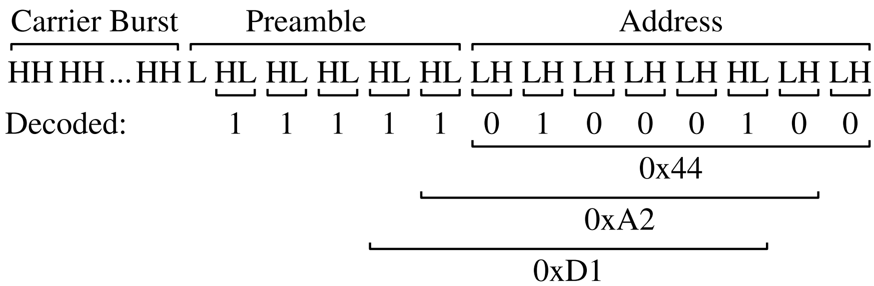

Figure 7: Visualization showing that the WuPt containing the address 0x44 can be received by LFPMs programmed to addresses 0x44, 0xA2, 0xD1, etc.

Testing all 256×256 combinations of receiver and transmitter addresses in hardware would take about a week. To speed up the process, we only verified every 16th address. All matching patterns identified during the hardware verification were marked with an orange cross in Figure 6.

Every combination tested in hardware matched our predictions exactly. As shown in Figure 6, it is obvious that this addressing pattern was far from univocal. Multiple WuPts are capable of triggering receivers programmed with different addresses. The pattern correlator of the LFPM works like a shift register, containing both the preamble and the pattern.

3.5 Investigation of Non-Manchester Coding

The primary problem associated with non-Manchester coding is the increased occurrence of consecutive symbols–run-length limit (RLL). A high RLL results in saturation of the slow envelope of the demodulator. When the slow envelope saturates, it leads to additional bit errors, coding failures, and PDPL.
We ran tests on a total of 256 patterns in hardware, each with different RLLs. The PER was measured for each pattern at a RF level of –55 dBm. Figure 8 shows the distribution of patterns grouped by RLL and PER.

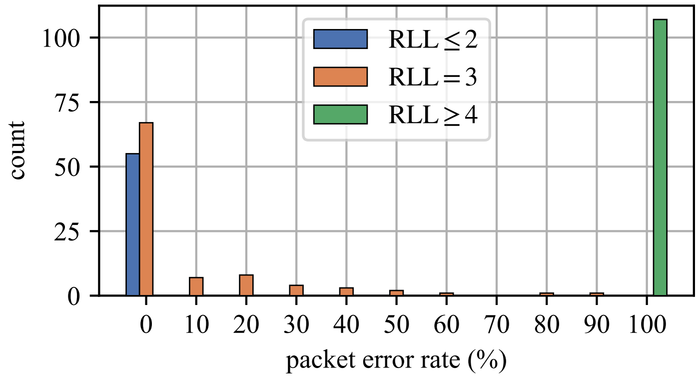

Figure 8: The number of patterns clustered by run-length limit (RLL) and measured packet error rate for non-Manchester coding.

Our measurements showed that patterns with RLL ≤ 2 had zero PDPL. However, the LFPM was unable to match any WuPts with RLL ≥ 4. In cases where RLL = 3, the PER showed variations in the range of 0 % to 90 %. Unfortunately, we could not find a clear criterion to determine whether a pattern with RLL = 3 would suffer from PDPL or not. For example, the pattern LH HHLH LLLH resulted in a PER of 90 %, while the pattern LH HHLH HHLH was consistently detected. Patterns with RLL = 3 appeared to be prone to PDPL and were subsequently excluded from consideration for the suggested addressing patterns.
With this additional information, we theoretically analyzed the 8-bit addressing pattern using non-Manchester coding. Figure 9 illustrates the results of this investigation.
In the diagram, points where the receiver and WuPt addresses do not match are shown in blue. These points represent instances of false wake-ups. A clear feature of Figure 9 are the vertical lines where a particular receiver address responds to almost all WuPt addresses. In such cases, the LFPM interprets the preamble as the pattern. Conversely, orange dots indicate correct wake-ups. In this example, 55 different valid patterns with RLL = 2 were identified.
We also analyzed the number of run-length-limited patterns possible for different

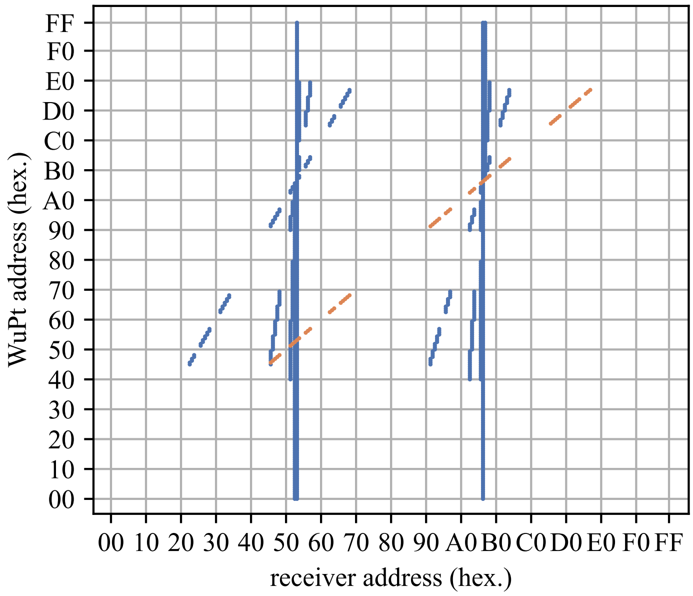

Figure 9: Analysis of 8-bit non-Manchester coding.

pattern sizes. The calculated values are presented in Table 2. The resulting code efficiency was calculated by estimating the number of address bits using binary logarithms. For patterns with higher symbol counts, the maximum code efficiency reached approximately 0.71. This code efficiency exceeds that of Manchester coding, which remains fixed at 0.5.

Table 2: Code Efficiency of Patterns with a Run-Length Limit of 2.

Symbol Count	2	4	8	12	16
Possible Combinations	3	8	55	377	2584
Address Bits	1.58	3.00	5.78	8.56	11.34
Code Efficiency	0.79	0.75	0.72	0.71	0.71

4 Proposed Addressing Patterns

In the previous section, we established what is necessary to achieve a reliable and univocal address space. In the following subsection, we propose four different addressing patterns. Each of them has different advantages for certain application areas. All of these addressing patterns are designed for our WuRx hardware presented in [FKD23]. It uses a voltage-doubler envelope detector tuned to 868 MHz. The LFPM is an AS3933. However, with slight variations, our investigation can be used for other WuRx implementations.

4.1 15-bit Manchester Coding

As shown in Figure 6, it is evident that the address space in the range 0x00 to 0x7F is univocal for both receiver and WuPt addresses. In the lower left quarter of this plot, you can see the diagonal line with only correct matches. In this region, all WuRxs are sensitive to only a single WuPt address. In the range 0x00 to 0x7F all addresses start with bit 0 and the pattern starts with symbols LH. To act as a separator, the first bit of both the pattern and the receiver address must be set to 0.

When using the AS3933 as LFPM, we can use its 32-symbol addressing mode. Therefore, a 15-bit address is proposed. The addressing range of the WSN is reduced to 32768 possible address combinations. This range seems to be sufficient for real-world scenarios.

Evaluating this addressing pattern in hardware was only possible by testing random samples and edge cases. Testing all 32768×32768 combinations of receiver addresses and patterns would take several years. The proposed address space is univocal and does not exhibit PDPL.

4.2 Variable Manchester Coding

Utilizing the separation sequences LH remains effective Using the LH separation sequence remains effective when using the 16-symbol mode of the AS3933. We have successfully implemented a 7-bit addressing pattern using this approach. With this addressing mode, we wanted to investigate a method to further reduce the addressing patterns, resulting in shorter WuPts. As we analyzed in subsection 3.4, parts of the preamble can be included in the pattern. Therefore, the number of address bits matched by the LFPM is variable. Figure 10 illustrates the implementation of both a 7-bit and a 4-bit addressing scheme. Note that 5-bit and 6-bit patterns can also be implemented using this approach.

Carrier Burst			Preamble				Sep.	Address								
HH HH ... HH	L	HL	HL	HL	HL		LH	LH	HL	LH	HL	HL	HL	LH	LH	...
Decoded:		1	1	1	1		0	0	1	0	1	1	1	0	0	...

7-bit Addressing: Pattern (0 0 1 0 1 1 1 0), Data (0 ...)

4-bit Addressing: Pattern (1 1 1 1 0 0 1 0), Data (1 1 1 0 0 ...)

Figure 10: An example WuPt showing the implementation of 7-bit and 4-bit Manchester addressing patterns.

Certain LFPMs, such as the AS3933, allow data to be received after the pattern match [AS3933]. We want to use this feature to further extend the address space.

The decoded data and clock are provided by the LFPM as output signals. The sensor node's microcontroller samples these signals and matches additional address bits accordingly. It is important to note that reading additional bits by the microcontroller increases the power consumption of the sensor node, but allows for more flexible addressing options. While the typical LFPM's pattern correlators can only be programmed to a single address, the microcontroller's sampling makes it possible to receive cluster broadcasts.

To use this feature, the AS3933 is programmed with a fixed address of width between 4 bit to 7 bit, which can be the cluster address. After pattern matching, the microcontroller samples an arbitrary number of bits. These address bits are then matched by the microcontroller, supporting multiple values and allowing the implementation of cluster broadcasts.

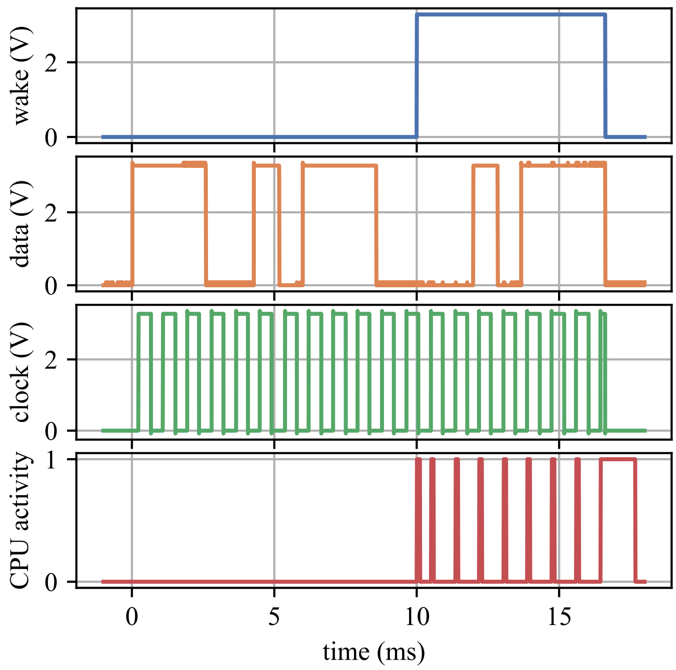

Figure 11: Typical LFPM output signals during reception of the 7-bit Manchester address 0x5C together with additional 8-bit data 0x2F. CPU activity of the microcontroller is measured by probing the main clock.

Figure 11 shows the signals captured by the LFPM while receiving the 7-bit Manchester address 0x5C, accompanied by an additional 8-bit data segment 0x2F. The Manchester decoder successfully recovered and output the clock and data signals. Both outputs started with the preamble and the separation sequence, visible for the time interval 0 ms to 3 ms. After the preamble, the LFPM correlated the programmed 7-bit address (0x5C). After correlating the last pattern symbol, the LFPM activated the wake output, triggering a microcontroller interrupt. The microcontroller then sampled the subsequent data bits of the wake-up pattern by

reading the data signal on the rising edge of the clock. After receiving a configured number of data bits, the microcontroller cleared the wake output.
We monitored the central processing unit (CPU) activity of the microcontroller by measuring the activity of the main clock. During the low-power mode, the main clock of the microcontroller remains disabled. The CPU activity due to the sampling of the data information is shown in the figure. Figure 11 also shows additional CPU activity that occurs after receiving WuPt.
In our experiment, we used the MSP430G2553 microcontroller clocked at 1 MHz. While sampling the 8-bit data information, the MSP430 remained active for approximately 850 clock cycles. According to the MSP430G2553 datasheet [MSP430G2x53], the active supply current is 330 μA. We estimate an additional consumption of 282 nAs per WuPt. In a highly active WSN with many wake-up pattern transmissions, this approach may increase power consumption. However, with less than one pattern match per second, the additional supply current becomes negligible.

4.3 Look-Up Table-Based Coding

To create a univocal address space with non-Manchester coding, a separation sequence is required. We have derived this sequence from the results shown in Figure 9. This address space is univocal in the ranges 0x60–0x6F and 0x90–0x9F. Therefore, we suggest using the HLLH separation sequence.
Our hardware investigations of subsection 3.5 revealed that the RLL should be 2 symbols to ensure reliable coding. While various run-length-limited line codes exist, none of them fully met our requirements for this particular use case. Since we used the non-Manchester mode of the AS3933 for our experiments, the pattern size is fixed at 16 symbols, leaving 12 symbols for the address. In Table 2 we analyzed that there are 377 address combinations available. This increases the code efficiency from Manchester code with $m = 0.5$ to $m = 0.71$.
To implement this addressing pattern in a sensor node, a lookup table is required to convert each address into a corresponding pattern. Accessing this lookup table is efficient because it is a one-way conversion. However, the size of the lookup table is highly dependent on the number of symbols used for coding. A 12-symbol coding can be easily implemented on small microcontrollers without large memory requirements. On the other hand, for 16-symbol coding, the lookup table would consume a significant portion of the microcontroller's memory.

4.4 3S2B Coding

In Table 2 it is shown that 12 symbols can effectively represent an 8-bit address while ensuring that RLL = 2. We have developed an algorithm that can convert 2 bits into 3 symbols, allowing us to directly convert any address that is $2 \cdot n$ bits wide into a pattern that is $3 \cdot n$ symbols wide. This addressing pattern is called 3 symbols, 2 bits (3S2B). With the proposed 3S2B addressing pattern, there is no need for lookup tables, and the code efficiency is $m = 2/3 \approx 0.667$.

```
Input: stream of 2-bit address sequences
Output: stream of 3-symbol pattern sequences
 1: for every 2-bit address sequence a do
 2:     if a = 00 then output LHL
 3:     else if a = 01 then output HLH
 4:     else if a = 10 then
 5:         if last output ended on H then output LLH
 6:         else output HHL end if
 7:     else if a = 11 then
 8:         get next 2-bit address sequence b
 9:         if b = 00 then output LHH LLH
10:         else if b = 01 then output LHH LHL
11:         else if b = 10 then output HLL LHL
12:         else if b = 11 then output HLL LLH end if
13:     end if
14: end for
```

Figure 12: 3S2B coding algorithm.

The coding algorithm for the proposed 3S2B coding is shown in Figure 12. There are six 3-symbol sequences with RLL = 2: LLH, LHL, LHH, HLL, HLH, and HHL. The sequences LHL and HLH are nearly independent of the preceding and following sequences. As shown in lines 2 and 3 of the algorithm, bit patterns 00 and 01 were decoded as LHL and HLH, respectively. LLH and HHL served as alternatives based on the last symbol of the preceding sequence. This is visualized in lines 5 and 6 of the algorithm. LLH was used when the previous sequence ended with an H, while HHL was used when the previous sequence ended with an L. The symbols LHH and HLL limit the possibilities for the following symbols. To ensure RLL = 2, the next two address bits were taken into account when using these symbols. This is demonstrated in lines 8–12 of the algorithm.

Adding the separation sequence HLLH leaves 12 symbols for the pattern. Therefore, we suggest using an 8-bit address when using the AS3933 as a LFPM. Importantly, this approach eliminates the need for a look-up table, and the address space is univocal. Extensive testing of this coding algorithm, through both theoretical investigation and hardware experiments, confirmed its reliability.

5 Conclusions

Based on our investigations, presented in section 3, we claimed that it is nearly impossible to implement recent wake-up receiver (WuRx)-based protocols in hardware. We identified three problems that make hardware integration nearly impossible with recent low-frequency pattern matcher (LFPM)-based WuRxs: unreliable and non-univocal address space, and lack of support for cluster broadcasts. In subsection 3.5, we presented our analysis of non-Manchester coding and emphasized that the address space is unreliable. A univocal address space ensures that when a wake-up packet (WuPt) containing a single address is sent, only the intended WuRx device will wake up. In contrast, a non-univocal address space can cause unwanted sensor nodes to wake up simultaneously. This results in a significantly increased collision probability within the wireless sensor network (WSN) when these uncontrolled wake-ups occur.
Based on the theoretical work done in section 4, we have proposed several addressing patterns. Through a combination of investigation and hardware testing, we have ensured that all of these address spaces are reliable and univocal. For our measurements, we used the hardware proposed in [FKD23]. In total, four different addressing patterns have been proposed in section 4. Each coding algorithm offers specific advantages suitable for different application scenarios. The summary of the proposed addressing patterns is shown in Table 3.

Table 3: Summary of the Proposed Addressing Patterns

Proposal	4.1	4.2				4.3	4.4
Pattern (symbol)	32	16				16	
Address (bit)	15	7	6	5	4	8.56	8
WuPt duration (ms)	15.9	9.02	8.40	7.78	7.15	9.02	
Manchester	yes	yes				no	
Separation seq.	LH	LH				HLLH	
Code efficiency	0.5	0.5				0.71	0.67
Cluster broadcast	no	yes				no	

Abbreviations: Separation sequence, wake-up packet (WuPt)

The 15-bit address pattern proposed in subsection 4.1 demonstrated the maximum address width that can be decoded by the LFPM without microcontroller support. This pattern used the 32-symbol mode of the AS3933. According to our measurements detailed in [FKD23], the WuPt duration can be reduced to 15.9 ms using this addressing pattern.
The variable Manchester coding scheme introduced in subsection 4.2 allowed the

LFPM to decode addresses in the range of 4 bit to 7 bit. As shown in Figure 10, parts of the preamble were matched within the pattern, allowing for shorter WuPts and address patterns. Most LFPMs output the decoded Manchester signal on their dedicated outputs. The address space can be further extended using a microcontroller. While most LFPMs support a single pattern match, by sampling their outputs with a microcontroller, it is possible to receive cluster broadcasts.

Two non-Manchester coded addressing patterns have been introduced in subsection 4.3 and subsection 4.4. With Manchester coding, the code efficiency is fixed at a rate of $m = 0.5$ bit/symbol. For non-Manchester coding, however, only 12 symbols are available due to the HLLH separation sequence when using the AS3933 as a LFPM. To prevent pattern-depended packet loss (PDPL) in the WuPt reception, the WuPt cannot exceed a run-length limit (RLL) of 2 symbols. With a 12-symbol pattern, there are a total of 377 possible combinations that satisfy this condition, corresponding to 8.56 bit. This results in an increased code efficiency of $m = 0.71$ bit/symbol.

In subsection 4.4 3S2B coding was introduced. We introduced an algorithm to convert two address bits into three pattern symbols (3S2B). This approach eliminates the need for look-up tables. An 8-bit address can be coded within the 12-symbol pattern. This configuration resulted in a WuPt duration of 9.02 ms, and the code efficiency was calculated to be $m = 0.667$.

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Author Contributions

R.F. contributed by way of conceptualization, methodology, original draft, writing, visualization, and editing. F.D. and O.K. contributed by way of supervision, reviewing, editing, and funding acquisition. All authors have read and agreed to the published version of the manuscript.