

WakeMod: A $6.9\ \mu\text{W}$ Wake-Up Radio Module with $-72.6\ \text{dBm}$ Sensitivity for On-Demand IoT

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Abstract—Large-scale Internet of Things (IoT) applications, such as asset tracking and remote sensing, demand multi-year battery lifetimes to minimize maintenance and operational costs. Traditional wireless protocols often employ duty cycling, introducing a tradeoff between latency and idle consumption – both unsuitable for event-driven and ultra-low power systems.

A promising approach to address these issues is the integration of always-on wake-up radios (WuRs). They provide asynchronous, ultra-low power communication to overcome these constraints.

This paper presents WAKEMOD, an open-source wake-up transceiver module for the 868 MHz ISM band. Designed for easy integration and ultra-low power consumption, it leverages the $-75\ \text{dBm}$ sensitive FH101RF WuR. WAKEMOD achieves a low idle power consumption of $6.9\ \mu\text{W}$ while maintaining responsiveness with a sensitivity of $-72.6\ \text{dBm}$. Reception of a wake-up call is possible from up to 130 m of distance with a $-2.1\ \text{dBi}$ antenna, consuming $17.7\ \mu\text{J}$ with a latency below 54.3 ms. WAKEMOD’s capabilities have further been demonstrated in an e-ink price tag application, achieving $7.17\ \mu\text{W}$ idle consumption and enabling an estimated 8-year battery life with daily updates on a standard CR2032 coin cell. WAKEMOD offers a practical solution for energy-constrained, long-term IoT deployments, requiring low-latency, and on-demand communication.

Index Terms—asynchronous, energy-efficient, IoT, ISM, on-demand, OOK, ultra-low power, wake-up

I. INTRODUCTION

The Internet of Things (IoT) is progressively driven by small, battery-operated devices designed for durability and optimized for specialized tasks. For large-scale applications such as asset tracking [1], structural monitoring [2], and sensor deployments in harsh and remote environments [3], a long battery lifetime is crucial to minimize costly maintenance. Energy harvesting from existing sources, such as solar [4], thermal [5], or radio frequency (RF) [6], can contribute energy to prolong operation. However, such techniques do not influence the system’s power needs. Whereas intelligent algorithms like context- and energy-aware sampling [7], [8] can help to reduce the average power consumption by dynamically adjusting data generation, often devices still need to transmit and receive data from a central control unit. However, while these solutions provide low-power configurations for reliable data transfer at variable data rates, they require periodic data exchange to maintain the connection state and synchronization with the gateway. This makes the RF frontend the most power-expensive subsystem, consuming significant power and limiting the devices’ lifetime [9], [10].

To reduce the impact of the communication interface on the energy budget, RF devices can be periodically deactivated, a method known as duty cycling [11]. However, while duty cycling can be effective, it inevitably introduces latency and does not eliminate power consumption during idle listening [12]. In

fact, most IoT devices are event-based [13] and do not need to send data periodically. They should rather have a long battery lifetime, be responsive to external events, and operate reliably for years to reduce maintenance and operational costs [14]. This is especially important for large-scale implementations, which require few, but if needed, real-time responses such as digital room reservation systems [15] or electronic price tags in supermarkets [16]. Ideally, such systems should consume no power in their idle state while still being responsive to external communication requests with low latency [12]. As a consequence, regular updates or synchronization events are not expedient, as they result in a tradeoff between latency and power consumption.

An alternative approach is the integration of always-on wireless receivers that have the ability to detect wireless messages of interest asynchronously, so-called wake-up calls (WuCs), while consuming power in the micro- to nano-watt range [17], [18] or even being fully passive [3]. Typically, such a wake-up radio (WuR) is combined with a traditional transceiver for highly efficient payload transfer [13]. Although this strategy minimizes transmission events, latency, and significantly reduces the power consumption, it does not eliminate it entirely [19]. Special attention is therefore required during hardware design to optimize power consumption during the idle state.

This work presents and characterizes WAKEMOD, an open-source 868 MHz wake-up transceiver module based on the ultra-low power FH101RF from RFICENT and MAX41462 from ANALOG DEVICES. It enables easy integration of wake-up capabilities into sensing devices and sensor networks by being a drop-in replacement for commercially available HOPERF sub-GHz modules such as the widely used RFMx modules. Specifically, this article makes the following contributions:

- 1) The design and implementation of an open-source and easy-to-integrate ultra-low power wake-up transceiver module for sub-GHz communication (WAKEMOD).
- 2) A full characterization of the wake-up transceiver, including a detailed power profiling during active and idle states, an analysis of the transmission power, receiver sensitivity, and packet delivery ratio (PDR).
- 3) The demonstration of WAKEMOD’s effectiveness in a real-world price tag application (WAKETAG) to show the significance of a WuR in large-scale applications.

The rest of this article is organized as follows: Section II gives a summary of state-of-the-art WuRs. Section III details the design and implementation of WAKEMOD and WAKETAG. The evaluation setup topology is outlined in Section IV, with the corresponding measurement results presented in Section V. Finally, Section VI concludes this work.

II. RELATED WORKS

Utilizing novel always-on ultra-low power WuR has the potential to significantly decrease the energy consumption in devices that must remain in idle-listening mode. This is particularly crucial in systems – such as real-time locating systems (RTLSs) [14] – where low latency is essential. Most solutions rely on on-off keying (OOK) modulation [20]–[22], as OOK is particularly suited for low-power receivers due to the simplicity of decoding messages using periodic sampling.

In [23] an ultra-low power application-specific integrated circuit (ASIC) WuR capable of sensing a wake-up pattern on 868 MHz is presented. The receiver built by using an envelope detector, together with a low-noise baseband amplifier, programmable gain amplifier (PGA) and a mixed-signal correlation unit is capable of sensing signals with a power of -71 dBm whilst consuming only $2.4 \mu\text{W}$ at 1 V.

Spenza et al. [24] introduced a WuR operating at 868 MHz, composed with commercially available components: a diode-based envelope detector, a comparator, and a microcontroller unit (MCU) managing the signal decoding. The WuR attained a sensitivity of -55 dBm with a power consumption of $1.276 \mu\text{W}$. Utilizing a transmission power of 10 dBm, they achieved a maximum wake-up range of 45 m.

A comparable system utilizing off-the-shelf components has been proposed by Sutton et al. [25]. The system comprises an OOK transmitter utilizing the TI CC110L, while the receiver employs a passive OOK demodulator succeeded by a AS3930 WuR for address decoding. The implemented system consumes $8.1 \mu\text{W}$ during active listening, exhibiting a sensitivity of -51 dBm .

Polonelli et al. [26] propose an ultra-low power WuR architecture based on ultra-wideband (UWB) specifically targeting location-aware applications. Their approach utilizes OOK modulation overlaid on the UWB signal, simplifying the receiver design for low-power operation. The discrete component solution achieved a sensitivity of -48 dBm with a power consumption of $100 \mu\text{W}$.

An ASIC implementation realizing the protocol described by Polonelli et al. was presented by Villani et al. in [28]. The chip complies with IEEE 802.15.4-2011, attaining a maximum sensitivity of -86 dBm with a wake-up latency of 524 ms, or -73 dBm with a latency of 55 ms. The power consumption is 36 nW and 93 nW, respectively. The wake-up range is not available due to the absence of in-field evaluations of the chip.

In [27], Kazdaridis et al. introduce the EWAKE architecture, in the form of a semi-active WuR. By employing a nano-power operation amplifier after the envelope detector, EWAKE aims to overcome some limitations of purely passive receivers. The authors report a sensitivity of -70 dBm whilst the power consumption could be kept below $2 \mu\text{W}$.

A final significant integrated circuit (IC) is the FH101RF from RFICIENT[®] [29]. The tri-band WuR can receive WuCs at 433 MHz, 868 MHz, and 2.4 GHz simultaneously. The chip achieves a sensitivity of -80 dBm and facilitates a configurable wake-up latency ranging from 1 ms to 121 ms, resulting in a power consumption between $2.7 \mu\text{W}$ and $87.3 \mu\text{W}$.

The proposed WAKEMOD is designed around the FH101RF WuR. Its commercial availability and state-of-the-art sensitivity make it an ideal choice. It outperforms similar solutions like the STM32WL3X from STMICROELECTRONICS, which falls short in sensitivity and power

efficiency for wake-up applications. Our work goes beyond simply comparing a WuR chip: we present a fully integrated wake-up radio module, designed with practical deployment in mind. The module encapsulates all necessary subsystems for seamless operation, enabling plug-and-play integration into larger wireless sensor networks. Its compact design, standardized interfaces, and robustness make it easily scalable and suitable for real-world, large-scale network deployments.

III. SYSTEM ARCHITECTURE

A. WakeMod

The designed WAKEMOD, as shown in Fig. 1, is a 868.35 MHz WuR transceiver, built around a careful selection of components aiming for an ultra-low power consumption. At its core is the RFICIENT FH101RF, serving as the WuR of the module. The FH101RF is an ultra-low power tri-band (433 MHz, 868/915 MHz, 2.4 GHz) WuR, capable of receiving OOK-modulated messages with a sensitivity of -75 dBm . After recognizing a one-bit preamble, the WuR can be addressed with a 16 bit wake-up address. The OOK-messages for both preamble and address are encoded using a 32 bit maximum length sequence (mls), configured individually with a data rate between $256 \frac{\text{bit}}{\text{s}}$ to $32.768 \frac{\text{kbit}}{\text{s}}$. This allows for a low-power consumption down to $4.7 \mu\text{W}$ during idle listening of the WuR, while still being able to achieve a wake-up latency below 150 ms. Additionally, a custom 6 B payload message can be received and decoded by the WuR¹.

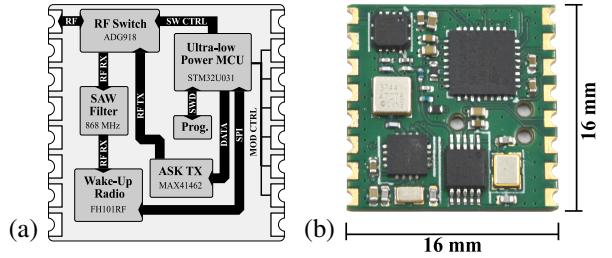


Fig. 1. System overview: High-level block diagram of the main platform WAKEMOD (a) and its hardware implementation (b).

To handle WuC transmission, the module incorporates the ANALOG DEVICES MAX41462 OOK transmitter, pre-configured for the 868.35 MHz band. The transmitter remains in shutdown state until a toggle on its data line triggers it to activate and modulate the incoming data using OOK. Additionally, the MAX41462 has an auto-shutdown feature that starts when data transmission stops, significantly lowering the transmitter's power consumption to 34.2 nW. However, on data rates below 1024 bps, sequences of '0's can trigger premature auto-shutdown, leading to message corruption due to the slow turn-on time.

To eliminate the need for connecting two antennas to WAKEMOD, thus reducing space requirements, cost, and complexity, the WuR and the transmitter are connected to a single antenna through an ANALOG DEVICES ADG918 RF switch.

The module's control logic is implemented using an STMICROELECTRONICS STM32U031 MCU. This specific MCU was chosen for its ultra-low shutdown consumption of only 29 nW together with its fast wake-up time of 290 μs , making it ideal for ultra-low power or even energy-harvesting based applications. Its inter-integrated circuit (I2C) slave capabilities are used to make the module controllable by an external host

¹The datasheet wrongly states a buffer of 40 bit, although it can hold 48 bit.

TABLE I
OVERVIEW OF STATE-OF-THE-ART WAKE-UP RADIOS.

	ISCAS '11 [23]	INFOCOM '15 [24]	SENSYS '15 [25]	WiMob '21 [26]	IPSN '21 [27]	ISCAS '24 [28]	RFICIENT [29]
Modulation	OOK	OOK	OOK	OOK	OOK	OOK	OOK
Carrier freq.	868 MHz	868 MHz	434 MHz	3.99 GHz UWB	868 MHz	3.99 GHz UWB	tri-band ^a
Technology	ASIC	Discrete	AS3930 + Disc.	Discrete	Discrete	ASIC	FH101RF
Idle power	2.4 μ W	1.28 μ W	8.1 μ W	100 μ W	1.73 μ W	36 – 93.2 nW	2.7 – 87.3 μ W
Wake-up latency	40 ms – 110 ms	16 ms	7.3 ms	156.7 ms	–	55 – 524 ms	1 – 121 ms
RX sensitivity	-71 dBm	-55 dBm	-51 dBm	-48 dBm	<-70 dBm	-86 – -73 dBm	-75 dBm
Wake-up range	304 m	45 m	30 m	1 m	–	–	100 m

^a433 MHz, 868 MHz, and 2.4 GHz

MCU to configure the WuR for a specific wake-up address, read out wake-up data, or adjust settings such as data rates or reception branch.

Having a similar 16 mm \times 16 mm footprint as the HOPERF RFMx modules, WAKEMOD can serve as a drop-in replacement for existing designs, allowing effortless retrofit of WuR capabilities into existing solutions. Furthermore, the design of WAKEMOD is published as open source on GITHUB², making it readily available to developers.

The firmware architecture of the module is optimized for ultra-low power consumption, keeping the STM32U031 as long as possible in shutdown mode. Doing so requires keeping critical data in the backup registers of the tamper block. Upon waking up, the MCU identifies the source of the wake-up event, which can be one of the following:

System Reset: In the event of a system reset, the MCU transitions immediately back to shutdown, ensuring minimal power consumption.

WuR interrupt request (IRQ): On a wake-up triggered by the WuR, the modules clears the interrupt and retrieves the interrupt source with up to 6 B of payload data from the WuR FIFO. This information is stored in the MCU's backup register, before the host MCU's IRQ is asserted and the module returns to shutdown.

Shutdown (SDN) pin: If the SDN pin transitions to low, the MCU wakes up and prepares itself to receive commands from the host over its I2C slave interface. Four commands are supported: (i) WhoAmI for device identification; (ii) SetupWuR, configuring the WuR with a wake-up address, low data-rate, and high data-rate. This includes a full calibration of the FH101RF; (iii) SendWuC, sending a WuC to a specific wake-up address via the MAX41462, utilizing serial peripheral interface (SPI) for accurate timing of preamble and address/payload transmission; (iv) IRQReason, retrieving the last wake-up event's reason and payload from backup registers.

B. WakeTag

To test WAKEMOD in a real-world application scenario and demonstrate the power-saving potential of asynchronous wireless updates using a wake-up receiver, a custom-designed e-ink display system named WAKETAG has been developed (see Fig. 2).

The ultra-low power Arm Cortex-M0+ MCU STM32U031 is the heart of the WAKETAG, handling the WAKEMOD initialization and controlling the single-colored 2.13-inch e-ink display with 250 \times 122 pixels of type ZJY122250-

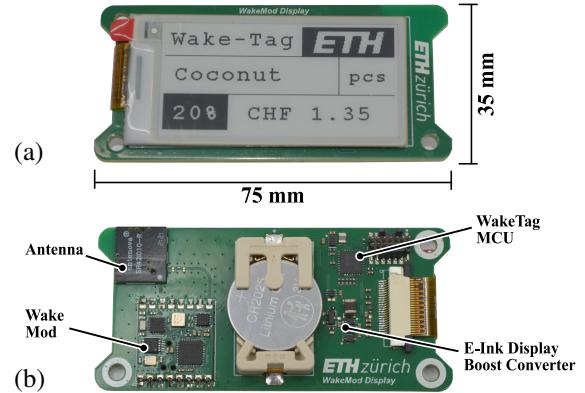


Fig. 2. WakeTag: (a) Front view, (b) Back view.

0213BBDMFGN-R. As the display needs at least 2.7 V, it is directly powered by the non-rechargeable CR2032-sized 3 V coin cell battery. A dedicated boost converter circuit generates the positive and negative voltages required to drive the pixel electrodes. Both sub-systems are powered through a VISHAY SIP32431 power switch and can be disconnected from the battery to minimize power consumption. To achieve the most efficient operating point for the WAKEMOD module, the digital communication over I2C and power supply of the display's microcontroller are set to 1.8 V, which is provided by the TI TPS62840 high-efficiency step-down converter. The SPI communication to the display is established through its internal level shifter, which can be separately powered from the VDDIO by the system voltage and is directly powered via a general purpose input-output (GPIO) from the microcontroller. Thus, the display can be fully decoupled from the power, eliminating its static power consumption. At the same time, the information remains visible due to the bistable nature of its electrophoretic particles, which only require power for state changes.

The WAKETAG firmware is kept very simple, prioritizing ultra-low power operation. Upon reset, its first action is to configure the WuR using the SetupWuR. Once configured, the MCU enters shutdown mode to conserve energy. On an IRQ signal received from the WAKEMOD, the firmware reads the IRQ reason. If the IRQ is caused by a WuR message, the 6 B payload is retrieved. This payload contains the information for the price tag application: item, price, discount, and marking if it's out of stock. The display is then activated and refreshed with this data before the system enters shutdown mode again.

IV. EXPERIMENTAL SETUP

The characterization of WAKEMOD has been conducted based on power consumption, communication range, spectral emission, and output power. Finally, WAKEMOD has been

²<https://github.com/ETH-PBL/WakeMod>

TABLE II
POWER CONSUMPTION AND TX POWER OF WAKEMOD DURING LISTENING AND TRANSMITTING

A) IDLE LISTENING CONSUMPTION		B) TX POWER AND CONSUMPTION			C) CONSUMPTION OF AUXILIARY OPERATIONS		
Data rate	Power consumption	Voltage	TX Power	Power consumption		Energy consumption	Duration
1024 bps	6.88 µW	1.8 V	2.78 dBm	26.08 mW	WAKEMOD WhoAmI	26.59 µJ	15.9 ms
2048 bps	10.08 µW	2.0 V	4.98 dBm	34.46 mW	WAKEMOD SetupWuR ^a	1.14 mJ	564.2 ms
4096 bps	16.54 µW	2.5 V	8.32 dBm	58.68 mW	WAKEMOD SendWuC ^b	106.15 µJ ^b	25.7 ms ^b
8192 bps	29.41 µW	2.75 V	9.31 dBm	73.04 mW	WAKEMOD IRQReason	57.54 µJ	18.9 ms
16 384 bps	55.01 µW	3.0 V	10.10 dBm	88.44 mW	IRQ handling (no payload)	15.88 µJ	7.4 ms
32 768 bps	105.88 µW	3.3 V	10.92 dBm	108.54 mW	IRQ handling (6 B payload)	46.64 µJ	19.6 ms

^a includes a full calibration of the FH101RF.

^b cost of the actual transaction must be added with TX power consumption multiplied by transmission duration.

tested within the WAKETAG application to demonstrate its functionality in a real-world application.

A. Power Consumption Measurements

Precise measurements were conducted using a KEYSIGHT N6705C DC Power Analyzer fitted with a KEYSIGHT N6781A source measure unit (SMU). The module's current draw has been characterized under the following conditions:

Idle/Sleep Mode: Measuring the baseline power consumption while the module awaits a WuC at different data rates. Thereby, the low data rate (LDR) is the data rate of the preamble's mls, and the high data rate (HDR) of the address and payload's mls.

Active Reception: Measuring the power consumption while the WuR is actively listening for and processing an incoming WuC.

Active Transmission: Measuring the power consumption while the MAX41462 transmitter actively sends a WuC.

Configuration Mode: Characterizing transient power draw during module initialization, whoami request, or IRQ readout via the host MCU.

For the active transmission and reception states, the characterization is performed across different configurations, including different data rates and varying payload sizes, to assess their impact on the overall energy consumption per event.

B. Transmitter and Receiver Characterization

An R&S SMBV100A signal generator was used to characterize WAKEMOD's sensitivity, configured to output an OOK signal on an 868.35 MHz carrier. This signal employed a 1024 bps data rate for the mls of the preamble and 32 768 bps for the address, utilizing a rectangular filter.

WAKEMOD's transmitter output power and spectrum were measured using an R&S FSIQ 3 signal analyzer. The signal analyzer was configured using 50 dB internal attenuation, a reference level of 20 dBm, and a resolution and video bandwidth of 20 kHz. The center frequency was 868.324 MHz with a span of 1 MHz. Measurements were performed by directly connecting a WAKEMOD soldered on a SMA-breakout board to the analyzer. To characterize the impact of system voltage on the transmit power, the spectrum was measured while varying the module's supply voltage from 1.8 V to 3.3 V.

C. Packet Delivery Ratio Characterization

The module's communication range was assessed outside in an open field. One WAKEMOD module was used as transmitter sending at 2.8 dBm, while a second one was used as receiver – both of them equipped with an omnidirectional dipole antenna

with a gain of -2.1 dBi (LINX ANT-868-CW-HWR-SMA). The ground truth distances up to 80 m were determined using a laser distance measurement device (BOSCH GLM150-27C), and using satellite photography up to 150 m. The PDR was characterized for different combinations of the low and high data rates. At each distance, a total of 100 WuC was sent.

D. WakeTag Demonstrator Evaluation

In addition to characterizing the core module, WAKETAG was used as a demonstration application, integrating WAKEMOD with an e-ink display. The overall power consumption of the complete WAKETAG system was measured using the same KEYSIGHT N6705C/N6781A setup. The characterization focused on the power profile during reception of a WuC with a payload of 6 B, the rendering of the display, and the sleep consumption of the device. For battery lifetime estimations, a CR2032 with 220 mAh at a nominal voltage of 3 V and an assumed 1% annual self-discharge rate is considered.

V. RESULTS

A. Power Consumption and Transmitter Spectrum

Measurements of the WuR operation revealed that the power consumption during both idle listening and active reception phases is primarily determined by the configured data rate. No significant difference in power draw was observed between the module merely listening for a preamble and actively processing an incoming signal. As detailed in Table II a), the consumption scales with the data rate, ranging from 6.88 µW at 1024 bps up to 105.88 µW at 32 768 bps. Notably, these figures represent the total consumption of the WAKEMOD module, including its MCU, OOK transmitter, and antenna switch – all operating in their deepest sleep state. This overall module consumption is approximately 9% lower than the typical consumption figures specified in [29] for the FH101RF itself. This data rate dependency allows for an energy-efficient strategy where a low data rate (e.g., 1024 bps) is used for the prolonged idle listening and preamble detection phase. Subsequently, the data rate can be increased for the shorter address decoding phase, reducing the active reception time and thereby minimizing latency and the required transmission duration for the sending device. For context, a preamble transmitted at 1024 bps requires 31.25 ms; while the address phase is 16 times longer in terms of bits, using a higher data rate significantly shortens its time duration. The selection of the LDR and HDR is thereby under the tradeoff between low-latency, WuC frequency, and power consumption.

The power consumption during the transmission of a WuC is presented in Table II b) and Fig. 3 b-c). A strong dependence

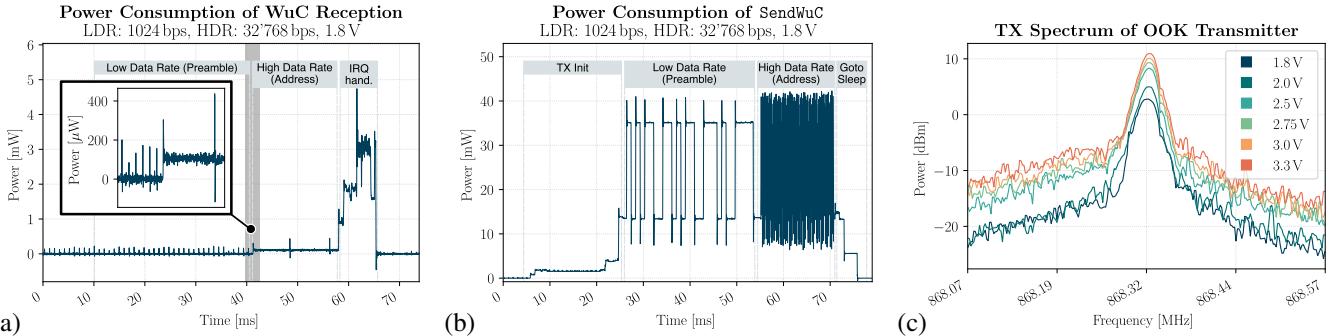


Fig. 3. Power consumption of WAKEMOD during reception (a) and transmission (b) of a WuC. (c) shows an analysis of the transmitter’s spectrum at 1.8 V.

on the supply voltage is evident. As the voltage increases from 1.8 V to 3.3 V, the transmitted power increases from 2.78 dBm to 10.92 dBm. Jointly, the module’s power consumption during transmission rises substantially, from 26.08 mW to 108.54 mW. Fig. 3 b) shows a typical WuC with the LDR being 1024 bps and the HDR being 32 768 bps.

Finally, Table II c) quantifies the energy consumption and duration of auxiliary operations that do not involve continuous RX or TX. These include internal tasks performed by the WAKEMOD’s MCU, such as handling an IRQ from the FH101RF upon wake-up detection, and the overhead associated with communication between an external host MCU and WAKEMOD. The baseline cost for the WAKEMOD MCU to handle an IRQ (without payload readout) is 15.88 μ J over 7.4 ms. Reading out an additional 6 B payload during IRQ handling increases the cost to 46.64 μ J over 19.6 ms. Communicating with the host incurs costs like 26.59 μ J for a WhoAmI command and 1.14 mJ for the SetupWuR operation (including WuR calibration). As noted in the table, the energy cost listed for SendWuC (106.15 μ J) represents only the command processing overhead and ramp up of transmitter; the significant energy consumption of the actual radio transmission must be added to determine the total energy cost of sending a WuC.

Comparing two potential WuC configurations highlights a key trade-off: Using a 1024 bps data rate to encode the preamble’s mls, and a 32 768 bps data rate to encode the address’ mls results in a sender energy cost of 1.33 mJ (over 72.58 ms), while the receiver consumes 17.75 μ J during 54.28 ms. Crucially, the receiver’s idle listening power in this mode is only 6.88 μ W. Conversely, using a faster 32 768 bps preamble (and address) significantly reduces the sender’s cost to 539.12 μ J in 42.3 ms and keeps a similar receiver’s energy of 17.64 μ J during 24.00 ms. However, this requires the receiver to idle listen at a much higher 105.88 μ W. Therefore, while the faster preamble configuration is considerably more energy-efficient for the sender and faster for both parties during the actual wake-up transaction, the slower preamble configuration offers substantially lower idle power consumption for the receiver, leading to potentially much longer battery life in deployments where wake-up events are infrequent.

B. Receiver Sensitivity and Packet Delivery Ratio

The receiver’s sensitivity was characterized to be -72.62 dBm with a peak envelope power of -70.18 dBm.

As presented in Fig. 4, using the setup described in Section IV-C, a high wake-up reliability with PDRs above 94% was observed for close ranges of 1.1 m up to a distance of 100 m. The PDR starts then to exponentially decrease to 11% at 130 m. No WuC were successfully received at distances

above 130 m, establishing the effective communication range limit under the tested conditions.

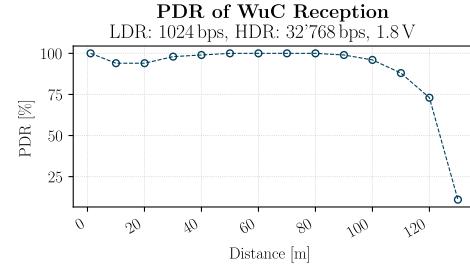


Fig. 4. PDR of wake-up calls sent and received by WAKEMOD across different distances.

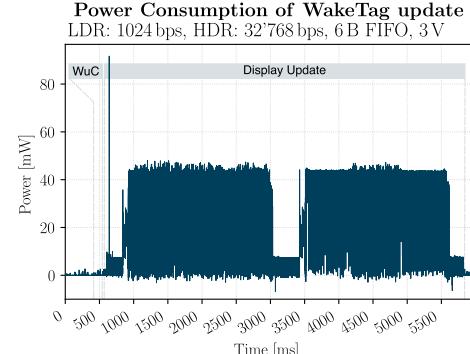


Fig. 5. Power profile of WAKETAG on receiving a single WuC and refreshing the display.

C. WakeTag Evaluation

The power consumption of WAKETAG, as illustrated in Fig. 5, is composed of three parts: idle-listening, the reception of the WuC, and the update of the display. With a consumption of 7.17 μ W in idle-listening, WAKETAG’s consumption is only marginally higher than that of WAKEMOD (but includes voltage conversion and a second MCU). As the update of the display costs 132.22 mJ, the reception of the WuC itself is negligible. The battery lifetime is therefore strongly correlating with the update frequency of the screen. High update frequencies of 0.1 Hz lead to a short estimated lifetime of 2 days, while an hourly update increases the lifetime to 1.7 years. With daily updates, the WAKETAG could theoretically operate for nearly 8 years. The lifetime converges then to 9.5 years when never an update of the display is initiated.

VI. CONCLUSION

In this paper, we present the design, the implementation, and a detailed evaluation of WAKEMOD, an open-source and ultra-low power wireless module leveraging a WuR for energy-efficient, on-demand IoT applications.

WAKEMOD's capabilities were evaluated in extensive experiments, achieving an ultra-low idle-listening consumption of just $6.9\text{ }\mu\text{W}$, and an energy consumption per WuC of $17.7\text{ }\mu\text{J}$. The corresponding wake-up latency was below 54.3 ms. The integrated transmitter was fully characterized using a spectrum analyzer, achieving a peak transmission power of 2.8 dBm at a power consumption of 26.1 mW . Depending on the configuration of the WuR, this enables the selective wake-up of remote IoT devices with as little as $539.1\text{ }\mu\text{J}$ and in less than 42.3 ms. Further performance evaluations confirmed reliable communication with a high sensitivity of -72.6 dBm , achieving PDRs exceeding 94% up to 100 m, and an operational range limit of approximately 130 m.

Finally, WAKEMOD was demonstrated in WAKETAG, an e-ink price tag application showcasing the practical potential of WAKEMOD. Through careful system design, multi-year battery lifetimes of up to 8 years are achievable on a standard CR2032 coin cell, while still allowing one display update per day. This illustrates the module's suitability for long-term, energy-constrained deployments where infrequent but low-latency communication is desired.

REFERENCES

- [1] M. Soori, B. Arezoo, and R. Dastres, "Internet of things for smart factories in industry 4.0, a review," *Internet of Things and Cyber-Physical Systems*, vol. 3, pp. 192–204, 2023. [Online]. Available: <http://dx.doi.org/10.1016/j.iotcps.2023.04.006>
- [2] N. Scharer, T. Polonelli, J. Deparday, and M. Magno, "Towards a non-invasive monitoring system for wind turbine blades," in *2024 IEEE International Instrumentation and Measurement Technology Conference (I2MTC)*, 5 2024, pp. 1–6. [Online]. Available: <http://dx.doi.org/10.1109/I2MTC60896.2024.10561240>
- [3] L. Schulthess, P. Mayer, L. Benini, and M. Magno, "A passive and asynchronous wake-up receiver for acoustic underwater communication," in *2024 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)*, 6 2024, pp. 480–485. [Online]. Available: <http://dx.doi.org/10.1109/SPEEDAM61530.2024.10609075>
- [4] D. C. Nath, I. Kundu, A. Sharma, P. Shivhare, A. Afzal, M. E. M. Soudagar, and S. G. Park, "Internet of things integrated with solar energy applications: a state-of-the-art review," *Environment, Development and Sustainability*, vol. 26, no. 10, pp. 24 597–24 652, 2023. [Online]. Available: <http://dx.doi.org/10.1007/s10668-023-03691-2>
- [5] T. T. K. Tuoi, N. V. Toan, and T. Ono, "Thermal energy harvester using ambient temperature fluctuations for self-powered wireless iot sensing systems: a review," *Nano Energy*, vol. 121, p. 109186, 2024. [Online]. Available: <http://dx.doi.org/10.1016/j.nanoen.2023.109186>
- [6] M. J. Makhetha, E. D. Markus, and A. M. Abu-Mahfouz, "Integration of wireless power transfer and low power wide area networks in iot applications-a review," *Sensors International*, vol. 5, p. 100284, 2024. [Online]. Available: <http://dx.doi.org/10.1016/j.sintl.2024.100284>
- [7] R. Bensaid, A. B. Mnaouer, and H. Boujemaa, "Energy efficient adaptive sensing framework for wsn-assisted iot applications," *IEEE Access*, vol. 12, pp. 93 033–93 050, 2024. [Online]. Available: <http://dx.doi.org/10.1109/ACCESS.2024.3423706>
- [8] G. Surrel, T. Teijeiro, A. Aminifar, D. Atienza, and M. Chevrier, "Event-triggered sensing for high-quality and low-power cardiovascular monitoring systems," *IEEE Design & Test*, vol. 37, no. 5, pp. 85–93, 2020. [Online]. Available: <http://dx.doi.org/10.1109/MDAT.2019.2951126>
- [9] A. C. Muhoza, E. Bergeret, C. Brdys, and F. Gary, "Power consumption reduction for iot devices thanks to edge-ai: Application to human activity recognition," *Internet of Things*, vol. 24, p. 100930, 2023. [Online]. Available: <http://dx.doi.org/10.1016/j.iot.2023.100930>
- [10] M. Masoudi and C. Cavdar, "Device vs edge computing for mobile services: Delay-aware decision making to minimize power consumption," *IEEE Transactions on Mobile Computing*, vol. 20, no. 12, pp. 3324–3337, 2021. [Online]. Available: <http://dx.doi.org/10.1109/TMC.2020.2999784>
- [11] M. Zimmerling, L. Mottola, and S. Santini, "Synchronous transmissions in low-power wireless," *ACM Computing Surveys*, vol. 53, no. 6, pp. 1–39, 2021. [Online]. Available: <http://dx.doi.org/10.1145/3410159>
- [12] M. Doudou, D. Djenouri, and N. Badache, "Survey on latency issues of asynchronous mac protocols in delay-sensitive wireless sensor networks," *IEEE Communications Surveys & Tutorials*, vol. 15, no. 2, pp. 528–550, 2013. [Online]. Available: <http://dx.doi.org/10.1109/SURV.2012.040412.00075>
- [13] F. Sutton, R. D. Forno, J. Beutel, and L. Thiele, "Blitz," *ACM Transactions on Sensor Networks*, vol. 15, no. 2, pp. 1–38, 2019. [Online]. Available: <http://dx.doi.org/10.1145/3309702>
- [14] S. Cortesi, C. Vogt, and M. Magno, "Wakeloc: an ultra-low power, accurate and scalable on-demand rtlcs using wake-up radios," 2025. [Online]. Available: <https://arxiv.org/abs/2504.20545>
- [15] C. Szabó, K.-T. Antal, L.-Z. Bartus, and K. Simon, "Energy-efficient timetable display for meeting rooms using e-paper technology and low-powered microcontrollers," in *2023 IEEE 21st Jubilee International Symposium on Intelligent Systems and Informatics (SISY)*, 9 2023, pp. 000 409–000 414. [Online]. Available: <http://dx.doi.org/10.1109/SISY60376.2023.10417947>
- [16] S. E. S. E. M, D. K. B. M, and D. S, "Intelligent integration of e-ink displays: Leveraging electronics for label automation and enhanced user experience," in *2024 2nd International Conference on Sustainable Computing and Smart Systems (ICSCSS)*, 7 2024, pp. 169–174. [Online]. Available: <http://dx.doi.org/10.1109/ICSCSS60660.2024.10625528>
- [17] S. Shellhammer, A. Asterjadhi, and Y. Sun, *Wak-up Radio Concept*. Wiley-IEEE Press, 2023, pp. 25–42. [Online]. Available: <http://dx.doi.org/10.1002/9781119671015.ch3>
- [18] A. A. Benbuk, N. Kouzayha, J. Costantine, and Z. Dawy, "Charging and wake-up of iot devices using harvested rf energy with near-zero power consumption," *IEEE Internet of Things Magazine*, vol. 6, no. 1, pp. 162–167, 2023. [Online]. Available: <http://dx.doi.org/10.1109/IOTM.001.2200202>
- [19] P. P. Mercier, B. H. Calhoun, P.-H. P. Wang, A. Dissanayake, L. Zhang, D. A. Hall, and S. M. Bowers, "Low-power rf wake-up receivers: Analysis, tradeoffs, and design," *IEEE Open Journal of the Solid-State Circuits Society*, vol. 2, pp. 144–164, 2022. [Online]. Available: <http://dx.doi.org/10.1109/OJSSCS.2022.3215099>
- [20] S. Bdiri, F. Derbel, and O. Kanoun, "A tuned-rf duty-cycled wake-up receiver with -90 dbm sensitivity," *Sensors*, vol. 18, no. 2, p. 86, 2017. [Online]. Available: <http://dx.doi.org/10.3390/s18010086>
- [21] K. Mikhaylov and H. Karvonen, "Wake-up radio enabled ble wearables: empirical and analytical evaluation of energy efficiency," in *2020 14th International Symposium on Medical Information Communication Technology (ISMICT)*, 5 2020. [Online]. Available: <http://dx.doi.org/10.1109/ismict48699.2020.9152699>
- [22] A. K. Sultania, C. Delgado, and J. Famaey, "Enabling low-latency bluetooth low energy on energy harvesting batteryless devices using wake-up radios," *Sensors*, vol. 20, no. 18, p. 5196, 2020. [Online]. Available: <http://dx.doi.org/10.3390/s20185196>
- [23] C. Hambeck, S. Mahlknecht, and T. Herndl, "A 2.4uw wake-up receiver for wireless sensor nodes with -71dbm sensitivity," in *2011 IEEE International Symposium of Circuits and Systems (ISCAS)*, 5 2011, pp. 534–537. [Online]. Available: <http://dx.doi.org/10.1109/ISCAS.2011.5937620>
- [24] D. Spenza, M. Magno, S. Basagni, L. Benini, M. Paoli, and C. Petrioli, "Beyond duty cycling: Wake-up radio with selective awakenings for long-lived wireless sensing systems," in *2015 IEEE Conference on Computer Communications (INFOCOM)*, 4 2015, p. 9. [Online]. Available: <http://dx.doi.org/10.1109/INFOCOM.2015.7218419>
- [25] F. Sutton, B. Buchli, J. Beutel, and L. Thiele, "Zippy," in *Proceedings of the 13th ACM Conference on Embedded Networked Sensor Systems*, 11 2015. [Online]. Available: <http://dx.doi.org/10.1145/2809695.2809705>
- [26] T. Polonelli, F. Villani, and M. Magno, "Ultra-low power wake-up receiver for location aware objects operating with uwb," in *2021 17th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*, 10 2021, p. 8. [Online]. Available: <http://dx.doi.org/10.1109/WiMob52687.2021.9606248>
- [27] G. Kazdaridis, N. Sidiropoulos, I. Zografopoulos, and T. Korakis, "A novel architecture for semi-active wake-up radios attaining sensitivity beyond -70dbm: Demo abstract," in *2021 20th International Conference on Information Processing in Sensor Networks*, 5 2021, pp. 398–399. [Online]. Available: <https://dx.doi.org/10.1145/3412382.3458782>
- [28] F. Villani, E. Masina, T. Burger, and M. Magno, "A 36nw ultra-wideband wake-up receiver with -86dbm sensitivity and addressing capabilities," in *2024 IEEE International Symposium on Circuits and Systems (ISCAS)*, 5 2024, p. 5. [Online]. Available: <http://dx.doi.org/10.1109/ISCAS58744.2024.10558556>
- [29] LZE GMBH, "Rficient® ultra-low power wake-up receiver fh101rf datasheet," Fraunhofer IIS, 2024, FH101RF LZE Datasheet Revision 1p3b A1. [Online]. Available: https://cdn.shopify.com/s/files/1/0315/0879/1435/files/FH101RF_LZE_Datasheet_Revision_1p3b_A_1.pdf