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Green and Sustainable Industrial Internet of Things Systems Leveraging Wake-Up Radio to Enable On-Demand IoT Communication

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Abstract: The industrial Internet of things (IIoT) is a major lever in Industry 4.0 development, where reducing the carbon footprint and energy consumption has become crucial for modern companies. Today's IIoT device infrastructure wastes large amounts of energy on wireless communication, limiting device lifetime and increasing power consumption and battery requirements. Communication capabilities seriously affect the responsiveness and availability of autonomous IoT devices when collecting data and retrieving commands to/from higher-level applications. Thus, the objective of optimizing communication remains paramount; in addition to typical optimization methods, such as algorithms and protocols, a new concept is emerging, known as wake-up radio (WuR). WuR provides novel on-demand radio communication schemes that can increase device efficiency. By expanding the lifespan of IoT devices while maintaining high reactivity and communication performance, the WuR approach paves the way for a "place-and-forget" IoT device deployment methodology that combines a small carbon footprint with an extended lifetime and highly responsive functionality. WuR technology, when applied to IoT devices, facilitates green IIoT, thereby enabling the emergence of a novel on-demand IoT (OD-IoT) concept. This article presents an analysis of the state-of-the-art WuR technology within the green IoT paradigm and details the OD-IoT concept. Furthermore, this review provides an overview of WuR applications and their impact on the IIoT, including relevant industry use cases. Finally, we describe our experimental performance evaluation of a WuR-enabled device that is commercially available off the shelf. Specifically, we focused on the communication range and energy consumption, successfully demonstrating the applicability of WuR and the strong potential that it has and the benefits that it offers for sustainable IIoT systems.

Keywords: green IoT; wake-up radio; data collection; industrial internet of things; energy efficiency; energy harvesting; Bluetooth low energy; wireless sensor network

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1. Introduction

Industries now represent a rising 22% of the total applications of the Internet of things (IoT) [1], and the industrial Internet of things (IIoT) has become an extremely active research area. The IIoT has application opportunities in a wide variety of fields, from process and manufacturing to logistics [2]. One of the main needs to be addressed is reducing the energy consumption of the IIoT [3]. The information and communications technology (ICT) sector consumes approximately 3.6% of the worldwide energy and produces 1.4% of the CO_2 emissions [4], in which the IoT constitutes an increasingly substantial portion. Projections indicate the proliferation of tens of billions of devices in the coming decade [5].

To overcome these challenges, a new paradigm called the Green IoT has emerged, which focuses on ensuring that the growth of the IoT is sustainable [6], mainly by reducing its energy consumption. The Green IoT relies on three principles: energy provision (the sources of the energy used), energy transfer (the transfer of green energy to the device), and energy efficiency (the minimum energy usage). These three principles in relation to the notion of sustainability are shown in Figure 1.

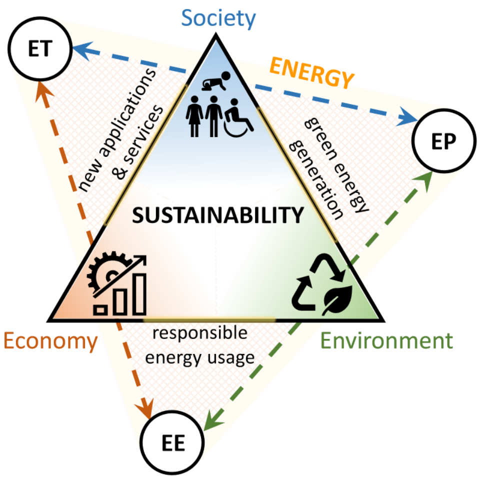


Figure 1. Sustainability triangle [6].

The Green IoT involves the application of several techniques, such as energy harvesting, more efficient communication hardware and protocols, or the better usage of the computing capabilities of edge and far-edge devices. The technique on which we focus in this review is wake-up radio (WuR), which is a technique used to explore and enable energy-efficient and eco-sustainable wireless sensor networks in the Green IoT [1].

WuR technology enables a device to wait for a wireless signal prior to activation, independent of an eventual duty-cycle schedule. The duty cycle indicates the fixed fraction or percentage of times a resource is busy, though it is a harsh constraint on device communication capability and reactivity. The transceivers consume most of the energy in IoT devices [7]. In more common duty-cycle systems, a constant trade-off exists: a low duty cycle increases latency, whereas a high duty cycle increases energy consumption. By allowing a device to keep a part of its radio system on while consuming little energy, WuR technology provides a solution to this trade-off issue and allows low latency and low energy consumption [8]. This combination considerably enhances reliability and battery longevity, thereby ensuring low energy consumption and enabling use in batteryless applications [9]. In addition, WuR facilitates innovative and efficient techniques for gathering data on-demand [10]; it is viable as a substitute for conventional communication systems, particularly for time-sensitive applications in Industry 4.0 [8]. In 2021, the IEEE 802.11 standard was amended [11], adding the possibility of WuR operation in standard wireless local area networks (WLANs). The next release of 3GPP, Release 18, is also expected to include WuR specifications.

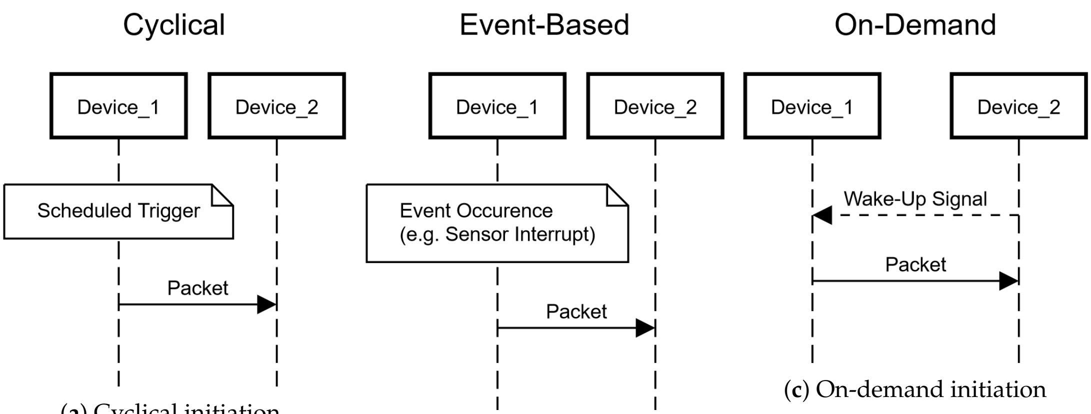
By using WuR to wake up devices on-demand, synergies could be created with the on-demand IoT (OD-IoT) or service-oriented IoT [12], conceptualized recently as the "fog of things" [13], which reuse existing IoT resources to provide infrastructure support to new applications. OD-IoT is a concept that should be extended further and integrated from the outset in devices, as we show that it can improve energy savings, data collection, and process flexibility.

We begin by presenting our proposal for the classification of communication–initiation mechanisms used in the IoT and how they enable the analysis of the current IIoT landscape. This is followed by a discussion of the state of the art of WuR technology, including its operating principles, current implementations, and dedicated protocols. We also discuss the connection between WuR and energy harvesting, as well as its implementation in novel data collection methods that enable the OD-IoT. Additionally, we provide a concise overview of unconventional WuR methods employed in specific domains. Following this, we present an overview of relevant industrial applications of WuR before evaluating its performance. Off-the-shelf solutions are discussed in the following section. Our evaluation leads to a conclusion on the relevance of WuR in the context of the IIoT and its potential to enable the OD-IoT.

2. Mechanisms of Initiating Device Communication

To improve the comprehension of the communication complexities in the current IoT systems, we categorize the different methods through which a device can initiate communication. We identified three approaches, illustrated using sequence diagrams in Figure 2.

- Cyclical communication relies on a time-based scheduling. Energy consumption is determined by the time frame. Depending on the primary optimization factor, which may include battery levels, sensor thresholds, time of the day, seasonality, and network activity, the period can be fixed or variable to accommodate application constraints related to process reactivity or energy consumption.
- Event-based communication is triggered by either an external event, typically a sensor reading or data processing (e.g., temperature alert) or by hardware interruption generated by a process event (e.g., shock or body fall). Energy consumption is strongly influenced by the frequency of events, which can be roughly estimated according to previous occurrences and process variability. Reactivity reaches a peak as information transmission is solely dependent on the speed of data processing.
- On-demand communication is initiated by a stimulus from an external process or device using a wireless wake-up mechanism, regardless of the device's ongoing task. Energy consumption is determined by the frequency of the stimulus, so it is mandated by external processes. The device's communication activity is driven by the external processes based on on-demand requests (e.g., for commissioning or sensing). Reactivity is entirely independent of process variability and solely dependent on external requests.



(**a**) Cyclical initiation
(**b**) Event-based initiation
(**c**) On-demand initiation

Figure 2. Sequence diagrams of three identified communication initiation mechanisms.

Considering the wide variety of communication initiation mechanisms between the devices, edge-cloud components, and systems used in IoT communication architectures, we propose the following classification of these mechanisms, which is supported by three major principles: cyclical, event-based, and on-demand principles. The communication mode of a device can be analyzed and decomposed using these three mechanisms, either exclusively with one of the three or according to a combination, as presented in Figure 3. This classification helps to identify how the device interacts at the communication level with higher layers or other devices in the IoT architecture and how the communication process can be improved on the device to change latency, reactivity, and energy consumption to create a sustainable approach.

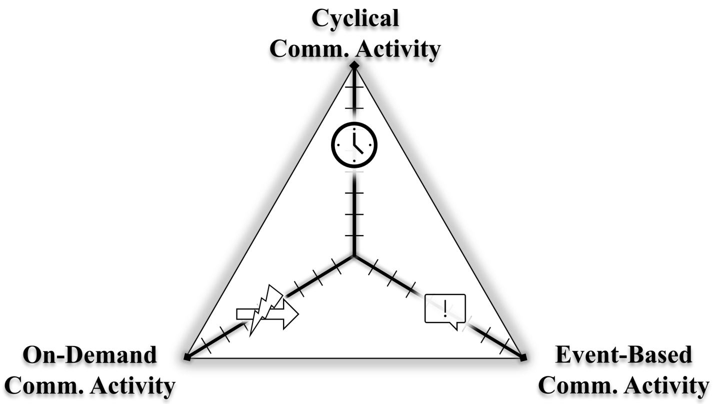
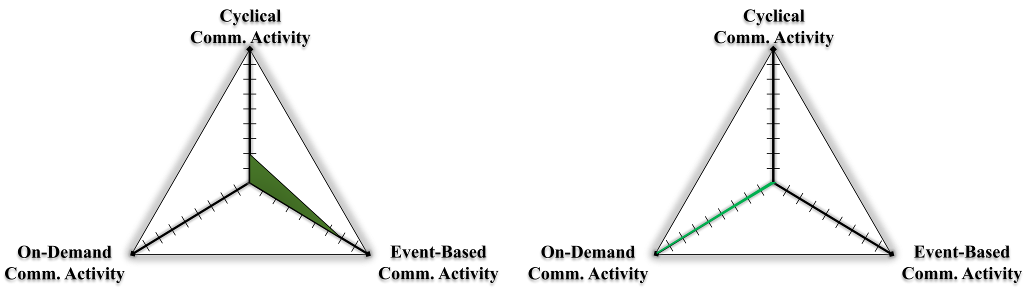


Figure 3. Device communication trigger modes reference diagram.

The trigger modes reference diagram can also be used to compare different device communication profiles. For instance, 80% of a device's communications can be event-based, whereas the remaining 20% can be used for either cyclical neighborhood detection or scheduled data upload (Figure 4a). The presence of event-driven communication increases reactivity at the cost of probabilistic energy consumption. Conversely, communication has fixed reactivity and deterministic energy consumption. The lack of on-demand communication means that the process cannot request data or wake up the device without relying on cyclical scheduling or probabilistic events. It also means that the energy consumption of the communication is not managed. In contrast, conventional radio frequency identification (RFID) devices fully perform on-demand communication activity (Figure 4b) and cannot initiate any communication on their own, relying entirely on the reader and having entirely managed energy consumption.

Overall, the diagram in Figure 3 illustrates the impact of each initiation mechanism on the device's reactivity and energy consumption in the present application. The occupied area in each third of the graph represents this impact.



(**a**) 80% Event-based/20% Cyclical profile (**b**) 100% On-demand profile (RFID)

Figure 4. Examples of communication initiation mechanism classifications.

Currently, the industry is mostly dominated by cyclical-based communication devices and applications. The majority of communication protocols use a schedule to plan their communication and neighbor discovery (e.g., advertising interval in Bluetooth low energy (BLE) [14]). These schedules may vary in response to device conditions and demands [15] but still rely on frequent planned communication, which limits their flexibility. Event-based protocols are currently under development [16], based on the amount of data generated, but solutions using publish/subscribe (PUB/SUB) schemes to transfer data on the occurrence of an event are already well-established (e.g., reading above a threshold) . Event-based communication could become more prominent owing to the artificial intelligence IoT (AIoT) that can be used for ultra-low-energy complex event recognition, as demonstrated, for example, by ECG recognition [17]. These complex event detections considerably extend the range of possible use-cases of event-based communication while limiting the volume of data communicated to the cloud, thus reducing energy consumption. On-demand communication is currently mostly confined to RFID, which is predominantly used for identification and tracking purposes [18]. Passive RFID devices lack innate communication potential, but active RFID devices do not experience this limitation. However, reading can only be conducted using relatively energy-hungry devices [19], limiting the reception task to short-lived or main-powered devices. Tag-to-tag communication is also an option [20], but it requires an external energy source to continuously feed energy to the devices. Therefore, an independent network primarily using on-demand communication is feasible, although RFID cannot be used. Currently, on-demand communication remains undervalued despite its potential for data collection applications and energy-efficient IoT technology. Consequently, we focus on wake-up radio technology, which is an enabler for OD-IoT applications.

3. State of the Art

3.1. Wake-Up Radio Principles

A WuR system permits a device to be awakened through a wireless wake-up signal (WuS) without the need for physical interaction. Typically, a device placed in a low-energy "sleeping" mode can switch to an active mode through a scheduled timer, a sensor interruption, or after receiving power wirelessly from a primary device (e.g., backscattering principle in RFID). Using WuR activation, a device can be woken up from afar, without using its main radio transceiver to perform idle listening, which is generally the most energy-consuming system of small IoT devices [7]. Typically, the part responsible for the detection and treatment of the WuS is called a wake-up receiver (WuRx), whereas the transmitting radio is called a wake-up transmitter (WuTx). A typical example of a WuR device is shown in Figure 5.

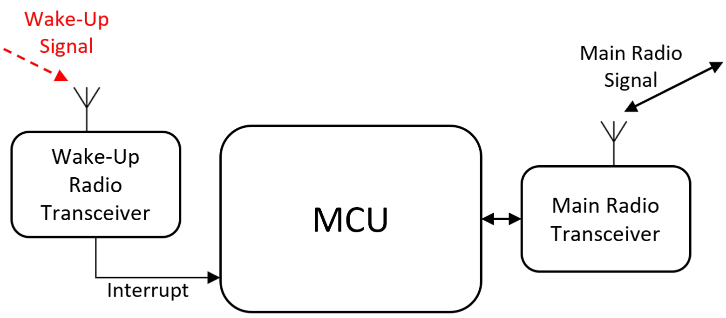


Figure 5. Principle of WuR: a WuR-enabled IoT node.

WuRs are classified as either passive, which is when they use the energy contained in the WuS to power themselves, or active, which is when they use an external energy source to operate (usually the device's battery). When integrated into a device, a WuR sharing the same frequency band as the main radio to transmit its WuS is considered in-band. In the alternative scenario, a WuR is referred as out-band. WuR has the capability to operate on a diverse range of frequencies.

Although some WuR implementations rely solely on the strength of the WuS to awaken the device, selective wake-up is preferable. This approach prevents unnecessary energy usage and permits selective device addressing at the lowest level. Therefore, most current implementations now integrate a unique identifier (UID) into the WuS. However, the demodulation and decoding of the code incur an energetic cost, which is a current research problem. Most passive WuRs use on-off keying (OOK) modulation, whereas active WuRs use more power expensive techniques, such as amplitude shift keying (ASK) and frequency shift keying (FSK) modulation [21].

3.2. WuR Implementations

Numerous implementations have been proposed in the literature, spanning from specifically designed Complementary Metal-Oxide Semiconductor (CMOS) circuits to discrete circuits. The performance of the latter is evaluated by integrating them into conventional IoT nodes. Their performance is estimated considering their power consumption in WuRx mode, their wake-up range, and their carrier frequency. A sample of the WuR-enabled IoT nodes mostly used for experimentation in the scientific community is presented in Table 1. The table details the performance of the WuR systems in terms of range and receiver energy consumption with regard to frequency and implementation technology.

Whereas some of these nodes operate on unlicensed frequencies bands [22] used by low-power wide area networks (LPWANs) such as LoRa [9,23–26], others use frequencies shared with a power transmitter [9], with Wi-Fi [27] or with a dedicated WuR IC [28]. Using LoRa or unlicensed WLAN frequencies enables building upon a well-established protocol and public communication infrastructure. Additionally, the application's power transmitter can merge data and power transmission in a single wired device. Using less common frequencies can prevent interference with other wireless protocols in the area.

Energy consumption widely varies depending on a large number of factors, such as range, frequency, and implementation technology. Long-range solutions [25,27] are the most energy-hungry implementations due to the power needed to amplify weak long-range signals. In particular, the implementation technology used strongly influences power consumption. For example, the AS3930-based solution [28], which depends on a nonoptimized demonstration board and the BEH solution [9], uses the analog-to-digital converter (ADC) of a microcontroller to measure the received radiofrequency (RF) energy instead of a dedicated WuRx circuit, which consumes far more than a dedicated WuRx circuit. This is a more recent and optimized solution.

Table 1. Nonexhaustive review of nodes proposed for WuR testing.

Implementation	Date	WuR Range	Frequency Band	Receiver Consumption
MagoNode++ [26]	2016	21 m [29]	433/868 MHz	1.3 μW
BEH [9]	2019	3 m	915 MHz	1.69 mW
WuLoRa [23]	2017	55 m	868 MHz	4.6 μW
ICARUS [24]	2021	1–2 m (1)	868 MHz	1.91 μW (2)
BLE + AS3930 [28]	2020	3 m	125 kHz	27 μW
LDWuR [27]	2015	1 km	2.4 GHz	27 mW
Long-Range LoRa [25]	2019	8.74 km	433 MHz	6 mW

(1) Estimated from −70 dBm [30]. (2) Calculated from the indicated 3.3 V supply and 580 nA consumption.

The technological solutions based on custom CMOS circuits enable a considerable reduction in energy consumption, with values of less than 100 nW, but they are generally not yet ready to be applied in industrial projects. So, we do not provide furether detail here. Nonetheless, this field of research is active, producing full AI-ready SoC with WuR capabilities, such as SamurAI [31], which consumes less than 40 nW in an idle mode.

3.3. Energy Harvesting

The topic of energy harvesting and its importance in WuR devices should not be dismissed. WuR facilitates low standby energy consumption while retaining communication capabilities, so this technology is the most compatible with energy harvesting.

Energy-harvesting devices use local energy production to complement their battery charge or to power themselves completely. Many kinds of energy can be harvested [32]: one of the most used in WuR devices is directed RF energy [33], as only an additional step is required beyond using the energy from the WuS to power the passive receiver. Another energy source that easily enables zero-standby solutions is the optical energy collected from a laser [34]. Those two methods are efficient on the receiver side, but they need dedicated transmitters in the vicinity of the nodes and even a line of sight for laser-based solutions. Alternatively, some solutions use ambient energy through photo-voltaic cells or ambient RF energy, providing the advantage of not requiring any additional transceiver. Even indoor harvesting is possible, depending on the existing ceiling light, which has very low illuminance requirements [35].

In some scenarios, specific energy sources may be employed. In wireless body area networks (WBANs), the body's thermal [36] and kinetic [37] energies can be harnessed. Acoustic energy can be harvested in urban or industrial settings [38], whereas for outdoor or agricultural environments, both soil [39] and plant [40] energy can serve as viable energy sources.

Many implementations and protocols operate under the assumption of energy harvesting, using dynamic energy distribution in the network [41] that routes data through the largest number of devices that have the best energy capabilities.

The topic of combining energy harvesting and WuR was previously addressed, mainly for the development of passive WuR [21], which uses RF energy. However, the combination of low-energy WuR communication and an efficient low-footprint energy harvester led to the development of devices with an extended lifetime and energy autonomy [23], some of them being battery-free [9].

3.4. WuR-Based Data Collection Protocols

WuR technology can be used to enforce an on-demand or receiver-initiated data collection paradigm by waking up long-term IoT nodes only when an update is necessary. Unmanned aerial vehicles (UAVs or drones) may be a key component of this system, efficiently gathering large amounts of dispersed data, as depicted in Figure 6. The viability of this scheme was previously demonstrated via simulation tools [42] and experimental evaluations [10]. To prevent transmission collisions during the waking-up process of a large number of nodes, hashing and partitioning schemes [43] have been proposed, including a variant tailored to mobile nodes.

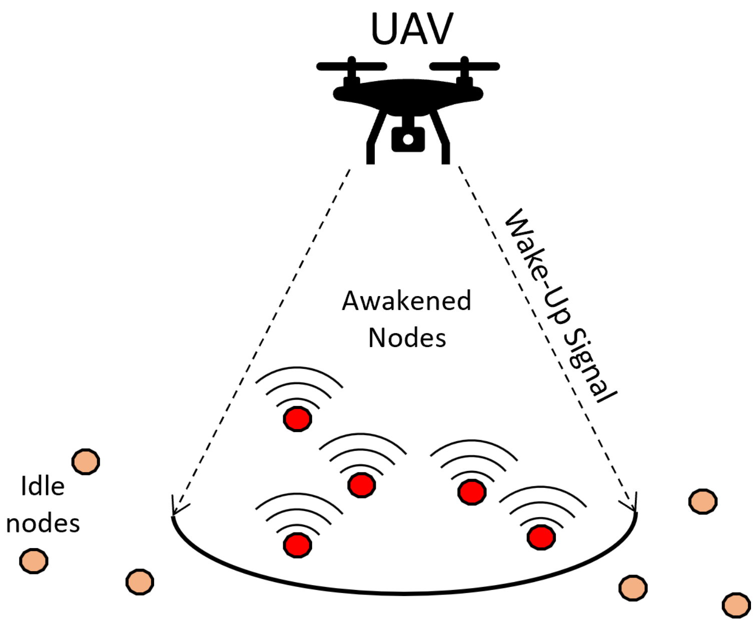


Figure 6. A general UAV-aided data-collection scenario.

Other methods can extensively use LoRa, expanding the capabilities of that protocol. The combination of long-range LoRa transmission and short-range WuR can be leveraged for on-demand data-collection without UAVs [44]. The proposed system depicted uses local cluster heads to trigger the on-demand waking up of nodes, enabling them to transmit data to a singular sink. This heterogeneous architecture and its associated protocol enhance latency by 1.72 times and extend node lifetime by 1.4 times compared to the listen-before-talk media access control (MAC) scheme for LoRa.

The radio on-demand sensor and actuator network (ROD-SAN) model [45], based on IEEE 802.15.4g, provides WuRx and WuTx to all network nodes to enable on-demand communication in contrast to the standardized duty-cycled schemes of IEEE 802.15.4g. The results of simulation studies demonstrated that ROD-SAN substantially enhances data collection. In comparison with duty-cycle approaches, ROD-SAN has a lower consumption rate and decreased latency. The results of a field test of 20 nodes showed that, with an active rate of 10%, ROD-SAN achieves a comparable performance to a standard network with a 100% active rate, while reducing energy consumption tenfold. Iterating on that approach, the creators of ROD-SAN found a method for aggregating data in the WuS [46,47] to benefit from the possible active state of the destination, thus reducing the energy consumption and latency even more. Embedding data in the WuS also allows content-based waking up [48], using the length of the WuS to prioritize the freshest data and avoid unnecessary wake ups [49].

WuR communication and data collection protocols can be simulated using various tools, such as Omnet ++ with the plugin Mixim [50], Castalia with GreenCastalia [51], or COOJA with the plugin WaCo [52]. They can also be modeled using Markov chain modeling [53], which has been used to test many protocols [54], allowing for the creation of a specific protocol for long-range and long-battery-life applications [25]. Developments have also covered the security aspects of such protocols, ensuring their suitability for industrial use [55].

3.5. Non-RF-Based WuRs

Previously, our attention was directed toward RF-based WuRs. However, RF signals are not viable in some settings. In industrial underwater environments, the use of acoustic waves is preferred as their absorption rate is three orders of magnitude lower than that of electromagnetic waves [56]. Acoustic wake-up receivers intended for underwater use have been proposed, providing energy-saving benefits for battery-powered nodes that are difficult to access [57]. This technology has potential for the long-term monitoring of wildlife, particularly whales, based on their vocalizations [58].

Optical technology can also be used for this purpose. A performance comparable to those achieved using RF-based wake-up receivers has been attained [59] through the use of infrared wake-up, which functions on the same principle as how a TV remote awakens a TV.

4. Industrial Applications

WuR technology has a wide range of applications in industry, health, and for the environment. Several use cases were analyzed [21] in the fields of remote environmental monitoring in rural applications, asset tracking in logistic supply chain, and medical applications for human-body monitoring. These application areas are detailed in the following list, with three new areas: source discovery, process monitoring, and RFID improvements.

- Remote environmental monitoring: Many remote environmental monitoring applications currently use LoRa, which can be upgraded through the use of WuR. Using a custom DC-MAC protocol [25], the energy consumption of LoRaWANs can be reduced, even allowing them to be powered entirely by energy-harvesting systems. This indicates that a large portion of current LoRaWAN applications can leverage WuR technology to reduce their consumption and increase their battery lifetime. Future IIoT 5G applications can also be equipped with WuR [60], benefiting from its advantages in terms of energy consumption and reactivity. The use of UAV-aided data collection Section 3.4) is also especially fit for this kind of application.

- Medical applications: New developments can use WuR-enabled devices to reduce their energy consumption and take advantage of on-demand communication. WuR-enabled smart lenses [61] can be used to monitor biomarkers in tears, which could find use in the monitoring of worker safety in hazardous industrial environments.
- Asset tracking: Asset tracking and localization can be improved using efficient and precise methods using nanodrones, especially in open industrial spaces [62]. The BATS protocol [63] provides a method of tracking wildlife and cattle, which can serve as a basis for improved asset tracking. Sensor networks embedded in concrete or other materials [64] can benefit from the increased lifetime and autonomy provided by WuR. Pairing this with on-demand data retrieval and energy harvesting techniques would enable nodes to perform more complex measurements and data processing tasks.
- Source discovery: A novel application of WuR is source localization. Using selective wake up, the source of a sensing observation (e.g., toxic gases) can be found [65]. Industrial safety monitoring would benefit from this application.
- Process monitoring: Communication between machines in industrial processes is essential; in the context of the Green IoT, the energy consumption of communication must be reduced while maintaining reactivity. WuR was also proposed as a solution to reduce the energy consumed in machine-type communication (i.e., M2M), in combination with neural networks that predict traffic patterns in MTC networks [66].
- RFID improvements: Using WuR, many challenges faced by RFID technology could be overcome (Figure 7). The inflexibility that is inherent to RFID is resolved by the potential of integrating a WuRx into any device. The relatively high cost of the reader can be mitigated by the ability of WuR-capable devices to use another protocol for main communications, which could act as a WuS for other devices [25]. To prevent message collisions, identity-based WuS addresses specific devices, whereas content-based WuS [48] retrieves only relevant data. Additionally, dedicated WuR anticollision algorithms [43] may be used.

  The range heavily relies on both frequency and energy consumption (Section 3.2). However, implementing multihop schemes, either with dedicated cluster heads [67] or without cluster heads [68], can effectively mitigate the issue. The use of energy harvesting in a device that is WuR-capable is not restricted by the decline in RF energy, which rapidly diminishes. The distance is regulated by the emission power. A wide range of options is available, depending on the application (Section 3.3). Smartphone support may be lacking, depending on the radio used. In applications requiring such support, Wi-Fi can be used, or either the Bluetooth primary radio or WuRx is preferable, relying on the recent IEEE 802.11ba amendment to WLAN [69].

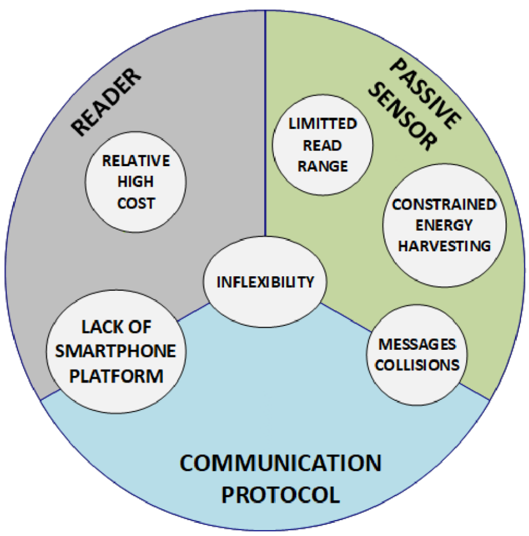
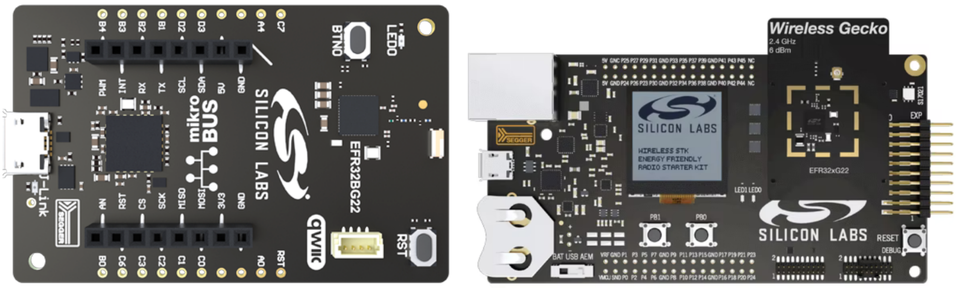


Figure 7. Overview of the main challenges facing RFID [18].

Overall, WuR is a valuable addition to the IIoT landscape, particularly for collecting data from isolated or long-term sensor nodes and addressing the challenges faced by certain RFID-based solutions.

5. Materials and Methods

For this study, we conducted communication experiments using two identical BG-22 Explorer Kit boards [70], which are based on the EFR32BG22 SoC manufactured by Silicon Labs. We selected this device due to its rare WuR capabilities among BLE boards. The microcontroller's WuR feature was also evaluated. The manufacturer refers to it as RFSense. Additionally, we used an EFR32xG22 Starter Kit that was equipped with the same SoC component. This kit was helpful for recording consumption measurements without the extra components present on the Explorer Kit boards. See Figure 8 for the two board variations.



(**a**) BG-22 Explorer Kit (**b**) EFR32xG22 Wireless Gecko Starter Kit

Figure 8. EFR32BG22 boards used in this study.

The EFR32BG22 features several energy-saving features included in its energy modes (EMs). One of those EMs is dedicated to the use of WuR, whereas the others are more classical and analogous to the idle and sleep modes of other micro-controllers. Table 2 summarizes the operating components made available for each EM. We began our study by measuring the RSSI of a BLE message sent from one board to another from different distances. As the RF front end was shared between the WuRx and the BLE transmitter, it provided insight in the range that could be expected of the WuR according to the sensitivity given by the manufacturer. We conducted consumption measurements on different EMs to emphasize the energy benefits of WuR. Additionally, we compared WuR with other common BLE microcontrollers and SoCs. Finally, we determined the experimental range for the WuR implementation. A concise guide to implementing the code is provided. Based on our comprehensive literature review, our study provides a pioneering contribution to experimentally analyze WuR performance in terms of energy consumption and RSSI ranges using EFRBG22-based devices. To our knowledge, no research work has previously explored this aspect.

Table 2. EFR32BG22 operating components available depending on EM [70].

Energy Mode	Description	Peripheral Made Available	Expected Current Consumption
EM0 (Active)	Fully operational system	ARM Cortex M33 processor with DSP, FPU and TrustZone	1.5 mA
EM1 (Sleep)	Processor is off, radio awaiting communication	Flash Memory, HF Oscillators, Main Radio Subsystem, USART, PDM, TRNG, Crypto Acceleration, Timer, Protocol Timer	0.96 mA

Table 2. *Cont.*

Energy Mode	Description	Peripheral Made Available	Expected Current Consumption
EM2 (Deep Sleep)	Processor is off, sensor monitoring	Fast Startup Oscillator, Precision LF Oscillator, EUART, Temperature Sensor	1.4 µA
EM3 (Stop)	Processor is off, awaiting timer or interrupt wake-up	Debug Interface, RAM, LDMA, Integrated Power Supplies, I2C, External Interrupts, ADC, Low Energy/Watchdog/RTC	1.34 µA
EM4 (Shutoff)	**Wake-Up Radio** enabled, minimal energy mode with no working memory retention	RFSense (**Wake-Up Radio**), GPIO, LF Crystal Oscillator, Ultra LF Oscillator, Reset, Brown-out detector, Backup RTC	440 nA

5.1. Experimental RSSI Analysis Protocol

To determine the range capabilities of the on-board BLE radio, we used the received signal strength indicator (RSSI). From the collected data, we determined how the range affected the strength of the signal and at which point the signal was too weak to trigger a wake up. RSSI was measured on a scale from 0 dBm (closest) to −127 dBm (farthest). The signal power can be theoretically determined by considering the signal waves as electromagnetic waves obeying the mechanisms of reflection, diffraction, and scattering [71].

A simplified equation for the RSSI (Pr) on the receiver side is as follows:

$$Pr = -10\eta \cdot log_{10}(d) + A$$

where Pr is the strength of the received signal; η is the signal propagation exponent; d is the relative distance between devices; and A is the nominal transmission power at 1 m.

The experiment was conducted indoors in an empty room, limiting external disturbances and the causes of wave reflections (objects, furniture, etc.). We measured the RSSI levels between two identical boards that were laid flat on the ground, separated by different experimental distances. One board periodically sent data (1 Hz), while the other one was in reception mode, recording RSSI levels for later analysis. We measured the RSSI levels with this configuration over 40 s for each fixed distance from 10 to 500 cm, with a variable incremental step. Until 100 cm, the incremental step was 10 cm. Above 100 cm, the incremental step was 50 cm. The variation chosen was linked to the high variability in short-distance RSSIs (usually below 100 cm). For each fixed distance, we calculated the RSSI by averaging 40 data points.

5.2. Energy Mode Consumption Experimental Protocol

We measured the current consumption of the EFR32BG22-based solution in its operating modes defined by the manufacturer. Six modes were tested: five native modes (EM0 to EM4) and one active mode (EM0) with and without BLE reception activation. We measured the baseline power consumption, without any computational or measurement task assigned to the processor. The measurement was recorded 3 s after the mode was set and consumption stabilized. The experimental setup is illustrated in Figure 9. Finally, the obtained results were compared with those of other widely used BLE SoCs available on the market.

For our experiment, we used an IoT power profiler and energy analyzer (Otii from Qoitech company [72]), which had an accuracy of ±(0.1% + 50 nA) and a sample rate of 4 ksps.

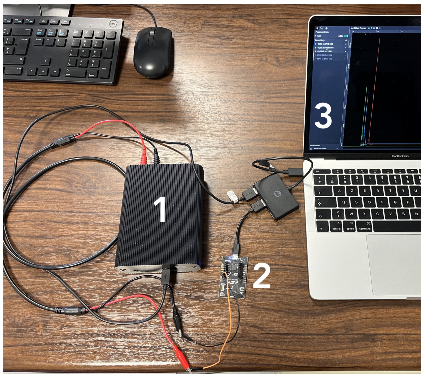


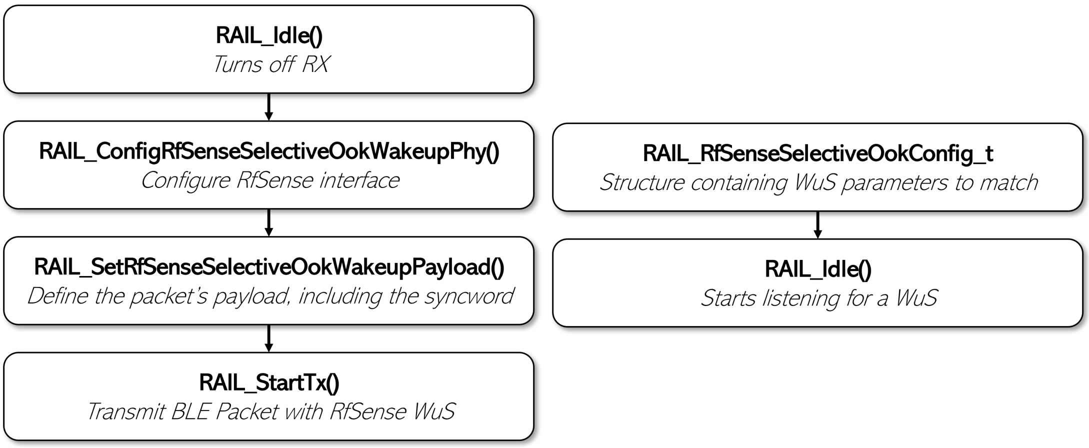
Figure 9. Energy consumption measurement. 1. Otii Arc [72]; 2. Microcontroller; 3. Otii software.

5.3. EFR32BG22 WuR Command Line Example

5.3.1. Principle

The 2.4 GHz carrier used for WuR is susceptible to interference. The established protocol considers this issue and provides two alternatives:

- Legacy mode
  The microcontroller uses a time-based filter to identify WuR packets. The system can be configured to monitor a selected frequency band for a specific duration, measured in microseconds. Choosing a longer sensing duration is recommended when operating under noisy conditions. To enable wake-up functionality, we used a Silicon Labs RAIL API [73]. The `RAIL_StartRfSense` function is responsible for this feature, and the receiving node must call it before entering EM2 or EM4 to be woken up. After sensing on the RF for the designated period, it transitions to EM0. Notably, calling `RAIL_StartRfSense` again is required to reuse the WuR.
- Selective mode
  This approach enhances the protocol's security through the use of a sync word, a 1 to 4 bytes code that must match between the sending and receiving nodes. This feature effectively thwarts accidental wake ups, although it does not combat sniffing. To use this mode, the setup differs on both ends. An example provided by Silicon Labs, illustrated in Figure 10, was used.



(**a**) Sending device configuration (**b**) Receiving device configuration

Figure 10. WuR (RFSense) usage on an EFR32BG22.

5.3.2. Wake-Up Example

For this experiment, the boards were placed next to each other, with their antennas placed face-to-face. This setup allowed for optimal transmission, and the following commands based on the RAIL API were sent through the serial monitor. We used the `RAIL - SoC RAIL Test` firmware provided by Silicon Labs.

- Receiving board
  This command enables WuR with the sync-word code, and then sets the node to EM4.

```
sleep 4 2 0xB16F 1
```

  We receive a log that the WuR packet was sensed when another board sends a signal.

```
{{(sleepWoke)}{EM:4s}{SerialWakeup:No}{RfSensed:Yes}}
```

- Sending board
  These commands set the configuration for RFSense and the setup of the sync word, and send the packet.

```
configRfSenseWakeupPhy
fifoModeTestOptions 1 0
setRfSenseTxPayload 0x2 0xB16F
tx 1
```

  We receive a response indicating that the packet is correctly sent.

```
{{(txEnd)}{txStatus:Complete}{transmitted:1}{lastTxTime:
187755304}{timePos:6}{lastTxStart:187703928}{ccaSuccess:0}
{failed:0}{lastTxStatus:0x000000000}{txRemain:0}{isAck:False}}
```

6. Results

6.1. RSSI Experimental Results

Following the experimental protocol described in Section 5.1, we obtained the results shown in Figure 11.

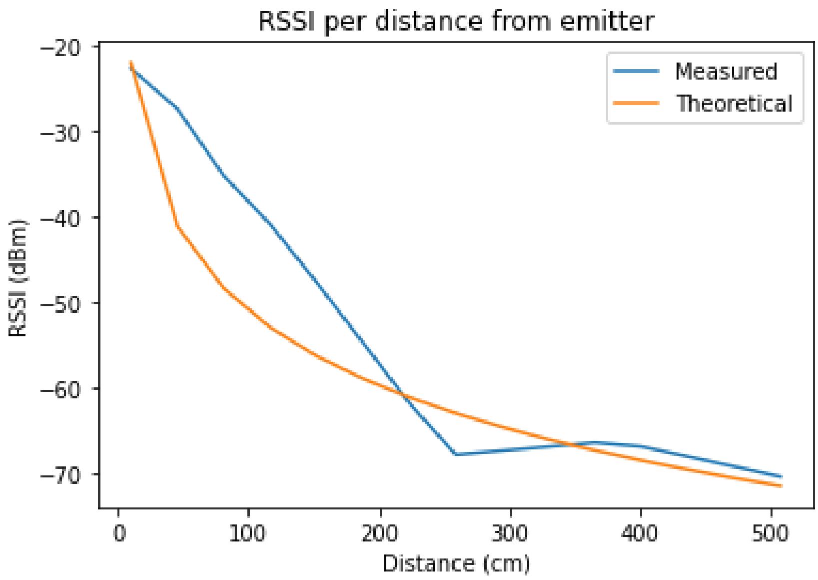


Figure 11. RSSI measurements.

Inaccuracies in the measured results were expected due to the RSSI's high sensitivity to interference and multipath and non-line-of-sight propagation [71]. From that, we obtained $A = -80$ dBm and $\eta = 3$. According to the manufacturer, the WuR sensitivity was between -28 and -40 dBm, which provided a wake-up range of, at most, 1.5 m in the current conditions.

6.2. Energy Mode Consumption

The results of the energy measurements are provided in Table 3, along with the advertised consumption of three BLE SoCs. As each manufacturer uses a different terminology for its EMs, the comparison was conducted based on the available functionalities. When no explicit data were given for a mode, a calculation using the consumption per megahertz and the base frequency of the SoC was performed to obtain a value. Despite this, some solutions simply lacked an equivalent comparison for each mode and are therefore not present in each row. The comparison did not account for frequencies or peripheral optimizations, as too many possible combinations exist, and most of them are application-specific.

Table 3. Measurement results in different EM compared with that of other solutions.

Energy Mode (EFR32 Name)	EFR32BG22 Manufacturer Value	EFR32BG22 Measured Value	ESP32-Equivalent Consumption [74]	CC2640-Equivalent Consumption [75]	NRF52840-Equivalent Consumption [76]
EM0 + RX (Active + Receiving Mode)	3.6 mA	5.12 mA	95 mA	5.9 mA	**4.6 mA**
EM0 (Active Mode)	1.5 mA	**1.97 mA**	30 mA	3 mA	3.3 mA
EM1 (Sleep)	0.96 mA	1.16 mA	**0.8 mA**	-	-
EM2 (Deep Sleep)	1.4 µA	**3.39 µA**	-	0.4 mA	-
EM3 (Stop)	1.34 µA	**1.03 µA**	10 µA	100 µA	1.5 µA
EM4 (Shutoff)	440 nA *	442 nA *	5 µA	**100 nA**	400 nA *

bold: Lowest consumption. * WuR available (2.4 GHz for EFR32, NFC for NRF52840).

Overall, we observed that the current consumption values advertised by Silicon Labs are lower than the measured values during the experimentation.

The most notable difference was found during reception mode. According to the manufacturer's value, EFR32BG22 should be the most energy-efficient SoC, but the measured value ranked it second. The difference was mainly due to the current consumption of the additional components (e.g., extra sensors, debugging IC, etc.) of the development board, which cannot be isolated.

Another variation occurred because some manufacturers advertised the average value obtained through a 50% RX duty cycle. However, although the EFR32BG22, CC2640, and NRF52840 were similar, ESP32 exhibited substantially higher energy consumption while in receive mode, making it the most energy-intensive of the four.

When in active mode (EM0), EFR32BG22 seemed to be the most efficient solution, consuming only half as much power as CC2640 and the NRF52840. Notably, this performance may vary based on the specific application and computing needs of the application. Of the four available SoCs, ESP32 was the most powerful; however, its power consumption was ten times that of the others.

When in their lowest energy state, both EFR32BG22 and NRF52840 could receive a WuS using 10,000 times less current than when in their main radio receiving state. This striking contrast in consumption highlights the benefits of this technology's WuR capabilities. The ESP32 system-on-a-chip (SoC) consumed the most power overall due to its superior computing capabilities. In comparison with the other solutions, ESP32 is less suitable for long-term devices in terms of energy efficiency. Nonetheless, it is still relevant in certain use cases where more intensive data processing is required, at the cost of the energy budget.

Overall, WuR implementations provide energy consumption results that are very close to that of the lowest non-WuR system (CC2640) while maintaining the ability to receive data. Of all the SoCs assessed in this study, EFR32BG22 appears to be the most energy-efficient, particularly when in sleep mode, although it was the only one that was experimentally tested.

6.3. Wake-Up Range

Using identical sending and receiving boards, we conducted experiments on the wake-up range. The best results were obtained at a distance of 15 cm, with an optimal orientation of the antennas. This distance is ten times shorter than the theoretical maximum distance of 1.5 m obtained in Section 6.1. We deduced that our assumption regarding the shared front-end between BLE and WuR resulting in similar performance was incorrect. The manufacturer suggested that the addition of a low-noise amplifier (LNA) to the reception circuit can lead to enhanced performance, albeit with a rise in energy consumption. As a result, the board can be used exclusively for development purposes or for wake ups within a limited range.

7. Discussion

WuR technology offers new opportunities for implementing the proposed On-Demand-IoT concept. OD-IoT enables switching from a traditional periodic communication mode to an on-demand communication mode, providing an optimum response to the needs of applications while considerably limiting the energy impact of data exchange. OD-IoT substantially reduces a device's communication link budget and therefore extends its lifespan while guaranteeing highly responsive data collection and analysis for higher-level applications in complex IoT architectures. The benefits of WuR-based OD-IoT are amplified by the concomitant use of energy harvesting and novel on-demand data collection techniques. The main areas of applications that can profit from OD-IoT include environmental data collection, asset tracking, and smart healthcare.

WuR technology has many potential implications for the sustainability of IoT-based industrial systems at the environmental, societal, and economic levels, with a major impact on energy savings.

By limiting energy consumption and increasing device lifespan, WuR holds great promise for improving the overall environmental sustainability in industrial systems, especially in the context of the large-scale deployment of IIoT devices.

In addition, the benefits of WuR in IIoT applications can have an impact on the well-being and safety of workers. By improving the reactivity and energy autonomy of IoT body area networks, as discussed in Section 4, health and quality-of-life monitoring can be enhanced by WuR. This technology could therefore have a positive impact on social sustainability.

In an economic context, through the extension of device operating life while limiting maintenance costs, thanks to improved autonomy, WuR can help reduce the total cost of ownership of IIoT devices. This technology could therefore satisfactorily meet the objectives of a sustainable economy. Finally, using OD-IoT as a conceptual framework for the use of WuR would make the most of its potential for implementation for a sustainable industry.

However, few WuR technology solutions are currently available on the market, and studied industrial applications are still rare. As demonstrated by the results of our experimentation, some limitations and constraints must be overcome, such as the limited range due to interference susceptibility and low-sensitivity receivers. Further studies are needed to improve the technology and to assess its scalability for large-scale IoT deployment. Currently, fundamental and standardization studies are in progress, which, once mature, should enable the wider adoption of the technology and its underlying OD-IoT concept.

8. Conclusions

In this paper, we introduced a pioneering paradigm called on-demand IoT (OD-IoT), outlining its advantages for developing both sustainable and energy-aware industrial IoT

(IIoT) systems using wake-up radio (WuR) technology that will enable the large-scale implementation of OD-IoT.

We first proposed a classification of the communication initiation mechanisms currently implemented in IoT devices. We aimed to demonstrate the largely untapped energy-saving potential of on-demand communication at the device level in comparison with that of current standard mechanisms such as cyclical and event-based messaging. Based on an extensive review of the state of the art of WuR technology, we compared and analyzed the current prototypes and their capabilities that are relevant to IIoT applications. The use of WuR enables efficient data collection mechanisms using the on-demand principle.

Finally, this paper presented a discussion of the experimental findings of a WuR-enabled off-the-shelf solution. Its performance was compared with that of several widely used IoT systems-on-a-chip, demonstrating the added value of WuR technology in the design of new sustainable and carbon-aware IoT applications and in their large-scale application.

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Abbreviations

The following abbreviations are used in this manuscript:

ASK	Amplitude Shift Keying
BLE	Bluetooth Low Energy
CMOS	Complementary Metal-Oxide Semiconductor
EM	Energy Mode
ICT	Information and Communication Technology
IoT	Internet of Things
IIOT	Industrial Internet of Things
FSK	Frequency Shift Keying
LNA	Low-Noise Amplifier
OD-IoT	On-Demand Internet of Things
OOK	On-Off Keying
RF	Radio Frequency
RFID	Radio Frequency Identification
RSSI	Received Signal Strength Information
SoC	System-on-Chip
UAV	Unmanned Aerial Vehicle
WLAN	Wireless Local Area Network
WBAN	Wireless Body Area Network
WuR	Wake-up Radio
WuS	Wake-up Signal
WuRx	Wake-up Receiver
WuTx	Wake-up Transmitter
WSN	Wireless Sensor Network

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