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Ultra-Low Power Wake-up Radio for 5G IoT

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***Abstract*—5G Internet of Things (5G IoT), which is currently under the development by 3GPP, paves the way for connecting diverse categories of devices to the IoT via cellular networks. For battery-powered low-cost IoT devices, wake-up radio (WuR) appears as an eminent technique for prolonging the lifetime of such devices, thanks to its outstanding energy consumption performance. However, only a part of small-size battery-powered IoT devices are able to transmit to a cellular IoT base station (BS) directly. In the article, we present W2B-IoT, a prototype implementation of a WuR-based two-tier system, which bridges cellular IoT BS and WuR via a Bluetooth low energy (BLE)-enabled Android smartphone. Such a WuR-enabled IoT device features a current consumption of merely 390 nA and a response time of 95 ms for decoding a wake-up call.**

I. INTRODUCTION

FIFTH generation cellular network based Internet of Things (5G IoT) is an emerging technology proposed by the Third Generation Partnership Project (3GPP) to provide low-power, low-data-rate, and wide-area coverage cellular connections to diverse types of IoT devices [1][2]. As an enabler to the inexorable development of IoT technologies, 5G IoT discloses enormous opportunities for connecting small-size, low-cost, typically battery-powered, and often densely populated devices to perform massive machine-type communications (mMTCs). With the wide deployment of 5G IoT technologies, a variety of envisaged IoT applications, including environmental surveillance, health-care, smart cities, and smart farms, are surging evidently from theory to reality.

There exist two categories of connections between an IoT device and the cellular network, i.e., via either a direct 3GPP connection by for instance narrowband IoT (NB-IoT) [3] or an indirect non-3GPP connection [4]. For NB-IoT, it requires merely 180 kHz as the minimum bandwidth for both uplink and downlink [5]. Since a global system for mobile communications (GSM) channel is designed to be 200 kHz, an operator can easily use one GSM channel for providing NB-IoT services. For a long term evolution (LTE) based NB-IoT connection, one or multiple resource blocks, each with 15 kHz bandwidth and 0.5 ms duration, may be utilized.

To support non-3GPP 5G IoT connections, a heterogeneous link combining a low-power wide-area network (LPWAN) with cellular networks via relay user equipment (UE) appears as a promising option [4]. Typically, LPWAN devices are battery-powered and have no direct cellular subscription. For the operation of such small-size IoT end devices, energy consumption and energy efficiency are of vital importance.

Traditionally, duty cycling (DC) has been a major mechanism for energy conservation in LPWANs, e.g., in wireless sensor networks (WSNs). By allowing nodes wake up and sleep periodically or aperiodically, a high percentage of energy saving is achieved. However, idle listening and overhearing occur in DC LPWANs. For example, a slave or peripheral node in a Bluetooth piconet has to wake up each cycle to check whether the master node has any messages to exchange. To reduce idle listening caused by DC mechanisms, one may extend sleep time to a longer period. This will anyhow cause a significant increase in the response time for data collection.

In the meantime, a paradigm shift from the traditional DC medium access control (MAC) operation to on-demand wake-up radio (WuR) operation has been envisaged, enabled by WuR's overwhelming energy consumption superiority. Basically, a WuR-enabled IoT end device consists of a micro-controller unit (MCU), which is associated with a main radio (MR) and a wake-up receiver (WuRx). The MCU and MR are in deep sleep most of the time. Upon receiving a request by means of a wake-up call (WuC) transmitted by an external node, the WuRx generates an interrupt signal, waking up the MCU to perform certain tasks and transmit any data back via its MR.

It has been shown in [6] that a WuRx's average power consumption is at the magnitude of 1000 times lower than that of the MR. Furthermore, the implemented WuR in [7] achieves around 70 times longer lifetime than DC protocols (with 1% duty cycling) under light traffic load. With such eminent energy consumption performance, WuR appears as a promising technique for achieving a lifespan of beyond 10 years, which is the expected lifetime for NB-IoT and 5G IoT devices [3][1]. Indeed, 3GPP is currently discussing the possible inclusion of WuR in Release 16.

In addition to this lifetime requirement, which is estimated based on the assumption that an IoT device transmits merely 200 bytes of data every two hours or per day on average, 5G IoT services require the latency of shorter than 10 seconds for data transmission [2][3]. Although a year-long battery lifetime may be achieved by extremely low duty cycling, low latency cannot be achieved at the same time since data transmission in DC happens only when nodes are active. On the other hand, the on-demand feature of WuR-enabled IoT devices achieves instantaneous response for data transmission, resulting in much shorter latency.

However, connecting diverse IoT devices to cellular networks is not an easy task, especially when jointly considering non-3GPP IoT connections and the long lifetime requirement of these devices. Although there have been a surge of research interests within the fields of both IoT and WuR, very few have investigated a combination of these two topics, especially from an implementation's perspective. Recently, a firmware design of an NB-IoT device supporting direct 3GPP connection has been reported in [8]. Another recent work [9] has performed a feasibility study on combining Bluetooth low energy (BLE)

TABLE I: A quantitative comparison of W2B-IoT with three popular WuR implementations

Implementations	WuRx Current (μA)	WuC Reception Current (μA)	LTE Connection	WuC/Data Transmission and Frequency (MHz)	Sensitivity (dBm)
SCM WuR [6]	3.5	8 μA	No	RF/RF, 868	-53
[7]	0.5	Not mentioned	No	RF/RF, 868	-32 $\sim$ -55
ALBA WuR [10]	0.7	Not mentioned	No	RF/RF, 868	up to -55
W2B-IoT	0.39	1.99 μA	Yes	RF/BLE, 433/2400	-37.4

with WuR to support two-tier NB-IoT connections. As a motivating example, one may consider a use case where ultra-low energy consumption IoT devices are deployed and data collection relies purely on a mobile relay that has a cellular connection. Indeed, how to connect WuR-enabled IoT devices that do not have direct cellular network connectivity remains as an open question.

In Table I, we summarize the main features of a few popular WuR implementations in comparison with our solution. From the table, our implementation is the only one that provides LTE connections to WuR-enabled IoT devices.

In this article, we present a prototype implementation of a working system, W2B-IoT, which integrates cellular IoT with WuC-enabled LPWAN via an Android smartphone functioning as a gateway/relay for non-3GPP connections. Our system has two-tiers, including an Android smartphone with an LTE connection as the first-tier and multiple WuR-enabled LPWAN devices as the second-tier. These two tiers are connected via a BLE channel for uplink data transmission and an ultra-high frequency (UHF) channel for downlink WuCs. The WuR implemented in our prototype has ultra-low power consumption below 1.3 μW and achieved transmission latency of 1 sec.

The rest of this article is organized as follows. We first provide a short introduction to WuR techniques and provide an overview of the implemented prototype that bridges WuR-enabled devices to cellular IoT. Then the design and implementation of the W2B-IoT testbed are described. Afterwards we present the test scenarios and experimental results.

II. CONNECTING WUR TO LTE/INTERNET

Evolved from a technique initially developed for energy saving in WSNs, WuR represents an emerging trend for achieving ultra-low energy consumption, long-lasting lifetime for IoT devices. The implementation of WuR has much less power consumption for LPWAN nodes as well as reduced response time. However, a WuR itself does not work alone. It is affiliated with a WSN or IoT device as an auxiliary component. The introduction of WuRx paves the way to allow both MCU and MR remain in the ultra-low power deep sleep mode and be activated on demand by means of a WuC.

To implement a WuR, one needs a wake-up transmitter (WuTx) and a WuRx. The WuTx will transmit a WuC consisting of the address of a targeted device over a given channel. The WuRx will demodulate the received signal and send an interrupt to the MCU for address validation. Once the WuC is decoded correctly, the receiving device will turn on its MR and perform data communications subsequently.

LPWAN-based IoT devices are generally unable to transmit their data uplink directly to an LTE IoT BS since they are typically operated over an unlicensed band. Nor are they equipped with a SIM card. Even though higher transmit power may be achieved, it is not beneficial considering the lifetime requirement for 5G IoT applications. In our W2B-IoT testbed, we provide a two-tier solution for connecting nano-watt WuR-enabled IoT devices via a smartphone that functions as a gateway.

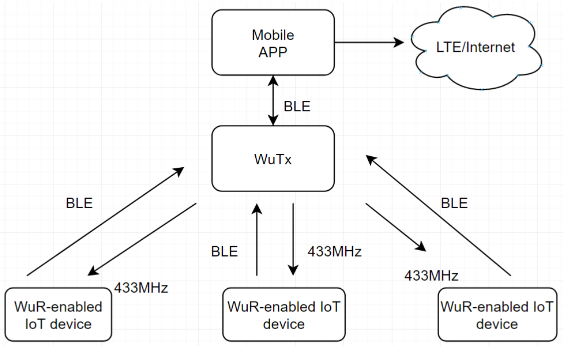


Fig. 1: Overview of the W2B-IoT testbed including two-tiers.

As shown in Figure 1, the prototype system consists of a mobile phone that is associated with a WuTx (tier-1) and multiple WuR-enabled IoT devices, each equipped with a WuRx and an MCU (tier-2). While the idle state, the WuRx and the MCU feature a combined average current consumption of only 390 nA and a response time of about 95 ms. The cellular connection to the Internet is provided by the mobile phone's LTE subscription.

To operate such a system, we have developed a mobile application (APP) on Android smartphones. If no data reporting or collection is required, the tier-2 devices are disconnected from the Internet but their WuRx is continuously listening to the channel. To collect data from a WuR-enabled IoT device, the mobile APP initiates a wake-up command to the WuTx via BLE. Then the WuTx sends a WuC to a tier-2 device at a carrier frequency of 433 MHz. The WuRx will demodulate the received WuC and its MCU will validate the wake-up signal by checking it with its WuC address. If it is the targeted receiver, the IoT device transmits the sensed data uplink via BLE to the WuTx and then the smartphone that bridges the LPWAN with cellular networks.

III. W2B-IOT TESTBED DESIGN

A. W2B-IoT System Requirements

The main goal of our prototype is to implement a working system as a WuR-enabled IoT solution connecting ultra-low energy consumption IoT devices with an IoT cloud via cellular networks. These battery-powered IoT devices have no direct 3GPP connection but they can connect to the Internet via a relay or gateway. More specifically, the system needs to meet the following requirements.

- Current consumption: The IoT devices need to consume much lower current than what is needed for a standard BLE-device, i.e., with an average current consumption level of lower than 1 μA. With the typical current consumption values, the lifetime requirement for IoT devices cannot be met by using BLE directly [11].
- Internet connection: Although the battery-powered IoT devices do not support *direct* cellular connections, they should be able to reach the Internet when needed.

- Latency: Transmission latency must be much shorter than 10 seconds, including both WuC latency and data transmission latency. The WuC latency is measured from the instant when a WuC with the address of the targeted WuRx is sent from the gateway via the WuTx until the address is correctly decoded and the BLE-protocol is up and running at the WuRx. The data transmission latency is the time used for transmitting a data packet from an IoT end device to received at the gateway.
- User interface: At the gateway, a user-friendly interface capable of initiating unicast data collection and sensor data reception should be developed.

B. W2B-IoT System Design

The W2B-IoT system consists of one gateway node with a dedicated mobile APP, one master node (WuTx) and multiple WuR-enabled IoT devices (WuRxs associated with MCUs). The master node or WuTx works as a peripheral unit of an Android smartphone that functions as the gateway to the Internet via LTE. The behavior of the WuTx is controlled by the Android smartphone through the mobile APP that decides which WuR-enabled IoT device will be woken up. To start data collection, an 8-bit WuC address sequence needs to be entered from the user interface of the APP. This sequence is sent to the WuTx over BLE. Then the WuTx generates an on-off keying (OOK) modulated signal based on the received 8-bit address from the mobile APP and transmits the wake-up signal to the targeted WuRx.

At the receiver side, the WuRx, which is always awake, will sense and demodulate the signal it received from the master node and wake up its own MCU from *deep sleep mode* to *light sleep mode* with an interrupt signal. At the light sleep mode, the MCU is able to check the received address sequence based upon the first positive clock flank of the first bit in the address sequence. If the received address sequence matches the pre-configured address of the MCU, the device will wake up and turn to the *active mode* and perform data transmission over BLE. After a packet transmission, the IoT device goes back to the deep sleep mode immediately. The WuTx will then send the data received from the WuRx to the mobile APP with a visual notification. The received data packets can be either forwarded to an IoT server, which is the Nordic UART Service (NUS) server provided by Nordic Semiconductor, instantaneously, or stored locally at the smartphone for later processing or forwarding.

Considering an indoor environment with a path loss exponent of 4, omni-directional antennas at both ends of the communication and transmit power and sensitivity values of +20 dBm and -37.4 dBm, the theoretical wake-up range is calculated at 6.3 meters. This fits well the data transmission range of BLE for indoor applications [11] and may apply to health-care and smart home scenarios. With a sensitivity level of -55 dBm as obtained in [7] or higher transmit current, e.g., 152 mA as used in [6], a much longer WuC transmission range could be achieved.

Another parameter that needs to be considered in system design is the wake-up address length. In general, there is a tradeoff between address length/node population and WuC latency. By extending the address length the system can accommodate more devices, but the WuC transmission latency will increase, and vice versa. With a 16-bit address length, the obtained WuC transmission time is 12.2 ms [6]. For the system design of W2B-IoT, we adopt an address sequence with a length of 8-bits, based on which up to 128 WuR-enabled IoT devices can be supported with distinct address sequences *by one WuTx* (to be explained in the next section). With multiple WuTxs, the number of supported WuR-enabled IoT devices in one W2B-IoT system can be greatly increased.

IV. WuR, MCU and Mobile APP Implementation

A. WuRx Hardware

As shown in Figure 2, the hardware of each WuRx consists of an impedance matching network, an envelope detector, a comparator, and a preamble detector.

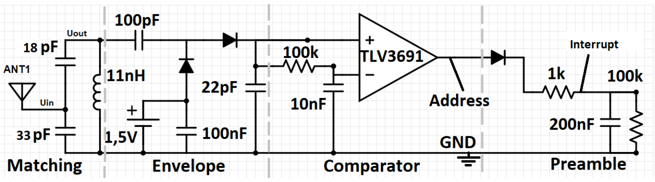


Fig. 2: Illustration of the WuRx hardware implementation in each tier-2 node.

The matching network consists of two capacitors and one inductor and is tuned to 50 Ω on the antenna input when the load is approximately 500 Ω. The bandwidth for receiving WuC signals is very narrow in order to minimize false WuCs. For the inductor and the two capacitors with very high Q values, the power on the antenna input, P_{in}, will be transferred to the peak detector, P_{out}. Since the impedance on the peak detector is higher than 50 Ω, the voltage on the peak detector, U_{out}, is higher than the voltage on the antenna input, U_{in}. Accordingly, $P_{in} = U_{in}^2/50 = P_{out} = U_{out}^2/500$, and $U_{out}^2/U_{in}^2 = 10$. Therefore, the voltage gain becomes $20\log(U_{out}/U_{in}) = 10$ dB.

The envelope detector demodulates the received OOK signal and generates pulses, which represent the '1's and '0's of the address sequence. The comparator generates pulses based on the signal received from the envelope detector so that the signal is distinguishable for the MCU (3V peak) and the address sequence can be read and verified. A nano-watt power comparator, TLV3691, which leads to a quiescent current consumption of merely 90 nA based on measurements, is implemented. As the output of the WuRx hardware, the preamble detector generates an interrupt signal to the reset pin of the MCU in order to wake it up from the deep sleep mode.

B. MCU and WuC Address Validation

The MCU associated with our implemented WuRx is an nRF52832 system-on-chip (SoC) from Nordic Semiconductor [12]. It is an ultra-low power SoC with multi-protocol support and an embedded 2.4 GHz transceiver, ideally suitable for BLE applications. nRF52832 is built around a 32-bit ARM Cortex-M4F CPU with 512 kB + 64 kB RAM. Without being

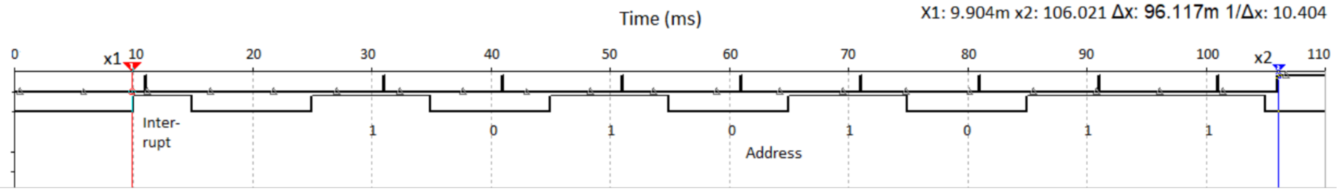


Fig. 3: Illustration of the address validation process with 8-bits.

interrupted, the MCU retains in the state of deep sleep at a current consumption level of 0.3 μA.

When nRF52832 receives an interrupt signal, it moves to the light sleep mode and initializes its *partial functions*, solely for the purpose of validating the address sequence. To prevent the MCU from waiting on an address sequence forever, a timeout timer is started when entering the light sleep mode. The SoC waits for the first positive clock flank of the address, meaning that the first bit of the address has to be '1'. Therefore only 128 devices are supported for an address length of 8 bits. This event then triggers the timer to check each bit of the received address sequence. To further save energy, the address decoding is performed in a bit-by-bit manner. In this way, much shorter delay and lower energy consumption can be achieved [13].

By default, the clock used in nRF52832 is a low frequency crystal oscillator with a startup time of 450 ms. This could represent an issue for the correct reception of WuCs since the clock needs to be initiated to validate the address sequence immediately after an interrupt signal is triggered. In our implementation, this problem is solved by replacing the default low frequency crystal oscillator clock with a low frequency clock that has a startup time of 600 μs. The latter clock provides an internal 32.768 kHz frequency clock oscillator for nRF52832, reducing the total validation time from 544.4 ms (450 ms - 600 μs + 95 ms) to 95 ms.

Figure 3 illustrates the address validation process of nRF52832 for an address sequence of 8 bits. It shows that the total start-up time of the MCU is 95 ms, where the duration needed for each bit is 10 ms. This is the achieved WuC latency for address decoding and MCU full operation, counted from the instant that the interrupt signal is triggered until the instant when the MCU enters its active state. In the active state, nRF52832 is ready for data transmission via BLE.

After the address of the targeted device is validated, the MCU initializes its software and enables the BLE component for data exchange. As illustrated in Figure 3, this step takes about 2 ms after the last bit of the address sequence is validated. Although this hardware-constrained switch time adds additional delay to the total data transmission latency, we demonstrate later through experiments that the implemented prototype satisfies the data transmission latency requirement specified for 5G IoT and NB-IoT [2][3].

C. *WuTx Hardware and Operation*

The WuTx provides the connection between the Android gateway and multiple WuR-enabled IoT devices. The implemented WuTx is built based on an nRF52 development kit [14]. It functions as both a peripheral unit to the smartphone and a central unit/master node for the covered WuRxs.

In W2B-IoT, a two-hop link between the smartphone and a WuR-enabled IoT device is implemented, one between the smartphone and the WuTx, and the other between the WuTx and the WuRxs. The WuTx has a multi-role capability operated as a slave or a master alternatively, supporting both BLE connections and WuC signal transmissions respectively. While the WuTx-smartphone connection relies purely on BLE, the WuTx-WuRx connectivity is provided at 433 MHz for downlink WuC transmission and BLE for uplink data transmission. Therefore, nRF52 needs to distinguish different types of services required for data collection.

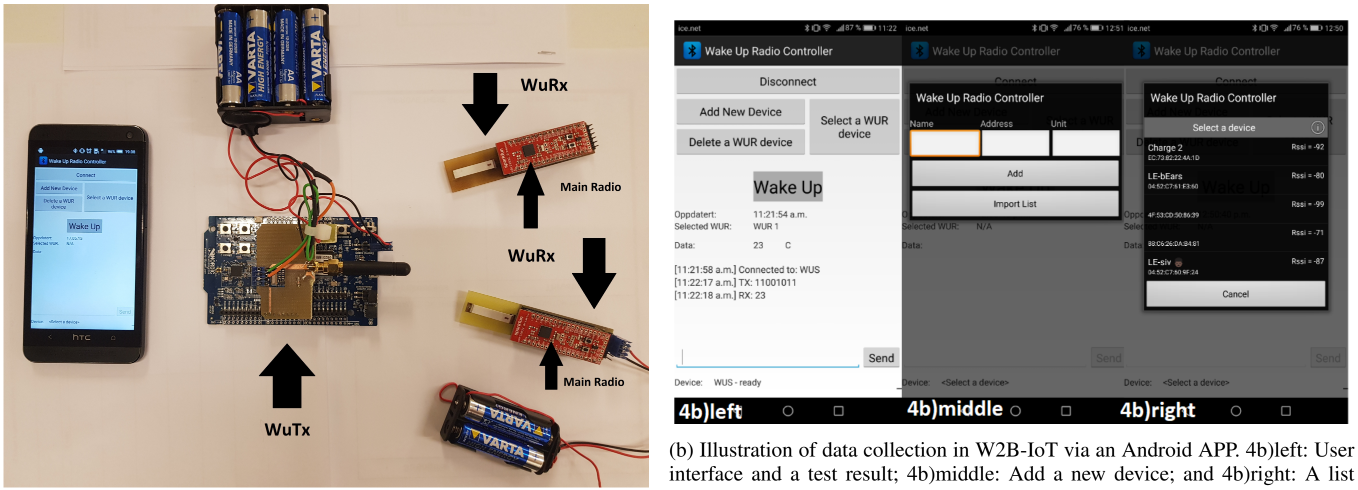
When nRF52 receives a BLE-event, it sorts out which type of BLE-event has been initiated. If it is a peripheral event, it receives the address sequence sent from the mobile APP. Once this address is received, it transmits a WuC signal with this received address. If it is a central event, meaning that an uplink data packet is being transmitted, it receives the packet and forwards it to the smartphone immediately.

D. *Mobile APP*

The mobile application implemented for the W2B-IoT gateway is an Android APP programmed in Android Studio, developed based on the nRF UART 2.0 mobile APP development kit. The Android-nRF-UART APP is used to connect BLE devices running a custom Nordic Semiconductor UART service. The APP initiates a data collection procedure by sending the wake-up address of the targeted IoT device to the WuTx. It then receives the sensor data from the WuRx via the WuTx. Inside the APP, multiple WuR-enabled IoT devices with IDs/names, address sequences, and a measurement unit can be stored.

The APP that functions as a WuR controller consists of four activities, as explained below.

- Main Activity: Used to navigate among the other activities. It is also used to represent the received sensor data from the WuR and to send the address sequence to the WuTx. The received data is decoded and represented with device ID/name, value, and time.
- Add/Delete New Devices: Used for adding, deleting, storing, and importing stored devices. This activity adds a device with its ID/name, address, and a measurement unit. It creates also a list of all stored devices.
- Select an IoT Device: This activity enables the user to select a stored WuR device, activating the APP to send the wake-up sequence to the WuTx. The targeted device is selected from the list of the IDs/names of the available WuR-enabled IoT devices.
- Connect: When multiple WuTxs exist in the proximity of the smartphone, this activity finds these BLE devices



Oppdatert: 11:21:54 a.m.
Selected WUR: WUR 1
Data: 23 C

[11:21:58 a.m.] Connected to: WUS
[11:22:17 a.m.] TX: 11001011
[11:22:18 a.m.] RX: 23

Device: WUS - ready

Selected WUR: N/A
Data:
Device: <Select a device>

Charge 2 EC:73:82:22:4A:1D Rssi = -92
LE-bEars 04:52:C7:61:E3:60 Rssi = -80
4F:53:CD:50:86:39 Rssi = -99
88:C6:26:DA:B4:81 Rssi = -71
LE-siv 04:52:C7:60:9F:24 Rssi = -87

Device: <Select a device>

(a) W2B-IoT testbed.

(b) Illustration of data collection in W2B-IoT via an Android APP. 4b)left: User interface and a test result; 4b)middle: Add a new device; and 4b)right: A list of active BLE devices in the vicinity of the WuTx.

Fig. 4: Illustration of the W2B-IoT testbed and the operation of the associated Android APP.

and selects one of them as the working WuTx from a list of WuTxs with the names, MAC-addresses, and received signal strength indicator (RSSI) values. Once a data collection procedure is finished, the APP may disconnect that WuTx.

V. PROTOTYPE ILLUSTRATION AND EXPERIMENTS

A. *Prototype Illustration and Functionality Verification*

Figure 4a) depicts the implemented prototype with one gateway, one WuTx, and two WuRxs. Based on the implemented testbed, we have performed a set of experiments to verify both the functionality of the prototype and the performance of the testbed in terms of power consumption, latency, and sensitivity.

As shown in Figure 4b)left, a WuTx with an address sequence of 11001011 is selected from a list of BLE devices and is connected, at [11:21:58 a.m.], to the Android smartphone, which has a cellular subscription. At [11:22:17 a.m.], a WuC is sent by pushing the Send button from the interface. After 1 second at [11:22:18 a.m.], the sensed data is received at the APP, reporting a temperature of 23°C. In other words, bounded by the Android refresh capability, a total latency of 1 second has been achieved. Figures 4b)middle and 4b)right illustrate, respectively, how to add a new device and the detected BLE devices around the smartphone together with their MAC addresses and RSSI values.

B. *Current Consumption Measurement*

To obtain the current consumption of a WuRx, we have measured its voltage drop over a 100 Ω resistor between Vcc of the comparator and Vcc (the voltage source). Based on our measurement result, $I = 9\,\mu V/99.86\,\Omega \approx 90$ nA, where the actual value of the resistor is 99.86 Ω. Since the comparator is the only component connected to Vcc in our WuRx implementation, the WuRx itself consumes merely 90 nA current.

As mentioned earlier, the MCU of the W2B-IoT device, nRF52832, has three modes: deep sleep, light sleep, and active with corresponding current consumption at each mode as 0.3 μA, 1.9 μA, and 4.1 mA [12], respectively. Note that the MCU remains in the deep sleep mode if no event occurs. Therefore, the total current consumption for a WuR-enabled IoT device in W2B-IoT is 0.3 μA + 90 nA = 390 nA.

C. *Energy Consumption and Lifetime Estimation*

A CR2032 coin cell battery is usually with nominal capacity of 220 mAh. A current consumption level of 390 nA implies a theoretical lifetime of 220 mAh/0.39 μA $\approx$ 64.38 years without considering data transmission, battery discharge, or circuit disintegration.

Let us consider now one data frame transmission at a time interval of T and an accompanied ACK afterwards. Denote by I_i, I_w, I_d, I_a, and T_i, T_w, T_d, T_a the currents and durations of idle, WuC, data, and ACK transmission, respectively. The total current consumption of an IoT sender during T is

$$\begin{aligned} I_T &= I_w T_w + I_d T_d + I_a T_a + I_i T_i \\ &= I_w T_w + I_d T_d + I_a T_a + I_i (T - T_w - T_d - T_a). \end{aligned} \quad (1)$$

Correspondingly, the average current consumption during T is $I_T^a = I_T/T$ (in A). Denote by C the capacity of the battery. The lifetime of this IoT device without considering discharging, LT, is estimated as $LT = C/I_T^a = CT/I_T$.

Consider two data transmission scenarios as, S1: Sporadic data transmission with $T = 2$ hours and a packet size of 200 bytes [3] and S2: Critical infrastructure monitoring with $T = 10$ seconds and a packet size of 30 bytes [13]. The estimated IoT device lifetimes are summarized in Table II. Comparing the lifetime of S1 with that of null data traffic, the results reveal that, *given the sporadic message transmission assumed in* [3], *the energy consumption for data transmission is much less significant in comparison with the idle power consumption.* As such, it is expected that WuR techniques would play an important role for massive IoT applications.

When considering a realistic battery discharging rate of 2% per year, the estimated lifetime of 62.79 or 13.93 years calculated above would become 40.27 or 12.16 years, respectively.

TABLE II: Summary of lifetime estimation under two traffic patterns. Assumptions: Battery capacity $C = 220$ mAh; data size = 200 (S1) or 30 bytes (S2); data rate = 125 kbps; WuC/data transmission and ACK reception current: 5.3 mA and 5.4 mA [12]; and battery discharging rate: 2%.

Packet arrival interval (T)	WuC and data current ($I_w = I_d$)	ACK reception current (I_a)	Idle current (I_i)	WuC duration (T_w)	Data/ACK duration (T_d/T_a)	Idle time (T_i)	Total current (I_T)	Average current (I_T^a)	Lifetime without discharging (LT)	Lifetime with discharging (LD)
S1: 7200 s	5.3 mA	5.4 mA	390 nA	95 ms	12.8/0.7 ms	7199.89 s	2879.79 μAs	0.39997 μA	62.79 years	40.27 years
S2: 10 s	5.3 mA	5.4 mA	390 nA	95 ms	1.92/0.7 ms	9.902 s	18.0286 μAs	1.80286 μA	13.93 years	12.16 years

In comparison, the lifetime for NB-IoT and 5G IoT estimated in [3][2] varies from 1.5 to 35 years under various conditions.

D. Sensitivity and Transmission Range Tradeoff

To validate the sensitivity of the implemented WuRx, we used an RF generator and a signal generator to mimic the radio signal transmitted from the WuTx. The RF-generator transmitted a carrier signal of 433 MHz with external modulation from the signal generator with a pulse signal of 50 Hz. This represents the signal transmitted from the WuTx.

The signal is directly fed onto the WuR. We have observed the output of the comparator and adjusted the signal power from the RF-generator to find the lowest possible signal that the WuR is able to interpret. By doing this, we have found the sensitivity of the WuR to be -37.4 dBm.

VI. CONCLUSIONS

In this article, we have presented a prototype implementation of a WuR-enabled IoT testbed with a two-tier end device to IoT server connection via BLE and LTE. The solution is targeted at a 5G IoT scenario where battery-powered massive IoT devices do not support direct 3GPP connections. The two-tier system is composed of an Android smartphone with a dedicated APP, a WuTx, and multiple nano-watt WuR-enabled IoT devices and has been implemented and validated. Through real-life measurements, we demonstrate that our system is able to satisfy the requirements for both lifetime (over 10 years) and data transmission latency (with a total application-layer latency level of 1 second) for providing emerging 5G IoT services.

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