

Enabling Early Sleeping and Early Data Transmission in Wake-up Radio-enabled IoT Networks

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Abstract

Wireless sensor networks (WSNs) are one of the key enabling technologies for the Internet of things (IoT). In such networks, wake-up radio (WuR) is gaining its popularity thanks to its on-demand transmission feature and overwhelming energy consumption superiority. Despite this advantage, overhearing still occurs when a wake-up receiver decodes the address of a wake-up call (WuC) which is not intended to it, causing a certain amount of extra energy waste in the network. Moreover, long latency may occur due to WuC address decoding since WuCs are transmitted at a very low data rate. In this paper, we propose two schemes, i.e., early sleeping (ES) and early data transmission (EDT), to further reduce energy consumption and latency in WuR-enabled IoT/WSNs. The ES scheme decodes and validates an address **bit-by-bit**, allowing those non-destined devices go to sleep at an earlier stage. The EDT scheme enables a sender to transmit small IoT data together with WuC packets so that the main radio does not have to be in full operation for data reception. We implement both schemes through a WuR testbed. Furthermore, we present a framework based on M/G/1 and assess the performance of the schemes through both theoretical analysis and simulations.

Keywords: **WSNs, IoT, WuR, early sleeping, early data transmission, implementation and testbed, modeling and performance evaluation.**

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1. Introduction

The 5th generation (5G) wireless network aims to facilitate various unprecedented capacities such as enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), as well as ultra-reliable low latency communications (URLLC) [2]. Furthermore, a heterogeneous network integrating 5G with the Internet of things (IoT) paves the way for massive IoT applications [3] [4]. With the inter-network connectivity 5G IoT provides to small-size, low-cost, and often battery-powered devices, a variety of applications are envisaged, ranging from mission-critical services, smart home and smart city, to industrial automation and smart farming [5][6][7]. In such massive IoT and wireless sensor network (WSN) applications, performing energy-efficient communication for battery powered IoT/WSN devices is of vital importance [8][9].

Traditionally, duty-cycled (DC) medium access control (MAC) mechanisms, which allow WSN devices sleep and wake up periodically or aperiodically, have been adopted to reduce energy consumption. However, idle listening and overhearing occur in DC-MAC mechanisms during their active periods when a node senses the channel for receiving control messages and when an unintended node overhears the transmission of other nodes respectively. In recent years, wake-up radio (WuR) has emerged as a convincing solution to replace DC-MAC for providing energy-efficient communication in IoT/WSN networks [10][11].

In a WuR-enabled IoT/WSN node, an auxiliary wake-up receiver (WuRx) is attached to the micro-controller unit (MCU) of a main radio (MR). While the MR, which is responsible for data transmission, is active only when necessary, the WuRx is always on, [waiting for](#) detecting wake-up calls (WuCs) at any time. The power consumption of a WuRx is 1000 times lower than that of the MR, i.e., the reception power of WuRx is in μW whereas it is in mW when a main radio is in full operation [10]-[16]. Upon the detection/reception of such a WuC sent by a transmitter, the destined WuRx triggers its MR to wake up from the sleep mode to perform data communication afterwards. In addition to

30 this overwhelming energy saving, another advantage of WuR is that it works in a purely asynchronous manner. Such an on-demand communication operation remarkably reduces latency in comparison with DC-based MAC operations.

WuR was initially developed for energy-efficient data collection and reporting in WSNs. Over time, the application scenarios of WuRs have been expanded
35 to diverse wireless networks including IoT, Wi-Fi, and mMTC. Despite the great superiority on energy consumption that WuR provides, overhearing is not eliminated in WuR-enabled IoT networks. Indeed, overhearing occurs when a node decodes and validates an address of a WuC which is not intended to it. Although a WuRx operates in μ W, the effect of overhearing in WuR-IoT
40 cannot be simply ignored considering the effect of energy-hungry (decoding and matching) components in WuRxs, long WuC duration, and network size. On the other hand, low latency communication is an important performance indicator in many IoT applications. Very recently, the third generation partnership project (3GPP) has started to work on standardizing early data transmissions (EDT)
45 as one of the 5G new radio techniques to further support energy-efficient and low latency communication for mMTC applications [17][18]. So far, little work can be found in the literature with respect to reducing overhearing and latency in WuR-enabled IoT considering WuC decoding and EDT. This paper makes an effort towards this direction.

50 In this paper, we propose two schemes, referred to as early sleeping (ES) and EDT respectively, tailored for eliminating overhearing and shortening latency in such networks. More specifically, ES decodes and matches the address of a WuC **bit-by-bit** so that the non-destined nodes can go to sleep at an earlier stage. EDT enables a transmitter to send IoT small data encoded with a WuC
55 so that a data transmission may be completed without fully waking up the MR. Both schemes are implemented through a WuR testbed. Furthermore, we develop a queuing model to evaluate the performance of the proposed schemes in WuR-IoT. Extensive simulations are performed to validate the accuracy of the analytical model. In brief, the main contributions of this work are as follows:

- 60 • Two energy-efficient schemes are proposed for WuR-enabled IoT, i.e., ES and EDT. While both schemes reduce the energy consumption of such a network, the latter one also minimizes the latency of data transmission.
- For proof of concept, the schemes are implemented [in a small-scale WuR testbed](#) and the functionalities of these schemes are demonstrated via the
65 testbed.
- To evaluate the performance of the ES and EDT schemes for a larger network, we present a generic framework based on an M/G/1 queuing model. The accuracy of the model is validated through discrete-event simulations.
- 70 • Analytical expressions for three performance parameters including packet delivery ratio (PDR), latency, and energy consumption are derived based on the proposed analytical framework.

The remainder of this paper is structured as follows. In [Section 2](#), we summarize the related work and highlight the qualitative differences between our
75 work and the existing ones. The network scenario and the WuR principle are presented in [Section 3](#). In [Sections 4 and 5](#), we first propose the ES and EDT schemes and then develop a generic M/G/1 queuing framework for performance evaluation of these schemes. The performance metrics are defined and derived in [Section 6](#), followed by testbed implementation and experimental validation
80 presented in [Section 7](#). The simulation results are explained in [Section 8](#), before the paper is concluded in [Section 9](#).

2. Related Work

In this section, we summarize briefly the related work relevant to this study from [four](#) perspectives, i.e, WuR prototype implementation, WuR protocol design,
85 [theoretical frameworks for WuR-enabled IoT networks](#), and early data transmission for 5G new radio. For more detailed surveys on the state-of-the-art WuR techniques, please refer to [19] [20].

2.1. *WuR Prototype Implementation*

The nanowatt wake-up radio [11] is a WuR prototype which focuses on ultra-
90 low power consumption for WuRxs, with a WuRx power consumption level
around $1 \mu\text{W}$ when listening to the channel. The prototype can operate in
different frequencies of the industrial, scientific and medical (ISM) band through
on-off keying (OOK) modulation. Its minimum sensitivity is -35 dBm and the
response time for an interrupt is $100 \mu\text{s}$. Subcarrier modulation WuR [13] is
95 another popular inband WuR circuitry design and its WuC can reach up to 100
meters. It also employs OOK modulation for sending addressable WuC with
a sensitivity level of around -53 dBm . A near-zero power WuRx design with
 -69 dBm sensitivity was proposed in [21], and it was implemented based on
an insulator complementary metal-oxide-semiconductor (CMOS) process using
100 metal-oxide-semiconductor field-effect transistor (MOSFET) devices. The wake-
up signal implemented therein is also OOK-modulated, but it is operated at
 113.5 MHz with a power consumption level of 4.5 nW . Furthermore, the authors
in [22] proposed a Bluetooth low energy (BLE)-compliant WuRx achieving a
sensitivity level of -80 dBm . It consumes power at 240 nW and maintains latency
105 at $200 \mu\text{s}$. Such ultra-low power consumption is achieved by employing a low
power bandpass filter-based frequency-shift keying (FSK) demodulator and a
correlator. Furthermore, a DC scheme and a packet structure were constructed
to maintain the tradeoff between latency and power consumption while ensuring
low false alarm rates.

110 2.2. *WuR Protocol Design*

Many WuR protocols have been proposed to show the benefits of WuR over
traditional DC-MAC based WSNs or to improve the performance of existing
WuR schemes. SCM-WuR [10] is a WuR scheme which relies on a single chan-
nel for WuC and data packet transmissions. No acknowledgment (ACK) is sent
115 after the successful delivery of a WuC but it is needed when a data packet
is received. The performance of SCM-WuR was evaluated using simulations,

showing its superior performance over DC-MAC protocols. Another energy-aware cross-layer scheme is OPWUM [14] which opportunistically selects the best relay nodes for forwarding packets based on neighbors' energy. Moreover, ALBA-WuR [15] employs semantic addressing for relay selection, providing a geographic cross-layer solution for WuR-enabled WSNs. Considering that multiple wake-up transmitters (WuTxs) may send WuCs at the same time, a backoff-enabled WuR scheme, BoWuR, was proposed in our earlier work in order to reduce collision probability for transmitter-initiated (TI) data reporting [23]. For receiver-initiated (RI) data collection, a multiple packet transmission MAC scheme has been proposed which reserves the channel for a node to send multiple packets consecutively [24]. Furthermore, the authors of [25] proposed to adopt a short local address to reduce the latency of WuC transmission. Their addressing scheme utilized partial functions of MCU to decode and match a full address. Improved performance over the correlator-based address decoding approach is shown therein. As part of this study, we proposed in [1] a bit-by-bit WuC address decoding scheme which is known as ES in this paper.

2.3. Theoretical Frameworks for WuR-enabled IoT

Although a number of theoretical frameworks for modeling IoT or massive IoT applications exist, e.g., [4], there are few frameworks which deal with WuR-enabled IoT networks. Among them, an analytical model which is based on an absorbing Markov chain was presented in [27] to assess the performance of WuR-enabled IoT networks. In [23], the performance of the BoWuR protocol was analyzed using a discrete time Markov chain for a single hop SCM-WuR enabled IoT network under saturated traffic conditions. Based on duty-cycled received-initiated WuR IoT networks, an analytical model was developed in [24] to evaluate the performance of aggregated packet transmissions. However, none of these frameworks considered an ES or/and EDT scheme for their performance evaluation.

145

Table 1: A comparative analysis of our schemes with the recent state-of-the-art WuR schemes

Considerations/Features	[10]	[15]	[16]	[27]	[25]	[23]	[24]	ES[1]	EDT
Collision probability	No	No	No	No	Yes	Yes	Yes	Yes	Yes
Testbed implementation	Yes	Yes	No	Yes	No	No	No	Yes	Yes
Theoretical analysis	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Discrete-event simulations	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes
Overhearing	No	Yes	Yes						
Address scheme for WuR	No	No	No	No	Yes	No	No	Yes	Yes

2.4. EDT for 5G New Radio

To enhance the capability of LTE towards 5G new radio, 3GPP is currently investigating EDT techniques for the purpose of further reducing power consumption and latency for mMTC in cellular networks [17][18]. More specifically, EDT applies to both uplink and downlink data transmission and it is performed during the random access procedure (after the physical random access channel (PRACH) transmission and before the radio resource control (RRC) connection setup is completed). With EDT, a small amount of data exchange can be achieved during the random access procedure *before* the data link is formally established.

However, none of the aforementioned WuR prototypes and protocols considered eliminating overhearing for WuC transmissions. In Table 1, we make a qualitative comparison of our schemes with a few state-of-the-art WuR protocols. To the best of our knowledge, this work is first effort which applies EDT to WuR-enabled IoT networks.

3. Network Topology and WuR Principle

In this section, we illustrate the network scenario as well as the design and operating principle of WuR.

3.1. Network Scenario and Assumptions

Consider a WuR-enabled IoT/WSN consisting of N number of nodes as shown in Fig. 1. All IoT/WSN devices are integrated with a WuR and can communicate with each other over a single-hop in a full mesh topology. Packet

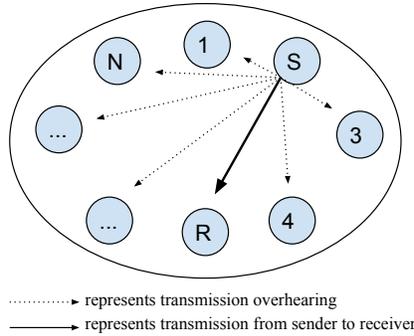


Figure 1: A single-hop WuR-IoT/WSN with N contending nodes where S and R stand for the sender and the receiver, and the solid and dashed arrows represent intended transmission and other nodes' overhearing, respectively.

arrivals follow a Poisson process with rate λ for each device. Assume further that the channel is error-free and no packet loss occurs due to buffer overflow. However, packet loss occurs due to collisions.

3.2. Operating Principle of WuR

In a WuR based IoT/WSN, a WuRx is embedded with the sensor node for awakening up the MCU of its MR in an on-demand manner. A data communication cycle in a WuR network starts with a WuC and ends with an ACK after the data packet is correctly received. WuR can operate either in the receiver-initiated or transmitter-initiated mode. While RI-WuR is suitable for data collection, TI-WuR fits better for event-triggered data reporting. In what

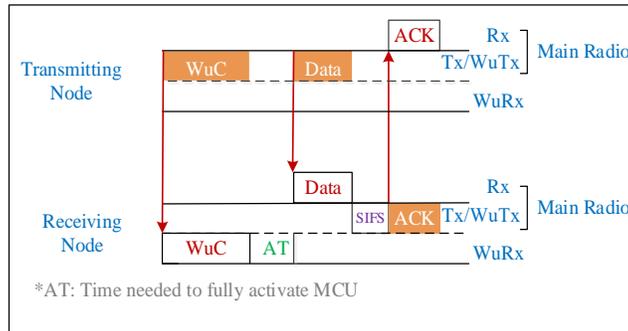


Figure 2: Illustration of a data transmission cycle of WuR.

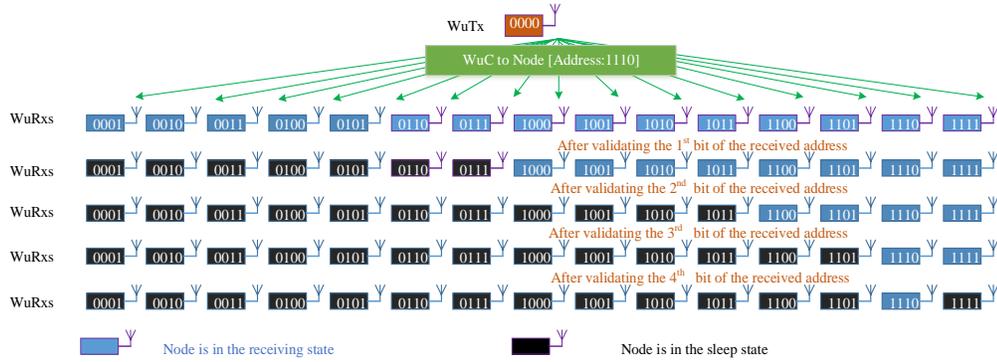


Figure 3: Operation of ES with a network which consists of 16 nodes and uses a 4-bit address.

follows, we focus on TI-WuR for performance evaluation of WuR-IoT. In TI-WuR, a node sends a WuC to the intended node once it has a packet to transmit. After receiving the WuC, the intended node turns on its main radio for data communication unless EDT without ACK, which will be presented in the next section, is employed. When both MRs are active, data communication is performed. A transmission cycle finishes with an ACK from the targeted receiver. It is worth mentioning that no ACK is necessary to acknowledge the successful delivery of a WuC transmission to avoid frequent switching of radio operation mode [10] [23]. The working principle of TI-WuR is shown in Fig. 2.

4. Enabling ES and EDT for WuR

In this section, we propose ES and EDT tailored for WuR-enabled IoT/WSNs and explain their working principles.

4.1. Early Sleeping for WuC Decoding

Typically a WuRx needs to decode the full address of a WuC before it decides whether to wake its MR up or not [25]. This procedure is referred to as full address decoding (FAD), which is a typical scheme for WuC address decoding. In this paper, we propose to decode an address bit-by-bit in order to improve the performance of FAD.

More specifically, the ES scheme defines an address decoding and validating rule that is able to diminish WuC overhearing energy cost for unintended WuRxs. It uses *partial MCU functions* to decode and validate the address. Different from FAD, ES allows a node to decode and match the received address **bit-by-bit** instead of decoding and validating a complete address after all bits are received. That means, the MCU decodes the first bit of the received address sequence and matches it with its corresponding address bit. If the first bit of the received address matches, then it will decode and validate the next bit. For an intended receiver, this process will continue until the whole address matches with its own address. For a non-intended receiver, whenever a bit of the received address mismatches with its own, the node stops the decoding and matching process and goes to sleep immediately. In this way, ES reduces energy consumption in a network by letting overhearing nodes sleep at an earlier stage before the whole WuC decoding procedure is complete.

As an example, consider a network cluster consisting of 16 nodes and let us use a 4-bit local address for illustration. All nodes in this cluster hear each other. Assume now that a sender (address: “0000”) transmits a WuC to wake up a targeted node (address: “1110”) for performing data communication. All unintended nodes overhear the WuC transmission. If ES is employed, 7 nodes with addresses “0XXX” will go to sleep right after decoding and validating the first bit. The remaining 8 nodes will decode the second bit. Among these 8 nodes, 4 nodes with addresses “10XX” will go to sleep right after decoding the second bit. This process will continue as more overhearing nodes go to sleep, thus reducing energy consumption for the whole network. In the end, only the intended node will wake up after decoding and validating all 4 bits. The hierarchical structure of the address decoding and matching stage of ES is illustrated in Fig. 3. Clearly, the number of sleeping nodes in a WuR with ES will be increased in comparison with WuR with FAD.

4.2. Early Data Transmission Together with WuC

225 In this subsection, we propose an early data transmission scheme which is tailored to WuR-enabled IoT/WSNs. The scheme is still referred to as EDT. The proposed EDT scheme defines a data transmission procedure in which a small-size data packet is jointly encoded with the WuRx address and transmitted through a WuC *before the MR is fully waken up*. That is, a WuR transmitter 230 performs data transmission simultaneously while sending a WuC with the support of *partial operation*¹ of the main radio of an intended node. Such a scheme reduces the latency it takes to transmit small data and improves the energy efficiency of WuRxs. Depending on whether an ACK upon the successful reception of a small data is needed or not, EDT can be operated in one of the following 235 two modes.

4.2.1. EDT with ACK

In this mode, the to-be-transmitted small data is encoded via an error-detecting code, e.g., cyclic redundancy check (CRC), at the transmitter side. The checksum for a given polynomial of CRC is appended to the small data. 240 After that, the appended data will be encoded with the intended WuRx address. Then the output bits of the XOR operation will be transmitted as the WuC frame. After receiving a WuC, the MCU of the MR performs partial functions to decode and validate the received the WuC.

More specifically, a reverse operation will be performed at the receiver side. 245 That is, the receiver will perform the XOR operation between its address and the received packet. The output bits of the XOR operation will be divided by the same polynomial used at the transmitter. If the result of this division is zero, then the WuRx will issue an interrupt to fully wake up the MR to the active mode for sending an ACK after each successful data transmission. If the

¹The hardware of the MR used in our implementation is nRF52832. It has three modes: deep sleep, light sleep, and active with corresponding current consumption at each mode as 0.3 μ A, 1.9 μ A, and 4.1 mA respectively (refer to Footnote 4). In the light sleep mode, the MCU is able to perform partial functions for WuC decoding.

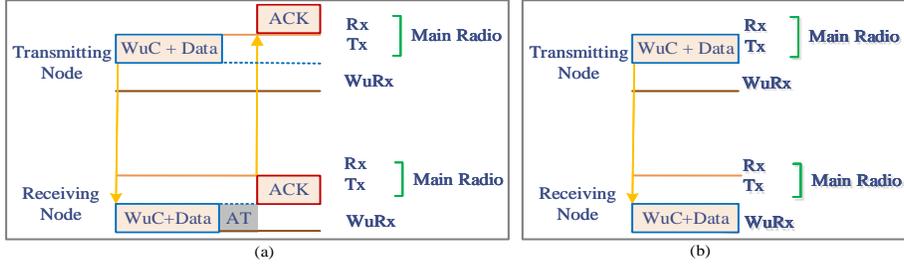


Figure 4: The data transmission cycle of EDT: (a) with and (b) without ACK.

250 result of the division is not equal to zero, it will treat the WuC as overhearing and the MCU will go to the deep sleep mode as soon as the decoding process is finished. The data transmission cycle of EDT with ACK is illustrated in Fig. 4(a) and its workflow chart is shown in Fig. 5 respectively.

As an example, consider a TI-WuR scenario where a sender intends to send a
 255 small data, e.g., humidity 53% (data “110101”) to an intended receiver (WuRx address “11111100”). For a given polynomial, $g(x) = x^2 + 1$ (101), the data packet with CRC will be “11010111”. Then, the CRC appended data packet will be encoded with the wake-up receiver address “11111100” using the XOR operation. The output bits of XOR, i.e., “00101011”, will be transmitted as an
 260 encoded WuC. At the receiver side, a reverse operation will be performed to extract the actual data message. That is, the intended receiver will perform XOR operation between its address “11111100” and the received WuC “00101011”. The output of this operation, “11010111”, will be checked with the same CRC polynomial using division. If the remainder is zero, the intended node removes
 265 the CRC bits to extract the actual data. The detailed procedures for this data encoding and decoding process at the transmitter and the receiver are presented in Fig. 6 respectively.

4.2.2. EDT without ACK

From the design principle of EDT with ACK, it is clear that EDT with ACK
 270 is well suited for IoT/WSN applications where ACK for a successful data reception is required. However, ACK might not always be beneficial if retransmission

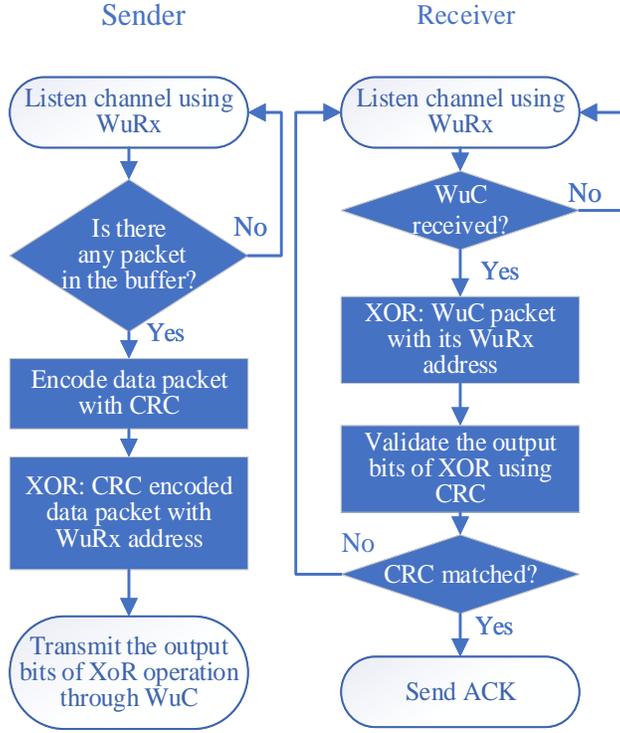


Figure 5: Operations of EDT with ACK at the transmitter and the receiver.

is not necessary in a network. Accordingly, we propose another variant of the EDT scheme, i.e., EDT without ACK, which disables ACK. In this case, no ACK is transmitted from the MR of the intended receiver back to the sender upon a successful data reception. As both data and ACK transmissions are performed when the MR is operated in the active mode, EDT without ACK further decreases latency and reduces power consumption since such a small data exchange cycle is accomplished without fully waking up the MR, as shown in Fig. 4(b).

Furthermore, both versions of EDT can be used to transmit a data packet based on a given WuC address length. In our prototype implementation to be presented in Section 7, we have designed the WuC address length as 16 bits, allocating 10 bits to represent data values. However, a shorter or longer address

Transmitter	Receiver
<p>Step 1. Encode data with CRC Data : 1 1 0 1 0 1, CRC polynomial:1 0 1 1 1 0 1 0 1 0 0 ÷ 1 0 1 Quotient:1 1 1 0 1, Remainder: 1 1 Message with CRC: 1 1 0 1 0 1 1 1</p> <p>Step 2. Message with CRC XOR WuRx address 1 1 0 1 0 1 1 1 XOR 1 1 1 1 1 1 0 0 Output: 0 0 1 0 1 0 1 1</p> <p>Step 3. Transmit output bits as WuC</p>	<p>Step 1. WuC packet XOR WuRx address 0 0 1 0 1 0 1 1 XOR 1 1 1 1 1 1 0 0 Output: 1 1 0 1 0 1 1 1</p> <p>Step 2. Check message for CRC error Data : 1 1 0 1 0 1 1 1, CRC polynomial:1 0 1 1 1 0 1 0 1 1 1 ÷ 1 0 1 Quotient:1 1 1 0 1, Remainder: 0 0 No error. Wake-up the MR</p> <p>Step 3. Send an ACK message</p>

Figure 6: Illustration of EDT with ACK: An example.

may apply. With a shorter WuC address, one value could represent a larger
285 range for the parameter of interest.

5. Modeling Data Transmission in WuR

In this section, we present a generic framework in order to model data trans-
mission in WuR-enabled IoT/WSNs with ES and/or EDT capability. This
framework is based on the analysis of a regenerative cycle of M/G/1 and it
290 applies to both ES and EDT based data transmissions². The notations used in
our analysis are summarized in Table 2.

In most of the existing unslotted carrier sense multiple access with collision
avoidance (CSMA-CA) based models, e.g., [29], a state transition is based on the
approximation of mini-slot/symbol duration. However, due to the on-demand
295 nature of data transmission in WuR-enabled IoT/WSNs, a node can wake up
(a sleep-to-active state transition) at any instant of time whenever it generates
a packet. In other words, a state transition in a WuR operation does not
necessarily occur at the mini-slot boundary. Moreover, the standard analytical
framework of ALOHA-alike schemes does not consider the buffer size of the

²The same model applies to both ES and EDT since the number of transmitting nodes is irrelevant to whether the address is decoded bit-by-bit (by ES) or as a whole (by FAD), or the WuC is encoded with small data (by EDT) or not.

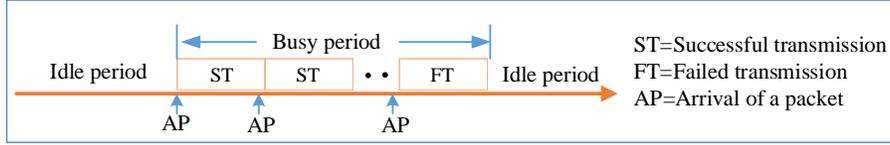


Figure 7: Illustration of a regenerative cycle.

300 nodes and assumes that the number of nodes in the network is very large ($n \rightarrow \infty$). Herein we develop a model based on M/G/1 which considers *small buffer size, limited number of nodes, and does not dependent on the assumption that state transitions occur only at mini-slot boundaries.*

In a WuR-enabled IoT/WSN, a node sends a WuC to the intended WuRx
 305 whenever it generates a data packet. A collision occurs when the transmissions of two or multiple nodes overlap with each other. Collisions cannot be avoided since no collision avoidance is adopted before sending a WuC.

Denote by P_c the probability of occurring a collision. A successful transmission of a device prevails when none of the other ($N - 1$) devices starts a busy
 310 period during the vulnerable period of the device. The busy period is defined as the period in which a device is continuously busy [30]. All packets arrived in a busy period will be served (successfully or unsuccessfully) in that busy period itself. The interval between two busy periods is an idle period. The regenerative cycle in our model is shown in Fig. 7.

315 A regenerative cycle consists of a busy and an idle period. For analysis simplicity, we consider that all busy periods have a constant duration which is equal to its mean value, T_B . For a given λ , this assumption is reasonable since no retransmission is allowed, the size of IoT small data packets (e.g., temperature, humidity, etc.) is identical (e.g., 2 bytes), and the duration of a successful
 320 transmission, T_{ST} , as well as that of an unsuccessful transmission, T_{FT} , have the same length. Even though T_{ST} and T_{FT} are scheme dependent, for a given scheme, i.e., ES or EDT, we have $T_{ST} \approx T_{FT}$ since the ACKtimeout duration, $T_{ack}^{out} \approx T_{SIFS} + T_{ack}$ where T_{ack} and T_{SIFS} are the duration of ACK and short inter-frame space (SIFS) respectively, is needed for identifying an unsuccessful

Table 2: Major Notations Used in the Analysis

Notation	Description
N	Number of nodes in the network/network cluster
λ	Packet arrival rate to a node
$E[\Gamma]$	Expected number of packets served in a busy period
P_s	Successful packet transmission probability
P_c	Collision probability
b_0	Probability that no packet arrives during the time a packet is at the head of the line
T_{FT}	Duration of an unsuccessful transmission
T_{ST}	Duration of a successful transmission
$E[T_B]$	Mean duration of a busy period

325 transmission whereas a successful transmission is confirmed when an ACK is received³. With this simplification, $E[T_B]$ is obtained as

$$E[T_B] = T_{ST}E[\Gamma], \quad (1)$$

where Γ is the number of packets served in a busy period of the M/G/1 queuing system with traffic intensity $\alpha = \lambda T_S$. $E[\Gamma]$ can be computed as

$$E[\Gamma] = \frac{1}{1 - \alpha}. \quad (2)$$

Thus, P_c can be approximated as

$$P_c \approx 1 - \left[e^{-\frac{\lambda}{E[\Gamma]}(E[T_B] + T_{ST})} \right]^{N-1}. \quad (3)$$

By inserting the value of $E[\Gamma]$, $E[T_B]$ for a given λ , the value of P_c can be
330 obtained.

6. Performance Metrics

In this section, we define three metrics for performance evaluation, i.e., packet delivery ratio, latency, and energy consumption and derive their expressions.

³Note that $T_{ack}^{out} = 0$ for EDT without ACK.

335 *6.1. Packet Delivery Ratio*

Denote by P_s the PDR. It is defined as the ratio between the number of successful transmissions and the total number of transmission attempts during a regenerative cycle. Since there exists only one reason for packet loss in this study, i.e., packet loss due to collisions, P_s can be computed from (3) as follows

$$P_s = (1 - P_c). \quad (4)$$

6.2. Latency

The average latency of a successfully delivered packet, denoted by T_d , is defined as the duration from the time instant that a packet arrives at the transmission queue of the data generation node until the moment the packet is successfully transmitted to the intended node. Since no retransmission is allowed, T_d for an unsuccessful transmission is almost the same and it is obtained by

$$T_d = T_{ST} \approx T_{FT} \quad (5)$$

where T_{ST} and T_{FT} are the duration of a successful transmission and a failed transmission respectively.

Furthermore, the obtained value of T_d depends on the scheme employed in the network. For ES, $T_{ST} = T_{wuc} + T_{AT} + T_{data} + 2T_{SIFS} + T_{ack}$ where T_{wuc} , T_{AT} , and T_{data} are the duration for WuC transmission, fully active MCU, and data transmission respectively. Since no separate transmission is required for sending data, the duration of a successful transmission for EDT with ACK or without ACK is $T_{ST} = T_{wuc} + T_{AT} + 2T_{SIFS} + T_{ack}$ or $T_{ST} = T_{wuc} + T_{SIFS}$ respectively.

345 *6.3. Energy Consumption*

Denote by E the energy consumption for the whole network consisting of one transmitting node, one destined node and $(N - 2)$ unintended nodes. We have

$$E = E_T + E_R, \quad (6)$$

where E_T is the energy consumption of the sending node for a packet transmission (successful/unsuccessful). It is given by

$$E_T = P_c E_c^T + P_s E_{Tx}, \quad (7)$$

where E_c^T and E_{Tx} are the energy consumed by the sender for a successful and unsuccessful packet respectively. E_R is the total reception energy consumed by the nodes in the network with N nodes for one packet transmission. It includes the energy consumed by the destined node for receiving a packet and the energy consumed by the other $(N - 2)$ unintended, i.e., overhearing nodes. E_R is given by

$$E_R = P_c E_c^R + P_s E_{Rx}, \quad (8)$$

where E_c^R represents the total reception energy consumed by a network for an unsuccessful transmission. Assuming that collisions happen due to the simultaneous transmissions of two nodes, then E_c^R can be estimated as $E_c^R = (N - 2)E_{\text{idle}}$. E_{idle} is the energy consumed by a node when it is actively monitoring the channel using WuRx. For a collided packet, a node (intended or unintended receiver) consumes the same energy as needed for idle listening since it cannot detect and decode the packet. The total reception energy consumed by the network for a successful packet, E_{Rx} , can be calculated as

$$E_{Rx} = E_{IN} + E_{UN}, \quad (9)$$

where E_{IN} and E_{UN} are the energy consumption of the destined node and the unintended nodes respectively. Lastly, the average reception energy consumed by a node for a packet transmission, denoted by E_R^{avg} , is obtained as

$$E_R^{avg} = \frac{E_R}{N - 1}. \quad (10)$$

Furthermore, the duration of a successful or an unsuccessful transmission will be scheme dependent since ES and EDT adopt different address decoding

rules. Thus, E_c^T , E_{Tx} , E_{IN} , and E_{UN} need to be calculated specifically for each scheme. For the ES scheme, we have

$$E_c^T = E_{wuc}^T + E_{AT} + E_{data}^T + E_{SIFS} + E_{ack}^{tout},$$

$$E_{Tx} = E_{wuc}^T + E_{AT} + E_{data}^T + 2E_{SIFS} + E_{ack}^R,$$

where E_{wuc}^T , E_{AT} , E_{data}^T , E_{SIFS} , E_{ack}^R , and E_{ack}^{tout} are the energy consumption for WuC transmission, fully activated MCU, data packet transmission, SIFS, ACK reception, and ACK timeout respectively. E_{IN} can be obtained as $E_{IN} = E_{wuc}^R + E_{AT} + E_{data}^R + E_{SIFS} + E_{ack}^T$ where E_{wuc}^R , E_{data}^R , and E_{ack}^T are the energy consumption respectively for WuC reception, data packet reception, and ACK transmission. With an assumption that N is exponential to the power of 2, E_{UN} for ES can be approximated as

$$E_{UN} \approx \sum_{i=1}^B i E_{vwuc}^R \lceil \frac{N-2}{2^i} \rceil + (N-2) E_{prm}^R, \quad (11)$$

$$E_{vwuc}^R = P_{wuc}^R T_b, \quad (12)$$

where P_{wuc}^R , T_b , E_{prm}^R , and B represent the reception power of WuC, the time
 355 needed to decode and validate 1 bit of an address, the energy needed for preamble detection and partially switching on MCU, and the total number of bits in the received address, respectively.

In EDT, no separate transmission is required for sending a small data packet.

Thus, E_c^T , E_{Tx} , and E_{IN} for EDT with ACK can be obtained as

$$E_c^T = E_{wuc}^T + E_{AT} + E_{SIFS} + E_{ack}^{tout},$$

$$E_{Tx} = E_{wuc}^T + E_{AT} + 2E_{SIFS} + E_{ack}^R,$$

$$E_{IN} = E_{wuc}^R + E_{AT} + E_{SIFS} + E_{ack}^T.$$

Furthermore, since no ACK is required for EDT without ACK, E_c^T , E_{Tx} , and E_{IN} are obtained as follows

$$E_c^T = E_{wuc}^T + E_{SIFS},$$

$$E_{Tx} = E_{wuc}^T + E_{SIFS},$$

$$E_{IN} = E_{wuc}^R.$$

Lastly, E_{UN} is the same for both EDT with and without ACK and it is given by

$$E_{UN} = (N - 2)(BE_{vwuc}^R + E_{prm}^R). \quad (13)$$

360 7. Testbed Implementation and Validation

In this section, we first give a brief overview regarding the prototype implementation of our WuR testbed and then present the experiments which validate the functionalities of the ES and EDT schemes.

7.1. Implementation Overview

365 Based on the principles presented above, we have implemented a small-scale WuR-enabled IoT/WSN testbed which supports both ES and EDT. As shown in Fig. 8, each IoT/WSN device is composed of two components, a self-designed circuit as the WuRx and a main radio built based on an nRF52832 system-on-chip (SoC) from Nordic Semiconductor⁴. nRF52832 is an ultra-low power SoC
 370 supporting multi-protocols especially suitable for BLE applications. It is built based on a 32-bit ARM Cortex-M4F CPU with a 512 kB + 64 kB RAM and an embedded 2.4 GHz transceiver. Without being interrupted, the MCU retains in the deep sleep mode consuming merely 0.3 μ A current.

As illustrated in Fig. 9, the WuRx consists of four blocks: a matching
 375 network, an envelope detector, a comparator, and a preamble detector. The

⁴Nordic Semiconductor, nRF52832 data sheet, [Online]. Available: http://infocenter.nordicsemi.com/pdf/nRF52832_PS_v1.3.pdf.

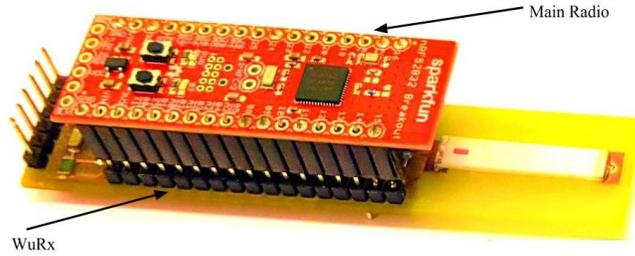
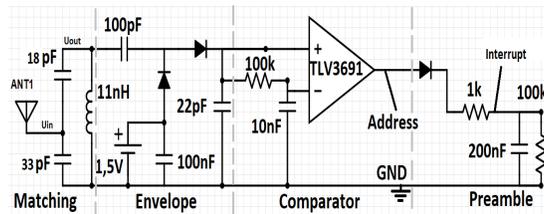
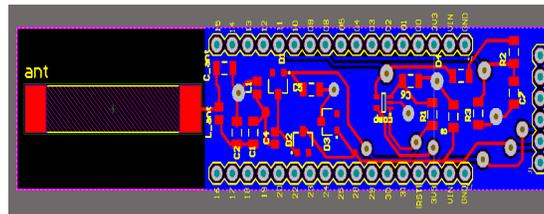


Figure 8: A prototype WuR device which consists of a WuRx and an MR.



(a) Schematic diagram



(b) PCB implementation

Figure 9: Illustration of the implemented WuRx: Schematic and PCB.

matching network provides impedance matching to the envelope detector. The envelope detector demodulates the received OOK signal and generates pulses which represent the ‘1’s and ‘0’s of the address sequence. Then, the comparator generates pulses based on the signal from the envelope detector so that it is readable by the MCU. The preamble detector provides an interrupt signal to the reset pin of the MCU to wake it up from the *deep sleep* mode to the *light sleep* mode (with $1.9 \mu\text{A}$ current consumption) under which the MCU can decode and validate the received address. When all bits of a received address match with its own, it activates the MCU fully to the *active* mode to perform data communication over BLE. Otherwise, it goes to deep sleep but continues

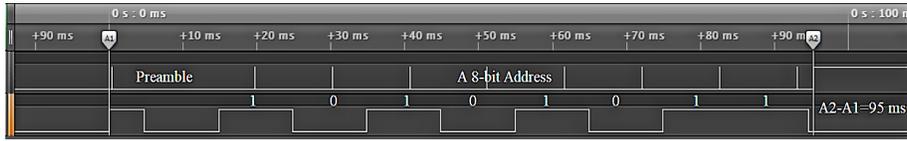


Figure 10: A WuC duration with 8-bit address in the Saleae logic analyzer.

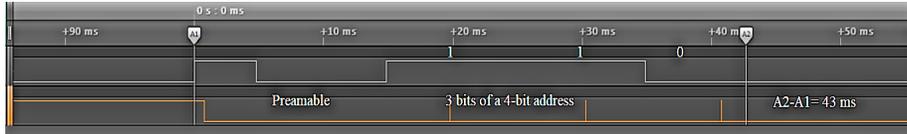


Figure 11: Time needed to decode and validate 3 bits of a 4-bit address.

listening to the channel. For address decoding, both the FAD and ES schemes are implemented in our testbed.

The WuRx implemented in our prototype consumes merely 90 nA current and it is always active, listening to the channel continuously. Since the current consumption at the deep sleep mode of the MCU is 0.3 μA , the current consumption level is 0.39 μA when no event happens. To decode an address, the current consumption is 1.909 μA when the MCU is operated at the light sleep mode. For data transmission when the MR is active, it is performed over BLE at a much higher data rate than the one used for WuC transmissions, at a current consumption level of 4.1 mA.

7.2. Experimental Validation of the ES Functionality

Based on the developed WuR prototype, we have performed various experiments to measure the duration of a WuC address decoding procedure for both FAD and ES. In both cases, whenever a WuRx detects a WuC signal, it starts to process it. As soon as the preamble detector detects a preamble, it provides an interrupt signal to the MCU to initialize a low frequency clock and general-purpose input/output so that address decoding can start, with the MCU in partial operation.

We have measured the duration to decode and validate one bit of a received WuC address and find out that it is 10 ms. As shown in Fig. 10, a WuC duration with an 8-bit address for FAD is measured using a Saleae logic analyzer. The

whole procedure lasts for 95 ms including preamble 13 ms, $8 \times 10 = 80$ ms for decoding and matching, and 2 ms to switch on the MCU to the active mode.

When ES is employed, the procedure is somewhat different. After a WuRx
410 observes the first clock flank of the address, it starts immediately the timeout
timer to check each bit of the received address in order to prevent the MCU
from acquiring for a complete sequence of the address. It fully activates the
MCU only if the received address matches completely with its own. Whenever
a bit of the received address mismatches, the WuR goes to the deep sleep mode
415 instantly. Continue the example shown in Fig. 3 where a 4-bit address is used.
It would take 55 ms to decode this address if FAD is used. Fig. 11 reveals that
the duration for a WuRx stops processing a WuC address after decoding and
validating the first three bits of a 4-bit address. It is observed that the WuRx
needs 43 ms (between A2 and A1) before it goes to sleep after decoding and
420 validating the first three bits of a 4-bit WuC address “1110” since the fourth
bit mismatches with its own.

7.3. Experimental Validation of the EDT Functionality

Based on the same prototype, experiments to validate the functionality of
EDT are also carried out. For EDT, a WuRx follows a similar procedure as
425 needed for FAD for WuC address decoding and data processing. After demod-
ulating the WuC packet, the XOR operation is performed between WuRx’s
address and the received packet. The output bits of XOR will be treated by
the CRC polynomial for error check. In case of EDT with ACK, the WuRx will
trigger the MR to wake it up from *light sleep* to *active* for sending an ACK upon
430 each successful data reception. When EDT without ACK is employed, however,
the WuRx will not trigger the MR for ACK transmission. It is worth mention-
ing that the measured duration to decode and validate one bit of a received
WuC packet in EDT is also 10 ms, indicating that EDT does not add any extra
latency for data processing. Instead, shorter latency can be achieved since no
435 data transmission is performed by the MR, in addition to energy saving.



Figure 12: A screenshot for EDT data sniffing for EDT without ACK.

Based on the nRF UART 2.0 mobile APP development kit ⁵, we have developed an Android APP programmed in Android Studio. Fig. 12 illustrates a screenshot for data sniffing of an EDT experiment when EDT without ACK was employed. In this example, a pair of WuR devices exchanged data and the developed APP is used as a sniffer to capture data transmission and reception. As mentioned earlier, the receiving node uses its WuRx and MCU in the light sleep mode for data reception but the MR is not fully activated. The address of the WuRx has 16 bits and the CRC polynomial is 101. For a data packet

⁵Nordic Semiconductor UART APP source code, [Online]. Available: <https://github.com/NordicSemiconductor/Android-nRF-UART>.

which has also 16 bits after CRC, we use 3 bits to represent up to 8 different
445 data types and 10 bits to represent data values.

For example, data types 000, 001, and 010 represent temperature, humidity,
and light intensity respectively. To report a temperature of 24 degrees Celsius,
i.e., binary ‘0000011000’, data type 000 will be appended. Then the data packet
will be ‘0000000011000’ before CRC. Assume that the address of the WuRx is
450 configured as ‘1010101110101011’. After the CRC and XOR operations, the to-
be-transmitted WuC packet will be ‘1010101111001000’. At the receiver side,
the WuRx performs reverse operation and extract the temperature value, as
shown on the second and third lines of the screenshot. In a similar way, other
parameters like humidity and light intensity can also be extracted from the
455 received WuC packet which is encoded with data and the WuRx address.

8. Numerical Results and Discussion

In this section, we first validate the theoretical framework by comparing the
analytical results with the simulation results, and then evaluate the performance
of the proposed schemes with respect to the defined metrics.

460 8.1. Simulation Configurations and Theoretical Framework Verification

Consider a WuR-enabled IoT network as presented in Fig. 1. To verify
the preciseness of the theoretical framework, we perform extensive computer
simulations based on this network with the following parameter configurations.
The numbers of devices is configured as $N = 32$ and the packet arrival rate
465 varies in the range of $\lambda \in \{0.1, 0.2, \dots, 0.5\}$ packet/s. The remaining parameters
are configured based on Table 3 unless otherwise stated.

To perform simulations, we constructed a custom-built discrete-event simu-
lator in MATLAB which is similar to the one we built in our early work [26].
The developed simulator mimics the behavior of the studied WuR-IoT with the
470 ES or EDT capabilities implemented respectively. That is, a node wakes up as
soon as a packet arrives in the queue and maintains a timestamp to track the

time duration of every single state. The sending node works in an on-demand manner, like in ALOHA, for sending its WuCs. Upon receiving a WuC, the targeted node decodes the WuC and switches on its MR for data communication (for FAD, ES, and EDT with ACK), or keeps its MR in the light sleep mode (for EDT without ACK) for small data transmission. On the other hand, the unintended nodes go to sleep earlier according to the ES principle described earlier.

When comparing FAD with ES in a network with 32 devices, we denote FAD and ES as FAD-5 and ES-5 respectively as a 5-bit address length would be sufficient. Since a 16-bit address is designed in our EDT implementation, these two schemes are denoted as FAD-16 and ES-16 respectively when comparing FAD/ES with EDT. Note however that in our simulations the number of devices in the network is always configured as 32 regardless of the adopted address length.

The analytical results which were obtained based on the M/G/1 model and the simulation results that were obtained from simulations are presented jointly in Figs. 13–19. In these figures, “analytical” and “simulation” represent the analytical and simulation results respectively. Furthermore, it is worth mentioning that *the obtained results from simulations are independent of the ones obtained from analytical expressions*. From Figs. 13–19, it is evident that the analytical and simulation results coincide with each other. Thus, the accuracy of the analytical model is verified.

8.2. Metric-based Performance Evaluation

In this subsection, we first evaluate the performance of the proposed schemes with respect to three parameters, e.g., packet delivery ratio, average latency, and energy consumption, and then estimate node lifetime.

8.2.1. Packet Delivery Ratio

Fig. 13 depicts the obtained PDR for FAD and ES as traffic load λ varies, for a network with 32 devices. As expected, a WuR-IoT network with both

Table 3: Parameter Configuration for Performance Evaluation [1] and Footnote 4

Radio type	Parameter	Value	Unit
Common	Supply voltage	3	V
	Battery Capacity	220	mAh
	Packet arrival rate	1-5	packets/s
Main radio	Data rate	125	kbps
	Transmission current	5.3	mA
	Reception current	5.4	mA
	Idle current	1.4	μ A
	SIFS duration	192	μ s
	Payload size	25	bytes
	ACK frame size	10	bytes
Wake-up radio	WuC duration (5 bit address for a network with 32 nodes)	55	ms
	Reception current (WuRx)	1.9	μ A
	Idle current	0.39	μ A
	Time to switch on MCU	2	ms
	Duration of preamble and partially switch on MCU	13	ms
	Time needed to decode and validate 1 bit address	10	ms

FAD and ES experiences lower PDR with a higher traffic load. This is due to the fact that collision probability increases with the injected traffic. A higher collision probability leads to a lower number of successful transmissions thus a lower PDR. Since ES does not have any impact on WuC duration for TI-WuR transmissions, both schemes show an equal amount of collisions under the same traffic load, hence achieving the same PDR.

Furthermore, the duration of WuCs, which is decided by the adopted address length and WuC data rate, has an impact on collision probability. The longer the WuC duration, the higher the P_c , and vice-versa. This is because a longer WuC occupies the channel for a longer period of time than a shorter WuC. When the channel is occupied over a longer period, the possibility of occurring overlapped transmissions increases, and consequently P_c rises. The difference between the WuC values used in Figs. 13 and 14, i.e., WuC duration = 65 versus 175 ms, explains why the achieved PDR in the upper figure is much higher than

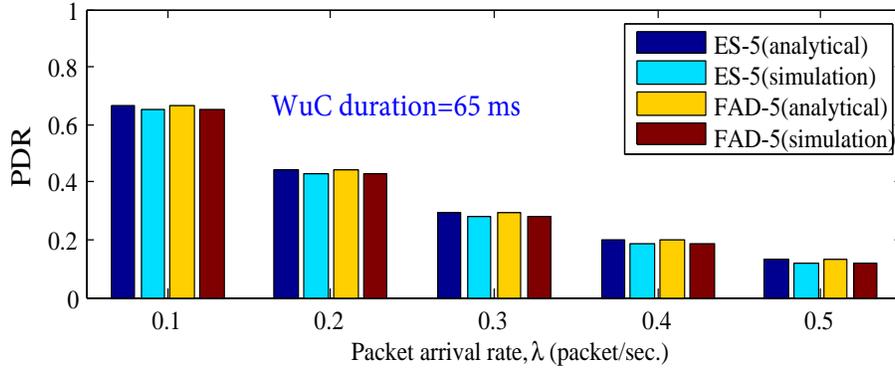


Figure 13: Packet delivery ratio: FAD-5 versus ES-5.

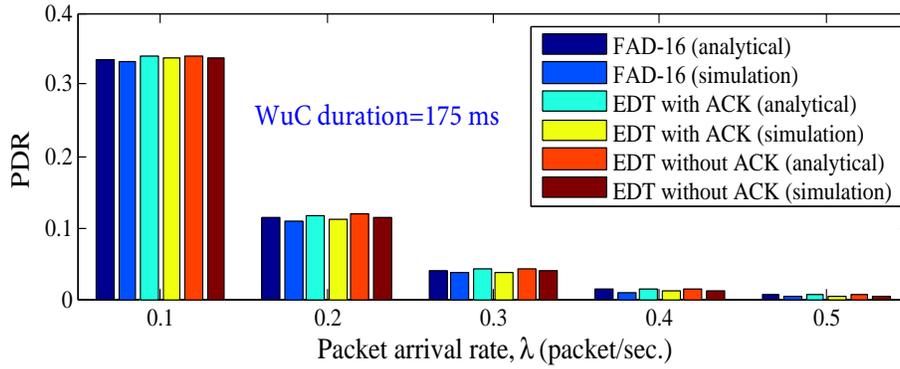


Figure 14: Packet delivery ratio: FAD-16 versus EDT with and without ACK.

515 the ones achieved in the lower figure.

From Fig. 14, a similar PDR trend is observed when EDT with and without ACK is compared with the FAD-16 scheme, i.e., PDR decreases with the traffic load. This is due to the fact mentioned earlier, i.e., collision probability increases with the traffic load and a higher collision probability leads to a lower PDR. Moreover, the achieved PDRs for FAD-16, EDT with or without ACK, are
 520 nearly equal since the WuC duration in all three cases are the same, as 175 ms.

8.2.2. Average Latency

Fig. 15 illustrates the achieved latency for FAD-5 versus ES-5. From this figure, it is clear that both address decoding schemes achieve the same delay

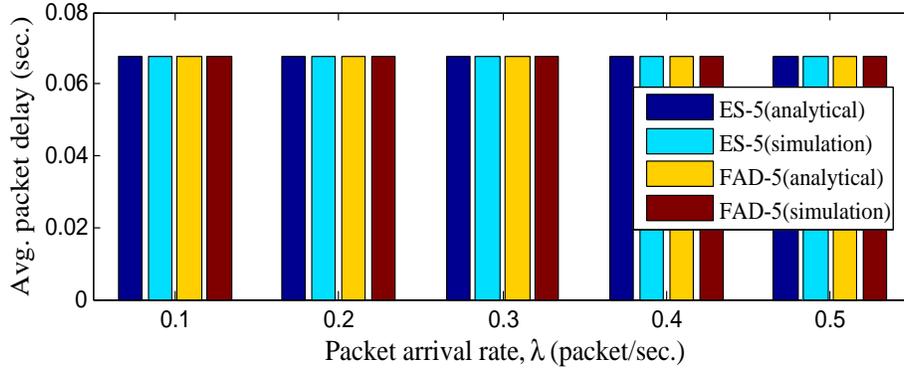


Figure 15: Latency: FAD-5 versus ES-5.

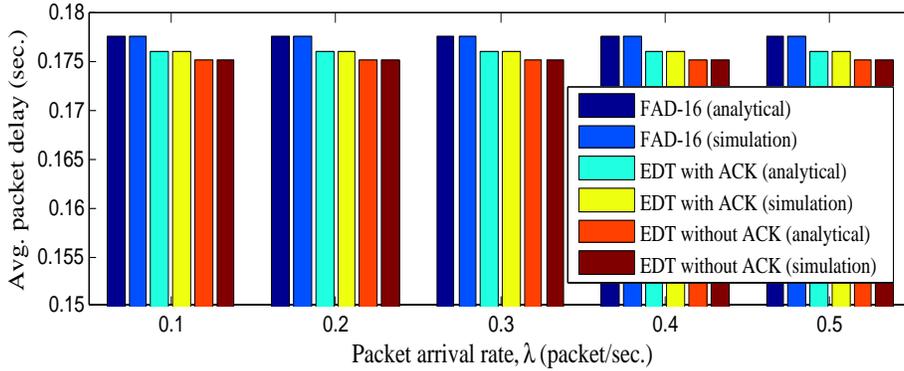


Figure 16: Latency: FAD-16 versus EDT with and without ACK.

525 performance and the resulted latency does not vary with traffic load. This is
 because the latency defined in this study is based on successfully transmitted
 packets. To receive a packet successfully, both FAD and ES have to decode all
 address bits in a WuC. Thus, a same data transmission procedure applies to
 both schemes.

530 Compare now the latency performance among FAD-16, EDT with and with-
 out ACK, in Fig. 16. It is clear that EDT without ACK achieves the best
 performance. This is due to the fact that EDT without ACK does not need to
 wake up the MR to transmit an ACK upon a successful data reception. Based
 on the parameter configuration mentioned above, approximately 2 and 1.7 ms
 535 less time is achieved when comparing the latency obtained based on FAD-16

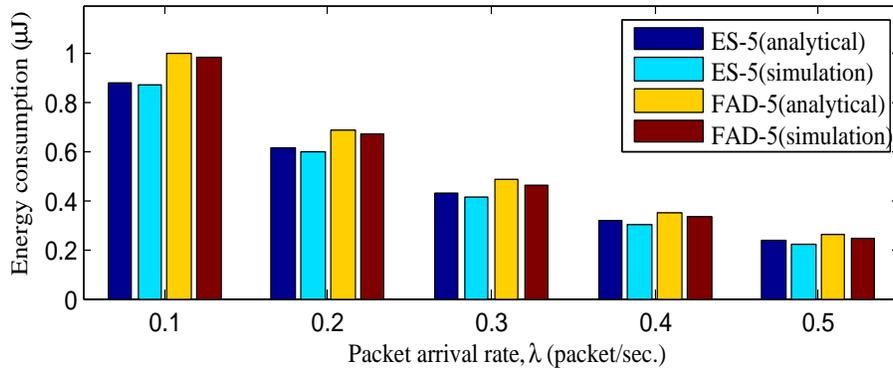


Figure 17: Average reception energy: FAD-5 versus ES-5.

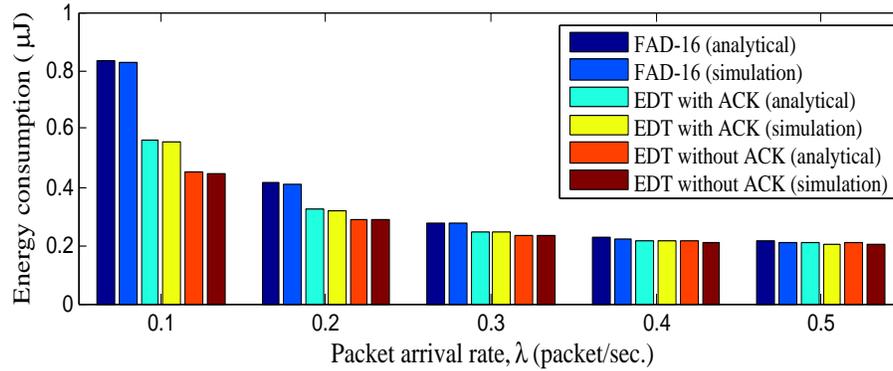


Figure 18: Average reception energy: FAD-16 versus EDT with/without EDT.

and EDT with ACK respectively⁶. It is worth mentioning herein that, although these two figures report the results for the same metric, they are based on two different address lengths which correspond to different network sizes. While Fig. 15 represents the obtained latency when the WuC address length is 5 bits (WuC duration = 65 ms), the results presented in Fig. 16 are based on a 16 bit address (WuC duration = 175 ms). Clearly, the latency from the latter case

will be longer than the one obtained from the former case.

8.2.3. Average Reception Energy Per Node

The average reception energy consumption per node for the FAD-5 and ES-5
545 schemes is shown in Fig. 17. For each data transmission, the overall reception
energy for the whole network includes the energy consumptions by the targeted
node as well as by the unintended nodes. The targeted node consumes energy
for receiving WuC, turning on MCU, data packet reception, radio switching,
and transmitting ACK, whereas the non-destined nodes need energy merely for
550 overhearing WuC transmissions. The theoretical average reception energy con-
sumption per node is obtained based on (10). We observe that FAD consumes
higher energy than ES under all configured traffic loads. This behavior is mainly
due to the efficient address decoding mechanism of ES in which non-destined
nodes go to sleep at an earlier stage. When traffic load increases, both schemes
555 exhibit a downward trend, as a result of higher collision probabilities which are
shown in Fig. 13.

Fig. 18 depicts the average reception energy consumption for FAD-16, EDT
with and without ACK respectively. When EDT is employed, no matter with or
without ACK, lower energy consumption is achieved in comparison with FAD-
560 16, for all studied traffic loads. This is because the EDT schemes transmit data
along with WuCs, saving energy for data transmission and reception. Among
FAD-16 and the two variants of EDT, EDT without ACK performs the best
since it takes full advantage of low power WuRx, i.e., the MR does not have to
wake up. When traffic load becomes heavier, however, the advantage of EDT
565 diminishes. This is because EDT itself does not have any mechanism to avoid
overhearing. With a heavy traffic load, the energy consumption due to over-
hearing becomes a dominant component for total device energy consumption,
compromising the benefit brought by EDT in comparison with ES.

Furthermore, when comparing the results from Figs. 17 and 18, we observe

⁶The reason that the achieved latency reduction is not very significant is as follows. In our testbed implementation, the WuC is sent at 100 bps, whereas the data rate is 125 kbps. With a higher WuC data rate, more significant benefits for EDT will be achieved.

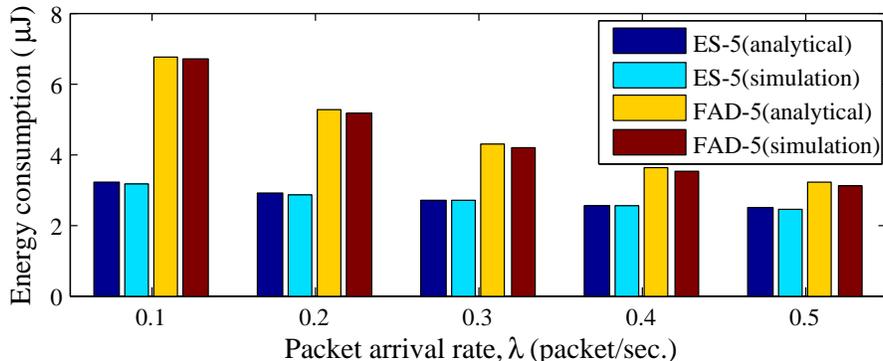


Figure 19: Overhearing energy consumption: FAD-5 versus ES-5.

570 that the EDT schemes perform better than the ES scheme despite that non-destined nodes can sleep earlier using ES. This is because no separate data packet transmission is required for data transmission in EDT. Note however that EDT applies only to small data, e.g., with 10 bits for data as mentioned earlier in our testbed experiments.

575 8.2.4. Overhearing Energy under Various Traffic Loads

Fig. 19 illustrates the variation of overhearing energy consumption of a WuR-IoT as traffic load varies, for ES versus FAD. In both cases, the overhearing energy consumption decreases with the traffic load. The reason is that the number of unsuccessful transmissions increases at a higher traffic load but the unintended nodes are not able to detect those collided packets. When comparing these two schemes, it is evident that ES performs better than FAD since ES reduces the number of overhearing nodes at each step of address decoding and matching. More specifically, ES reduces approximately one half of the number of overhearing nodes after decoding the first bit of a WuC address, and this trend continues bit-by-bit in the address decoding procedure. In the end, only one overhearing node, or none, decodes and validates a whole address in ES, whereas all $(N-2)$ overhearing nodes decode and validate an address in FAD. As observed in this figure, ES reduces overhearing energy wastage by approximately 30% – 50% as compared to FAD for all the traffic loads.

Table 4: Estimated Lifetime (in years)

FAD-16	ES-16	EDT with ACK	EDT without ACK
142.6392	142.7832	107.9190	108.2350

590 As mentioned in the previous subsection, EDT does not avoid overhearing. To activate EDT, all nodes in the network need to decode and validate the full range of the WuC address. Thus, the overhearing energy consumptions for FAD, EDT with and without ACK are the same. When ES is employed, however, it will perform best in terms of minimizing overhearing since an unintended ES
595 node needs only partial address decoding before going to sleep.

8.2.5. Lifetime Estimation

Let us now calculate the expected lifetime of the studied network. Assume an ideal homogeneous network in which all nodes behave identically under a collision-free condition. Then the network lifetime is the same as the lifetime
600 of a randomly selected node, assuming that all nodes have the same amount of initial energy, deplete their energy at the same rate, and have therefore the same node lifetime. To perform our lifetime estimation, we follow the packet arrival pattern for typical IoT applications considered in [2, 3], i.e., one packet per every other hour. We further assume that each device is powered by a 3V
605 button/coin cell battery with capacity 220 mAh. A decreasing rate of 2% for battery self-discharging is included in our calculations.

Table 4 depicts the network lifetime for the studies schemes, i.e., FAD, ES, and EDT with two flavors. From Table 4, we observe that ES performs slightly better than FAD. Among without EDT, EDT with ACK, and EDT without
610 ACK, the EDT scheme without ACK is the best in terms of lifetime. The lifetime of ES is longer than all other schemes since it uses short local WuC address (e.g., 5 bits for the network with $N=32$) and bit-by-bit address decoding scheme.

The reason for this insignificant lifetime extension of ES over FAD or EDT
615 over without EDT is the fact that the energy consumed for one successful packet

transmission is higher than the energy consumed for reception in a WuR-IoT device, i.e., WuC transmission energy is dominating the total energy consumption of a network. We argue, however, the proposed schemes are still meaningful since a real-life WSN/IoT application for environment surveillance may experience much lower traffic load as configured in this study.

8.3. Further Discussions

Finally, it is worth mentioning that in this study we regard concurrent transmissions of two or more devices as collisions regardless of the interference level. When capture effect is taken into account, a transmission which is much stronger than other transmission(s) to the same receiver may survive. In such a case, the achieved packet delivery ratio would be slightly higher but the obtained delay and energy consumption would be basically the same since our schemes do not allow retransmission and a collided packet consumes the same amount of energy. To precisely analyze the performance under more realistic conditions, one may consider that packet losses due to capture effect and channel impairments are statistically independent of losses due to protocol behavior [28].

9. Conclusions and Future Work

In this paper, we have proposed two schemes, i.e., early sleep and early data transmission, for the purpose of further reducing overhearing and latency in WuR-enabled IoT/WSNs. The proposed schemes are implemented in a small-scale WuR testbed with self-designed wake-up receivers supporting both ES and EDT. The functionalities of these two schemes are demonstrated via real-life experiments. To evaluate the performance of the proposed schemes in larger networks, we developed an M/G/1 model and derived expressions for three parameters. Through analysis and discrete-event simulations, we demonstrate that ES performs better than full address decoding in terms of average energy consumption. Moreover, EDT shows its performance superiority in terms of latency.

A definite direction for our future work is analytically exploring the performance of the proposed schemes by investigating the effect of interference levels among concurrent transmissions, especially under realistic channel conditions. Another direction is to expand our testbed to a larger scale and perform more real-life experiments for metric based performance evaluation.

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