Appropriate Integration of Wake-up Receivers in Simulations Tools based on Real Experiments

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Abstract: Wireless Sensor Networks (WSNs) are an emerging and promising approach to Internet of Things (IoT). However, energy consumption is regarded as one of the most critical problems in WSNs due to the devices' limits.To address this problem, an ultra-low-power radio receiver known as a wake-up receiver (WuRx) is used to handle idle listening while the main radio is turned off. Since simulators for performance prediction have become almost indispensable in the design and management of new hardware equipment and components, we will present in this paper the design of a wake-up receiver module, that could be a solution to the energy consumption's challenge, in OMNeT++ and compare it to experimental results, focusing on energy performance and reliability factors.

1 INTRODUCTION

Wireless sensor networks (WSNs) have piqued the interest of the scientific community in the last decade and in the coming years, allowing us to realize their numerous applications in disciplines such as medicine, military, the environment, and academics. WSNs are made up of hundreds, if not thousands, of sensor nodes that are powered by batteries with limited energy (Cheour et al., 2013a), processing, storage, and transmission capabilities. The sensor node's energy supply is limited, and the radio consumes a significant amount of the node's energy (Nithyanandh et al., 2017) and (Shabbir et al., 2017). When there is no communication, the ideal approach in sensor networks is to put the radio into sleep mode to save energy. There are two primary groups in these works: Duty-Cycling Media Access Control(MAC) protocols (Shabbir et al., 2017) and wake-up receivers (Sadok et al., 2016) and (Marinkovic and Popovici, 2011). Duty-cycling is a simple method for conserving resources and extending the overall network lifespan. For a set period of time, the node will turn off its transceiver, only to wake up periodically to determine whether or not to receive the message. The goal of this strategy is to reduce idle listening and, as a result, power consumption when communicating with nodes. Different MAC protocols have also been proposed for this approach. Most provide the basic parameter of duty-cycle, which specifies the percentage of time a node stays asleep and does not communicate.

Existing MAC protocols can be classified as synchronous or asynchronous duty-cycling. The coordination of wake-up periods between neighboring nodes is implied by synchronous duty-cycling. This enables message exchange in agreed-upon time slots with no additional interaction for each message. Coordination, on the other hand, usually implies a constant overhead even when no messages are exchanged, also this type of duty-cycling can present difficulty when it comes to the synchronization. This coordination is not used by asynchronous duty-cycling, which negotiates medium access only when messages are to be exchanged. In receiver initiated (RI) asynchronous duty-cycling, nodes wake up from deep sleep on a regular basis to check the radio medium. However, in some cases this category of duty-cycling might present a low reliability in some applications for example the tracking and localization (Guidara et al., 2019) , where the reference node can be unaware about the presence of the target.

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To overcome these short-comes, the wake-up radios that are triggered by events propose a solution to the problem of idle listening. Wake-up radios previously published are characterized by low-power and low-sensitivity (Sadok et al., 2016) and (Marinkovic and Popovici, 2011). The WuRx uses far less power than the main transceiver and only sends an interrupt when a packet with a user-defined address is received. Embedding such a device allows for better event-triggered applications where real-time behavior and a longer lifetime are required. To evaluate the new design where the WuRx is integrated for a WSN, numerous trials with various representative scenarios are required. Furthermore, in order to generate statistically significant findings, these tests should ideally be repeated numerous times. Performing these studies in the real world takes a lot of effort and money. As a result,a simulator should be used to test this proposed design(Halkes and Langendoen, 2014). Simulators are a low-cost and quick approach to run a large number of experiments with various typologies and parameter settings(Cheour et al., 2013b).In other words, Simulators can be utilized in research experiments to get more fine-grained results than similar real-world investigations(Dwivedi et al., 2011). One issue with simulators is that it is difficult to demonstrate that a simulation experiment matches a similar real-world experiment. The goal of this contribution is to look at how well simulation findings for the wake up receiver module and the difference between simulation and real-world results will be highlighted due to different attenuation (Ketata et al., 2020) with the help of experimental result.

2 RELATED WORK

Studies on wake-up receivers consist mainly of two parts: Hardware development for low-power wake-up circuitry and software development for networking protocols that utilize wake-up receivers. The functioning principles of the wake up receiver technologies proposed in the literature or available on the market vary. The Wake up receiver concepts can be divided into two types based on their energy sources: passive wake up receivers, in which the wake up circuitry is triggered by an external energy source, and active wake up receivers, in which the internal battery is used to power the wake up receiver.

2.1 Hardware Development

There are commercialized wake-up receivers that can use an active wake-up receiver to achieve low energy consumption. For example, there is a three-channel wake-up receiver on the market. It features three types of power management: sleep, standby, and receive. Many of the channels are turned off in sleep mode. In the receive mode, the channel's correlator is working and the channel scans the input signal waveform for a correct wake-up pattern. After an adjustable timeout duration, the channel returns to its standby mode if no feedback.

The current values presented in table 1 are for all cases where there are three channels enabled.

Table 1: The current consumption of different WuRx in the market [3].

Operating states	Regulator on $V_{CC} = 3\,V$	Regulator off $V_{CC} = 2.4\,V$
Sleep current	0.8 µA	0.3 µA
Standby current	7.0 µA	6.5 µA
Receiving current	7.2 µA	6.8 µA

There are further proposals for hardware based on the super-regenerative principle (Joehl et al., 2001). A second lower-frequency oscillator is used by super-generative receivers to supply a single lower-frequency oscillator. Six orders of magnitude for system circuit profits. This second oscillation interrupts occasionally, the primary radio frequency (RF) oscillation, which enables the steady buildup of the RF signal. Therefore, they make active wake-up receivers that are very low-power. A prior study by Joehl et al. (Joehl et al., 2001) presents an implementation of a super-regenerative transceiver that consumes 3.6 mW for a receiver sensitivity of −105 dBm, and the emitter current consumption is 6 mA for 0 dBm output power. Recently, a super-regenerative transceiver that consumes 400 µW on reception and 1.6 mW on transmission is proposed for wireless sensor networks by (Otis et al., 2005). Also another study done by (Sadok et al., 2016) presents a novel architecture to enhance the WuRx sensitivity to be −60 dBm while consuming 2.53 µA in channel monitoring and it is also able to decode a 16 bit wake-up pattern.

2.2 Software Development

Although wake-up receivers offer numerous advantages and are academically used in wireless sensor networks, there are few media access control (MAC) or routing protocols that support their use, and the majority of available protocols are limited to simulations. The current wake-up receiver protocols like E2RMAC (Vivek et al., 2007), WUR MAC (Guidara et al., 2019) , RTWAC [9] and GWRMAC (Karvonen et al., 2014) support single hop contact only. Compared to synchronous or asynchronous MAC protocols, these protocols indicate superior energy needs, yet their efficiency is only focused on simulation data. In (Miller and Vaidya, 2005) a loop using preamble based synchronization between the transmitter and the receiver is used. A triggered wake-up is often specified, in addition to wake-up with preamble messaging, in which each node wakes up once at duration T. In order to minimize the overall energy consumption, the authors attempt to optimize the T values based on the given packet arrival rate. Since the wake-up delay increases the data packets end-to-end delay, a range of protocols are proposed to reduce the wake-up delay experienced. One such protocol is Latency Reduced Energy Efficient MAC (LEEM) and it is a reservation hop. head scheme (Dhanaraj et al., 2005). The concept is to reserve the next hop's channel, that is, to wake-up the next hop in advance of the destination. To support broadcasting and dedicated messages, each node in Radio Triggered Wake-up with Addressing Capabilities (RTWAC) has a unique and shared wake-up address. However, the sole purpose of wake-up messages is to initiate an event occurrence, such as a sensor reading at the receiver node. Data communication is realized by a more common Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) MAC protocol that is not further specified, using the main radio. wake-up receivers may be used as used in (Shah and Rabaey, 2002). Since it suggests a routing protocol. The basic MAC protocol is specified for sending on a radio station, a wake-up signal. The channel access is CSMA/CA. The use of a similar approach is in (Shah and Rabaey, 2002), where a MAC protocol incorporating CSMA and code-division is introduced by the authors for multiple access (CDMA). A summary of seven separate WuRx implementations was compiled by (Marinkovic and Popovici, 2011). Their usage was however, not in the area of WSNs, but in the region of networks for Wireless Body Area (WBANs).

3 SIMULATION'S ENVIRONMENT AND RESULTS

In order to get a better understanding for the power-hungry processes inside each sensor node and to prove the effectiveness of the WuRx-based communication, network simulations will be run. For verifying, managing, and predicting the behavior of WSNs in a controlled and reproducible environment, network simulation is used as a powerful evaluation methodology since it is featured by the ease of implementation, low cost and scalability. for this work, the simulation tool that chosen is OMNeT++. this simulator supports multiple radio interfaces and multiple channels and offers an easy access to change the physical layer properties which in our case was needed to add the new WuRx interface. for the evaluation of the new added module, we comapred it to two duty cycling mac protocols X-MAC and B-MAC that are predefined in OMNeT++. in Table 2 , the different power states values and the used parameters are presented.

Table 2: Simulation Parameter Set.

Approach	Parameter	Value
Wake-Up Radio	Carrier Frequency	868 MHz
	Preamble Duration	0
	Header Bit Length	0
	Antenna Type	Isotropic
	Bitrate	8000 bps
	Modulation	FSK
	Protocol	CsmaCa
	Acknowledgements	False
	Receiving Power	7.5 μW
Data Radio	Carrier Frequency	868 MHz
	Antenna Type	Isotropic
	Transmitter Power	24 mW
	Protocol	CsmaCa
	Acknowledgments	True

3.1 WuRx Architecture in OMNeT++

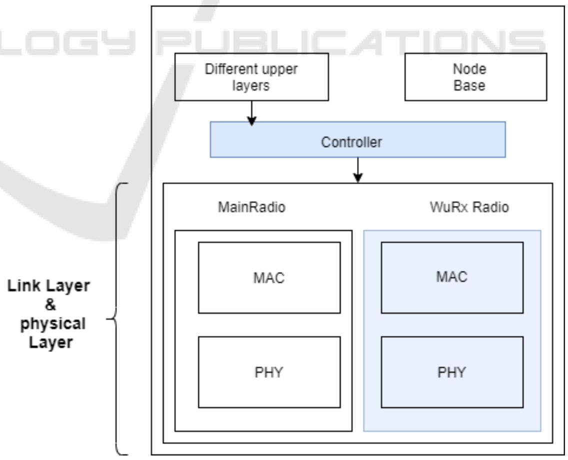

Figure 1: New proposed model of the wake-up based node in OMNeT++.

A new model was built and implemented into the node structure in order to investigate the WuRx behavior in our nodes. To put it in other words, the INET node structure was kept with the exception of modifying the wireless interface by adding a second one to include the WuRx-necessary components and a controller to manage communication between the data link layer, physical layer (both of which are regarded as one in this work), and network layer. Figure 1 depicts the node's new planned architecture. This model is based on the research published in (Whichi et al., 2021) . Basically, when evaluating WuRx nodes, the main radio is managed by a Transceiver Controller module, depicted as Control block in 1 which allows the application to monitor and control the status of the transceiver as is done in WuRx platforms

3.2 Simulation Results

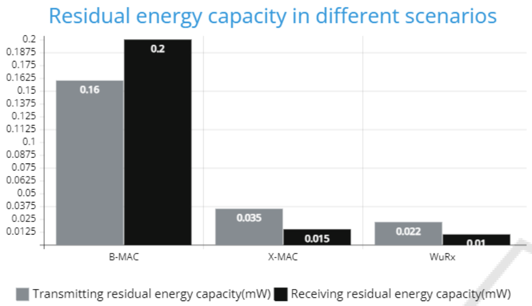

Figure 2: Residual energy capacity in different scenarios.

Based on (Whichi et al., 2021), the scenario is a simple peer to peer communication where the main goal was to compare the performance of the added module with LPL protocols. to get a more reliable results a physical environment was added to the network. At the end of simulations, the WuRx module showed better results on both aspects power consumption and reliability(number of received packets). compared to X-MAc, the WuRx module consumed 37 % less power. as in the case of the B-MAc protocol, the WuRx consumed 90 % less energy. However, these results only show the performance of the new structure with the simulation environment and in order to evaluate the module properly the same scenario should be conducted using a WuRx hardware design. The following section presents a set of experimental measurement done using a BJT WuRx design done within our laboratory.

4 EXPERIMENTAL ENVIRONMENT AND RESULTS

The experimental measurements will be built up using two sensor node ultilizing the MSP430G2553 where one node is a transmitter and the other will just receive. The MSP430 is a series of ultra-low-power mixed-signal microcontrollers. I also used a WuRx implementation developed by (Fromm et al., 2021).

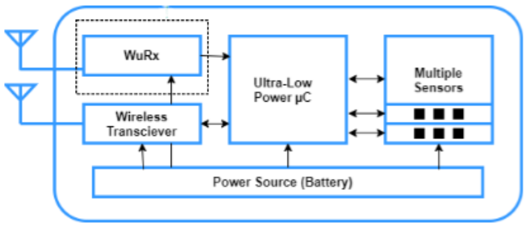

Figure 3: Building blocks of the WuRx-based sensor node.

The used WuRx implementation can be divided into multiple building blocks. Figure 3 depicts the circuit's block diagram. The antenna receives the transmitted electromagnetic waves. They have a low amplitude, a high noise figure, and are usually affected due interferences, reflection and diffractions. A bandpass filter is typically used to pass only signals in the appropriate frequency bands. However, in-band interferences between different systems operating in the same environment are to be expected. The 868 MHz band is employed in the proposed circuit by selecting an appropriate surface acoustic wave (SAW) filter. This filter's input and output impedances are typically 50 Ω (Fromm et al., 2021).

The experimental results were carried out inside a laboratory.the measurements were carried using an msp430G2553. To be able to measure the current the following set up was set: A 1 Ω resistor was integrated in the cable that was connected to our oscilloscope. For the power we used a 3 V lithium battery.

4.1 Experimental Results

4.1.1 Experimental Results from WuRx

Figure 6 shows the graph of the current while receiving the wake-up packet. It is in the order of 12 µA, based on the data sheet, which explains why the graph is noisy.

Table 3: Comparison of currents while tranmission and reception from datasheet, experiments and simulation for Wupt only.

Results	Transmitting current	Receiving current
Datasheet	21 mA	12 µA
Experimental	25 mA	12.57 mA
Simulation	23.1 mA	9.9 µA

In table 3 we present the comparison between the simulation, Data sheet and experimental measurements of the WuRx. These measurements intend to evaluate the performance of the added module in OMNeT++. Due to the low value of the receiving current, an amplifier was used in order to be able to detect the signal. As shown in the table, both the receiving and transmitted current is approximately the same as the data sheet and experimental measurements. The difference could be explained by the Various physical environment factors, such as scattering, reflection, or diffraction, that can influence radio transmission in conventional wireless communication systems. In addition to that the transmitted signal could reach the receiving antenna through Many paths (also see known as multi-path propagation) as a result of some obstacles that obstruct the Line-Of-Sight (LOS) path as well as reflections from the physical environment. These multi path components have different terms of time delay and amplitude attenuation and phase shift data (Liyanage et al., 2018). Though OMNeT++ has a physical environment module that is implemented in the different scenarios , the difference between simulation and hardware still exists since it does not contain all the attenuation that could be found in reality.

4.1.2 Experimental Results for the Node

This section presents our measurements using the same set up mentioned in the previous section but with a10 Ω resistor.

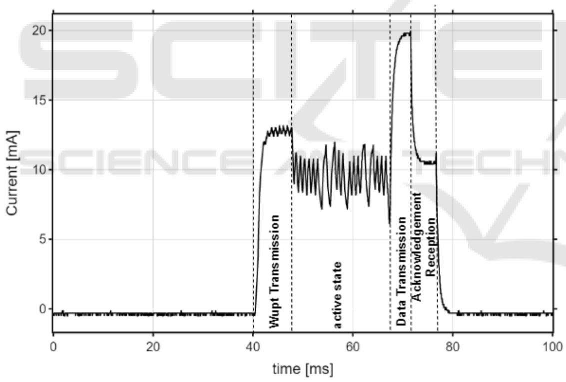

Figure 4: Current signal of the transmitter.

This figure 4 shows the current of the transmitter during the 4 different states. The wake up packet (Wupt) transmission, the active state, the Data transmission state and the reception of the acknowledgement. The current in the Wupt transmission is around 14 mA. This value could be explained by the fact that during the transmission, the WuRx uses the OOK modulation. Since the life cycle is 50 % we can conclude that the value of the current should be (21 mA +7 mA)/2=14mA , where 21 mA is the current while transmitting in +11 dBm and 7 mA is the current while transmitting in -7 dBm. In the same graph while it is amplified, a false detection of a Wupt can be seen.

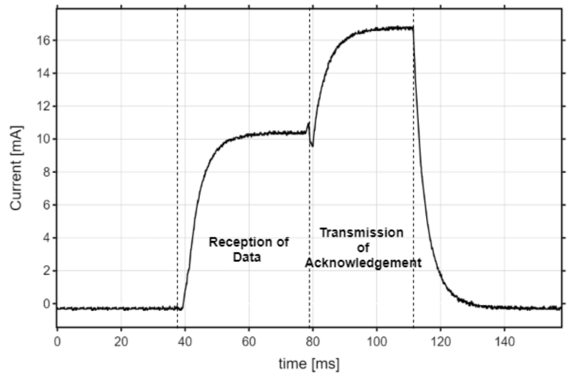

Figure 5: Current signal of the Receiver.

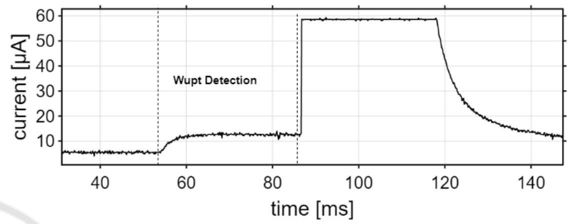

Figure 6: Detection of WuPt using an amplifier.

In figure 5 the signal of the Receiver and its different states were shown.the first state is the data reception and it is of 10 mA value and the second state is the transmission of the acknowledgement state and it is of 17 mA. Figure 6 is the same figure but using the amplifier in order to detect the reception of the Wupt that is in the order of 12 µA.

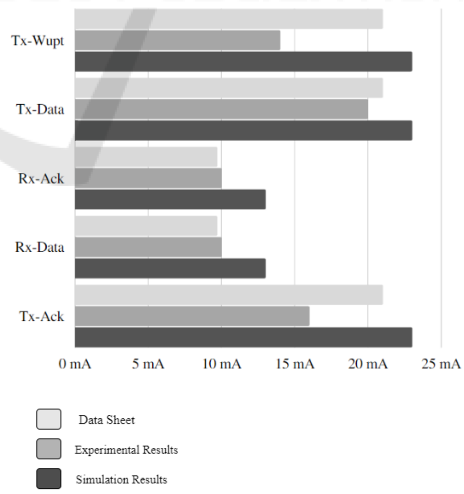

Figure 7: Bar chart with the different power consumption in different states.

The figure 7 shows the different states in all the different environments and the power consumption. It can be seen that even between data sheet and experimental results there is a deviation due to the different set ups where the measurements were done and different conditions. Also, the performance of the added module in the simulation has a merge of error of 9 %.This could be explained by the lack of attenuation and interference that occurs when carrying the experimental measurements.

5 CONCLUSIONS AND FUTURE WORK

In this work, an evaluation of a WuRx model in a simulation tool is presented. In order to have a full comprehension of the model performance, both the simulation and experimental set ups were done under the same conditions and using the same power parameters and same message length at a carrier frequency of 868 MHz. Upon comparison of the results, the simulation's WuRx model showed a small divergence from the results shown using the MSP430G2553. This could be explained by the fact that in general the simulations, even with introducing environment models, are still working without taking consideration of the material quality, other machines interference, cables' interference. To improve the results of the simulation, a new model of a CPU will be built in order to be able to introduce different parameters of different boards. Also new environmental modules will be implemented to ensure precise results.

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REFERENCES

Cheour, R., Derbel, F., Kanoun, O., and Abid, M. (2013a). Wireless sensor networks with power management for low energy consumption. In *Systems, Signals I& Devices (SSD), 2013 10th International Multi-Conference on Systems Signals and Devices Hammamet Tunisia*, pages 1–6. IEEE Conference Publication.

Cheour, R., Jmal, M., Lay-Ekuakille, A., Derbel, F., Kanoun, O., and Abid, M. (2013b). Choice of efficient simulator tool for wireless sensor networks. In *Measurements and Networking Proceedings (M I&N) 2013 IEEE International Workshop on Systems, Signals and Devices*, pages 210–213. IEEE Conference Publication.

Dhanaraj, M., Manoj, B., and Murthy, C. S. R. (2005). A New Energy Efficient Protocol for Minimizing Multi-Hop Latency in Wireless Sensor Networks.

Dwivedi, V. K., PatleO, K., and Vyas, P. (2011). Investigation on Effectiveness of Simulation Results for Wireless Sensor Networks.

Fromm, R., Schott, L., and Derbel, F. (2021). An Efficient Low-Power Wake-Up Receiver Architecture for Power Saving for Transmitter and Receiver Communications.

Guidara, A., Derbel, F., Fersi, G., Bdiri, S., and Ben Jemaa, M. (2019). Energy-Efficient On-Demand Indoor Localization Platform based on Wireless Sensor Networks using Low Power Wake up Receiver.

Halkes, G. and Langendoen, K. (2014). Experimental Evaluation of Simulation Abstractions for Wireless Sensor Network MAC Protocols.

Joehl, N., Dehollai, C., Favre, P., Deval, P., and Declerq, M. (2001). A Low-Power 1-GHz Super-Regenerative Transceiver with Time-Shared PLL Control.

Karvonen, H., Juha, P., Jari, I., Matti, H., and Carlos, P.-R. (2014). A generic wake-up radio based MAC protocol for energy efficient short range communication. In Personal, Indoor, and Mobile Radio Communication(PIMRC).

Ketata, I., Fakhfakh, A., and Derbel, F. (2020). Advanced evaluation platform-based rf attenuators for wireless sensor networks. In *2020 IEEE 6th World Forum on Internet of Things (WF-IoT)*, pages 1–6. IEEE.

Liyanage, M., Chang1, C., Srirama, S., and Loke, S. (2018). Indoor people density sensing using wi-fi and channel state information.

Marinkovic, S. and Popovici, E. (2011). Nano-Power Wireless Wake-Up Receiver With Serial Peripheral Interface.

Miller, M. and Vaidya, N. (2005). A MAC Protocol toReduce Sensor Network Energy Consumption Using a Wakeup Radio.

Nithyanandh, s., , and Jaiganesh, D. (2017). Wireless Sensor Networks Overview and Study of Various Applications and Environmental Factors in WSNs.

Otis, B., Chee, Y. H., and Rabaey, J. (2005). A 400mW-RX 1.6mW-TX Super-Regenerative Transceiver for Wireless Sensor Networks.

Sadok, B., Faouzi, D., and Olfa, K. (2016). An 868 MHz 7.5 µW wake-up receiver with -60 dBm sensitivity.

Shabbir, N., , and Hassan, S. (2017). Routing Protocols for Wireless Sensor Networks (WSNs).

Shah, R. and Rabaey, J. (2002). Energy Aware Routing for Low Energy Ad Hoc Sensor Networks.

Vivek, J., Ratnabali, B., and Dharma, P. A. (2007). Energy-efficient and reliable medium access in sensor networks. In World of Wireless, Mobile and Multimedia Networks.

Whichi, A., Derbel, F., Fakhfakh, S., Weber, M., and Ktata, I. (2021). Simulation of Wireless Sensor Nodes based onWake-Up Receivers.