Experimental analysis of a Bluetooth low energy wake-up radio solution

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Abstract Nowadays, the use of Internet of Things has became part of our daily lives and an important technology in industries. All these interconnected devices bring one major concern that is energy consumption. This need of energy is mostly due to data sensing, data processing and communications but it also comes from the high waste of energy induced by idle listening. These devices are commonly supplied by external power source and thus have very limited lifetime. All these needs are not only expensive but they also are a threat to the environment. Fortunately, many improvements have been found during the past years from improving energy efficiency to energy harvesting. One major enhancement was brought with wake-up radio technology. Thanks to radio frequency energy harvesting techniques, nodes are able to become active only after receiving a wake-up signal thus reducing idle listening and improving latency. This paper proposes a state of the art of wake-up radio technology along with the several optimizations that could possibly be applied. Then, some analysis of current microcontrollers communication performance and energy efficiency is displayed. Finally, the paper determine the limits of the practical implementation of wake-up radio technology on such devices.

Key words: Bluetooth Low Energy, Wake-Up Radio, Internet of Things, Energy efficiency, Wireless Sensor Network

1 Introduction

Over the past few years, society became more and more interconnected. With the advent of wireless sensor networks (WSNs) and the Internet of Things (IoT), autonomous and connected machines of all sorts became part of our everyday life. In 2019, the number of these devices were estimated between 26 and 50 billion and this number keeps increasing as the demand is perpetually growing [1]. However battery capacity is a limiting factor these wireless communications.. Indeed, the radio interface, part of these devices, is an high energy consuming component. More precisely, the transceiver is responsible for most part of the energy consumption [2]. This is due to the fact that the device, even if it isn't actively receiving or sending, needs to continuously listen for any incoming signal. Otherwise, the nodes could suffer from data latency which could be a critical issue for some system. Being perpetually listening for any information is what we call Idle Listening. Furthermore, IoT devices can be limited in size, thus restricting the size and capacity of onboard batteries. That is why, maximizing energy efficiency is crucial. Furthermore, an estimation

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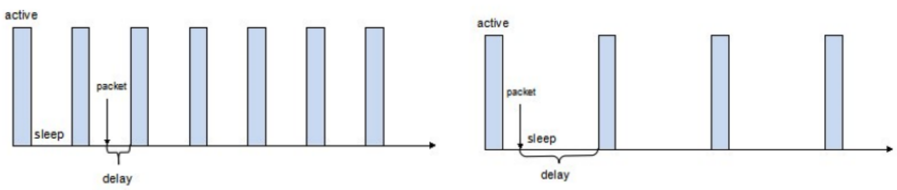
indicate that the ICT sector (Information and Communications Technology) is responsible of about 3.6% of global energy consumption along with 1.4% of CO_2 emissions [3]. These are the reasons why energy efficiency is an important issue. To save energy, many solutions have been brought, from both hardware and software level as described in [4] and [5]. In this paper, we will be focusing on software solutions. One of them consist of using a sleep mode (which disables energy-consuming functionality and hardware parts) along with duty-cycling. Duty-cycling allows a device to switch between sleep and active mode for a specified period. The goal is to stay asleep as much as possible and gather all the information during the short time awake. Unfortunately, a period too long may bring undesirable latency and a duty-cycle would still consume too much energy as depicted by Fig.1. That is why duty-cycling is not as efficient as expected.



(a) shorter delay, higher energy consumption (b) longer delay, lower energy consumption

Fig. 1 Energy-latency trade-off

This issues can be addressed using Wake-Up Radio (WuR) technology [6]. It allows a device to be active only when receiving a wake-up packet, making it independent of a duty-cycling schedule. Protocols [7] to use WuR in industrial environments are currently developed, due to the reduced latency and energy consumption of the technology. Our goal is to study current WuR's performances particularly in terms of range and energy efficiency for a further potential use in an IoT structures with restricted resources .

We first present the Wake-Up Radio technology and its advantages, as well as the chosen device for this analysis. Then, we show a study of its range and WuR capabilities. Finally, we conclude on the state of the performance of the chosen microcontroller.

Acronyms used in this paper can be found in Table 1.

Table 1 List of Acronyms

BLE	Bluetooth Low Energy
EM	Energy Mode
IoT	Internet of Things
RSSI	Received Signal Strength Information
WuR	Wake up Radio
WuRx	Wake-up Receiver
WuTx	Wake-up Transmitter
WSN	Wireless Sensor Network

2 Approach and contribution

For this study, we experimented communication with two identical BG-22 Explorer Kit(BG22-EK4108A) boards on which no hardware modification was made [8], based on the EFR32BG22 made by Silicon Labs. We chose this device as it is one of the rare BLE board with WuR capabilities. Finally, these cards offer several saving energy mode that can disable specific peripherals and present specific performances. Fig.3 sums up the operating components available for each EM. We first started to measure the RSSI and the energy consumption at different distances. Then, we determined the energy consumption of each energy saving mode featured by the controller. We finally repeated the RSSI analysis with wake-up radio technology to determine the limits of such a protocol. Based on our literature review, and to our knowledge, this study is the first contribution that experimentally analyzes the WuR performances in terms of energy consumption and RSSI ranges using BG22-EK4108A devices.

3 State of the art

3.1 Wake Up Radio Introduction

While waiting for a wake-up signal, the main processor is deactivated and thus consumes less energy. Once received, the receiver will "wake up" the main device which takes in charge the communication and then deactivates itself. Compared to duty cycling, WuRs reduce idle listening time, thus saving energy. Although WuRs are now well known in the field, there are currently no standardized protocols for their implementation. Indeed, WuRs come along with many configurations and optimizations. An example of a WuR node is shown in Fig. 2.

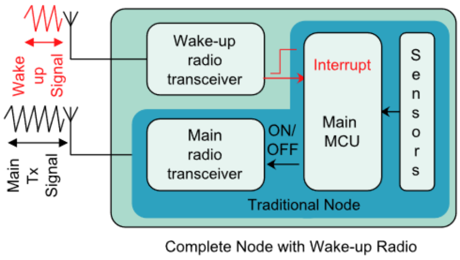


Fig. 2 Principle of a WuR [9]

3.2 Range and frequency

Two parameters to consider are the distance between radios and the frequency used by receivers. Range of WuR technology have been tested with frequencies of 433 MHz and 868 MHz indoor and outdoor, reaching at least 21 m [10]. However, studies of the range of a purely Bluetooth WuR are not available yet.

Furthermore, there is two possibilities that can be used to classify the choice of frequency of a WuR node.

3.2.1 In-Band

With In-Band communication, the main device transceiver and the WuR share the same frequency and can split the same antenna. As only one antenna is needed, this implementation is usually economical.

3.2.2 Out-Band

Conversely, Out-Band communication presents distinct transceivers and frequencies for the principal node and WuRx. It allows us to wake-up specific sleeping nodes and thus not only lower the chances of interference with adjacent node but also strengthen the signal [5]. As the device is equipped with two antennas and transceivers, such an implementation tends to be more expensive.

As the point of our study is to determine the limits of low cost WuR we will use the In-Band communication provided by our boards during our experiment.

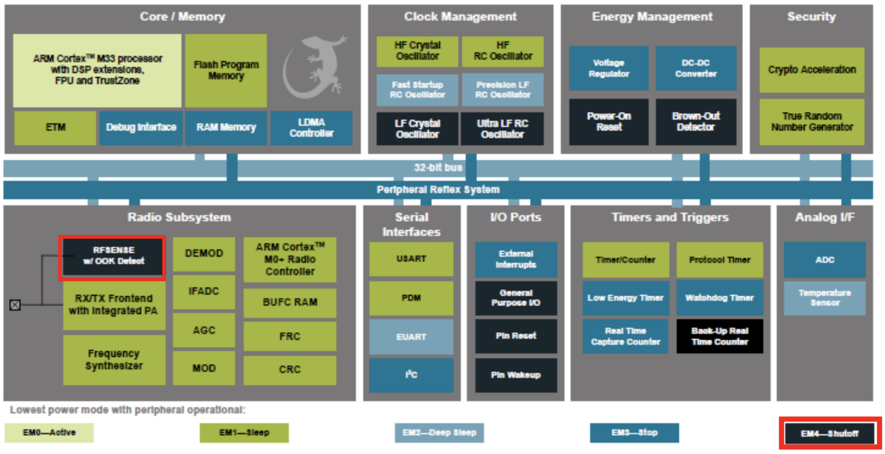


Fig. 3 Operating components available depending on EM [8]

3.3 Bluetooth Low Energy

Bluetooth Low Energy (BLE) is a very low-power wireless standards for communication at short range. Indeed, generally speaking, BLE consumes half less energy than plain Bluetooth. Although they both work with UHF (Ultra High Frequency) like Wi-Fi does, they are different on the set of channels they use. While Bluetooth uses 79 1-MHz channels, BLE uses 40 2-MHz channels [11]. To reduce energy consumption, BLE sends short duration messages. BLE can be detected thanks to a procedure using three distinct frequencies (channels). These channels are labelled 37, 38, and 39 and are widely spaced at 2402 MHz, 2426 MHz and 2480 MHz. These three frequencies were chosen in order to avoid interference with Wi-Fi as much as possible. The advertising device sends a packet on at least one of these three channels, with a repetition period called the advertising interval. Also, BLE is easy to implement and coexists well with other protocols on the same frequency band. Indeed it is currently equipped on many connected devices such as smartwatch and smartphones, making it really reachable. Furthermore, previous studies have shown that a wake-up receiver along with BLE non-connectable advertising could save up to 30% energy [12].

3.4 Different kind of wake up receivers (WuRx)

There are two kinds of WuRx available based on whether the receiver relies on a power supply or not. These are called active and passive WuR and both have their pros and cons in terms of performances or battery usage [13]. Furthermore, a last type of hybrid WuR was developped using both active and passive. These hybrid wake-up radios try to take advantages of the benefit from both active and passive forms. The following items presents each of them.

- *Active receivers* These are actually a second low power radio that uses battery power as energy source and require continuous power supply. Any active receivers thus require a power source. They are often more sensitive and therefore benefit from a longer range.
- *Passive receivers* As the number of connected devices and the demand for self-sustainable WuR both began to grow, providing an external battery wasn't satisfactory enough. That's why solutions of WuRx that power themselves by harvesting energy from the wake-up signal transmitted by wake up transmitters (WuTx) has been proposed. Electromagnetic waves from the WuTx are converted into electricity thanks to a rectenna (rectifying antenna) [4]. Unlike active receivers, they don't need any attached power source but act at a much shorter range.
- *Hybrid receivers* An hybrid solution has been proposed to overcome the high energy consumption of active WuR and the short range of passive WuR. In this solution, wake-up radio circuitry components such as the comparator and microcontroller are battery powered while others components are supplied by energy harvesting of surrounding environment and incoming signal.

For our study and in order to implement this solution, we use an ultra-low power active receiver that will be listening to the 2.4 GHz channel for a wake-up signal.

3.5 Use of WuR in IoT and mobile sensor networks

There is two things that need to be considered when using WuR instead of duty-cycling :

- *Topology* : efficient use of WuR depends on the placement of devices in a network. Different studies about topology in standard sensor networks exists [14] but it would need to be adjusted to take into account WuR constraints. The solution to this problem is easier when each device is able to both receive and send WuR packets.
- *Mobility* : when used with either a mobile sink or with mobile devices, WuR proves to have a lot of advantages. Studies show that using duty-cycling when the devices are mobile can lead to miss connectivity with others [15]. In fact, it is only possible to achieve a high rate of connectivity when the duty cycle is high, meaning more energy usage. WuR can help on that aspect by sending WuR packets periodically while moving to wake up the devices and then collect data from them when needed. Thus, the only thing to consider would be the range of the wake-up signals. Using WuR in the context of mobility would lead to energy consumption reductions and more reliable networks.

4 RSSI and Range Analysis

4.1 Protocol

To determine the range capabilities of the on-board BLE radio, we used RSSI (Received Signal Strength Indicator) as an indicator of the signal quality at different ranges. From this data, we can determine how the range affects the quality of the signal and at which point the signal is too weak to be processed. RSSI is measured on a scale going from 0 dBm (closest) to -127 dBm (farthest). The signal power can be determined theoretically by considering the signal waves as electromagnetic waves obeying the mechanism of reflection, diffraction and scattering [16].

The obtained formula for the RSSI on the receiver side is as follow :

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

- Pr: strength of the received signal
- η: signal propagation exponent
- d: relative distance between devices
- A: nominal transmission power at 1 m

For the experiment, we measured RSSI levels between two identical boards, one board was sending data periodically while the other one was in reception mode and logged the RSSI level to a serial monitor for later analysis. We measured RSSI levels with this configuration for different ranges in step of 10 cm up to 1 meter and then further increased the steps to get long range data. For each fixed distance, we took at least 40 data points to then make an average of the RSSI signal measured for better precision. We then exported the logged data as CSV files and then used a Python script for the analysis and graph generation. We determined empirically that the parameters A and η had a value of -80 and 3 respectively for the theoretical formula.

4.2 Measurements

As can be seen by the results below in Fig.4, the signal strength is first losing strength rapidly below 2 meters and then steadily decreases. The signal strength is optimal for a distance lower than 2 meters as it stays higher than -60 dBm which assures an optimal transmission of desired data.

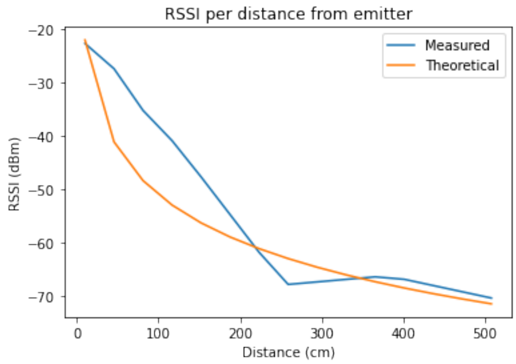


Fig. 4 RSSI measurements

The results of this experiment shows that it becomes harder to measure the signal strength at higher distances because of the noise and interference. Furthermore, this experiment was made indoor and thus the metallic room furniture could also disturb the measured data. To better measure RSSI at high distances, it would be preferable to do a similar experience outdoor.

5 Energy Mode Consumption

5.1 Protocol

In order to determine the consumption of each energy mode, we used an Otii, an accurate energy analyzer. We tested 5 energy modes (from EM0 to EM4). While in EM0, called Active/Run Mode, all peripherals can be enabled and we can take advantage of an high performance when needed. As the energy mode increases, fewer peripherals are available and the performance level is lowered [8] (Fig.3). Fig.5 shows a snapshot of the experiment with the used Otii.

For each measurement, we execute a script on the controller that will activate the specified energy mode after a short while. Once activated, we wait a few seconds in order to be able to have an average consumption.

5.2 Energy Consumption

Results of the different EM are shown in Table 2 and compared in the bar chart of Fig.6. The *transition* bar represents the consumption during the short delay before setting the desired energy mode. The *Energy Saving Mode* bar represents the consumption once the EM is activated. EM0/EM1 and EM2/EM3 seem to have the same energy consumption for two reasons. First, the difference between some energy modes only affects the transmission and the reception of data which we did not test. Second, the debugger of the board, which consumption is significant, could only be disabled in EM4. This problem also appear in the comparison with manufacturer values. Nevertheless, we can see that when in EM4, as the debugger is disabled, the measured consumption is approaching manufacturer values. Although the cards used aren't optimized, it is apparent that EM4 is much more interesting in terms of energy efficiency as it allows to reduce energy consumption by a factor of approximately a thousand when waiting for a WuR packet.

Table 2 EM values comparison

Energy Mode	Manufacturer value	Measured value
EM0	1497 µA	1460 µA
EM1	960 µA	1460 µA
EM2	2 µA	1030 µA
EM3	1.34 µA	1030 nA
EM4	440 nA	442 nA

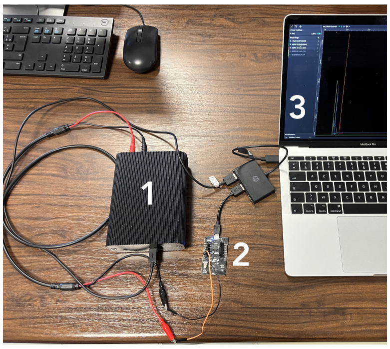


Fig. 5 Energy consumption measurement.
1. Otii Arc; 2. Microcontroller; 3. Otii software (www.qoitech.com)

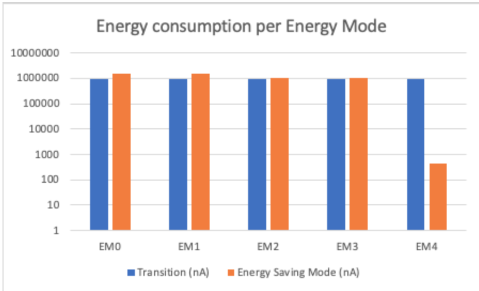


Fig. 6 Graph of energy mode consumption

6 Wake Up Implementation

6.1 Protocol

The carrier used for WuR, 2.4 GHz, is vulnerable to interference. The protocol has taken this into account and gives us two options :

- *Legacy mode*
  The microcontroller uses a time-based filter to recognize WuR packets. We can chose to sense for a given band and for a certain amount of time in microseconds. Particularly, it is advised to choose a longer sensing time for noisy environments.
  To implement the wake up, we used Silicon Labs RAIL API [17]. The function responsible for this functionality is `RAIL_StartRfSense`. The receiving node should call this before going to EM2 or EM4 in order to be woken up. As soon as energy has been sensed on the RF for the specified time, it switches to EM0. Note that it is needed to call `RAIL_StartRfSense` again in order to be able to reuse the WuR.
- *Selective mode*
  This solution adds authentication to the protocol by using a sync-word. It is made up of 1 to 4 bytes that should match between the sending and receiving node. This prevents accidental wake-ups but does not prevent sniffing.
  In order to use this mode, the setup is different on both ends. We used an example provided by Silicon Labs for the API showed in Fig.7 and Fig.8.

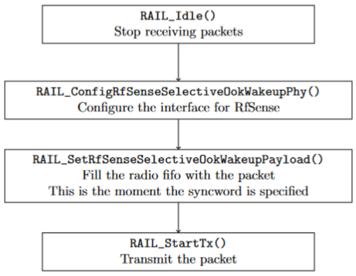


Fig. 7 Sending device configuration

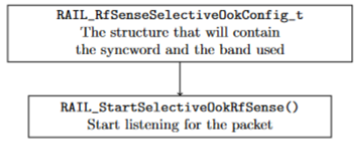


Fig. 8 Receiving device configuration

6.2 Wake-Up example

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

- *Receiving board*
  This command enables WuR with the syncword and then sets the node to EM4.
  ```
  sleep 4 2 0xB16F 1
  ```
  We receive a log that the WuR packet is sensed when another board send a signal.
  ```
  {{(sleepWoke)}{EM:4s}{SerialWakeup:No}{RfSensed:Yes}}
  ```
- *Sending board*
  These commands set the configuration for RfSense, the setup of the syncword and send the packet.
  ```
  configRfSenseWakeupPhy
  fifoModeTestOptions 1 0
  setRfSenseTxPayload 0x2 0xB16F
  tx 1
  ```
  We receive a response indicating that the packet is correctly sent.
  ```
  {{(txEnd)}{txStatus:Complete}{transmitted:1}{lastTxTime:
  187755304}{timePos:6}{lastTxStart:187703928}{ccaSuccess:0}
  {failed:0}{lastTxStatus:0x000000000}{txRemain:0}{isAck:False}}
  ```

6.3 RSSI Impact on WuR

We first experimented WuR technology in both indoor and outdoor environments. For an indoor environment, the maximum distance at which two boards can wake up is 11 meters with a RSSI of -70 dBm. Outdoor, we can reach 20 meters with a RSSI of -75 dBm. We reiterated our experiment in another indoor environment but this time, the range was much more different as we couldn't wake up further than 25 cm. We concluded that interference highly disturb the maximum range achievable. Results are also affected by the antenna on board, which could be replaced by a more sensitive antenna or benefit from an active amplification stage.

7 Conclusion

In this paper, we considered the topic of improving low energy consuming networks using WuR technology. An introduction of the microcontroller used for our study was presented along with our approach. We provided a state of the art on WuR, detailing a variety of possible hardware and software configurations with their advantages and drawbacks. We studied via RSSI and range parameters the capabilities of the used on-board BLE radio and found that above 2 meters, optimal transmission cannot be guaranteed in an indoor environment. We also determined the energy consumption of the microcontroller in it's several energy saving modes and compared it to manufacturers value. We concluded that EM4 was an interesting trade-off. Finally, we have been able to test the WuR capability of the EFR32BG22 and we successfully achieved wake up from EM4. Despite that success, more studies are needed to determine the best conditions for a WuR-based network in an industry, using improved boards. This paper is an exploratory study on IoT as part of the I2RM (21-SIOM-0007-02) project funded by the French National Research Agency.

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