# Ultra Low Power Asynchronous MAC Protocol using Wake-Up Radio for Energy Neutral WSN

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## ABSTRACT

To extend the system lifetime of WSN, energy harvesting techniques have been considered as potential solutions for long-term operations. Instead of minimizing the consumed energy as for the case of battery-powered systems, the harvesting node is adapted to Energy Neutral Operation (ENO) to achieve a theoretically infinite lifetime. Therefore, consumed energy due to communications is the critical issue to increase the system performance. In this paper, a nanowatt wake-up radio receiver (WUR) is used cooperatively with the main transceiver in order to reduce the wasted energy of idle listening in asynchronous MAC protocols where the node is waiting for potential messages, while still maintaining the same reactivity. Simulation results show that the throughput can be improve up to 82% with 53% energy saving compared to non-WUR approach of the TICER protocol. Our simulations are performed on OMNET++ with three different widely radio chips CC2420, CC2500 and CC1100 using models with measured data.

## Categories and Subject Descriptors

C.4 [**Performance of Systems**]: Measurement Techniques; C2.2 [**Network Protocols**]: Protocol architecture

## General Terms

Experimentation, Measurement, Performance, Theory

## Keywords

Energy harvesting, MAC protocol, wake-up radio receiver

## 1. INTRODUCTION

WSN consists of a large number of wireless nodes, which are densely deployed in remote places and cooperatively transmit collected data to base stations via radio frequency (RF) communications [2]. Many types of sensors including seismic, magnetic, thermal, visual, infrared and acoustic provide various monitoring applications ranging from home automation, automotive industry to patient healthcare [19]. However, limited energy in batteries cannot meet long-term operations in such applications. To overcome this problem, WSN may rely on environmental energy sources such as solar [17], wind [16] and thermal [11]. Since the ambient energy can be scavenged as long as desired, the system can reach a theoretically infinite lifetime.

Moreover, a power manager (PM) is embedded in the energy harvesting node to adapt the consumed energy and computation loads according to the harvested energy. The PM ensures that the consumed energy is equal to the harvested energy over a long period. This leads to an Energy Neutral Operation (ENO) [8] energy harvesting (EH) WSNs. Adaptive duty cycle is the most popular PM technique in recent approaches [8][15] [6] as it is used to control the radio activity (MAC protocol), which is usually the dominant component of the consumed energy in WSN applications [5].

When the node has satisfied the ENO, optimizing the consumed energy of MAC protocols is the key to increase Quality of Service (QoS) of the system. Idle listening is the most wasted energy in asynchronous MAC protocols as the node does not know when it is allowed to transmit. Most of the time the radio is consuming while idle, just waiting to awake to be reactive. In this paper, a nano-watt wake-up radio receiver (WUR) in [14] is embedded in an EH-WSN node in order to drastically reduce the idle listening time, which is the most significant source of energy consumption in MAC protocols, especially with asynchronous protocols [5]. We focus on system level considerations for a single-hop EH-WSN (see Fig. 1), where a base station node (BS) (Node[0]) collects data from other end device nodes (ED) (Node[1...N]). Particularly, the performance of the TICER protocol (Transmitter Initiated Cycled Receiver) [12] with and without the WUR is investigated in an autonomous EH-WSN.

The rest of this paper is organized as follows. In Section II, related works are presented. The architecture of the EH-WSN node with a WUR is depicted in Section III. The duty-cycle PM which adapts the wake-up period of the WSN node to satisfy ENO is explained in Section IV. The TICER protocol based WUR is proposed in Section V. Simulated results are presented in Section VI. Finally, the paper ends with conclusions (Section VII).

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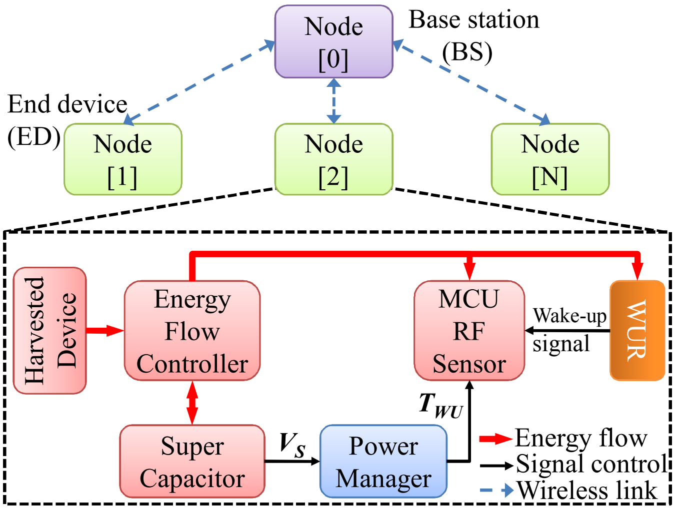

**Figure 1: Single-hop EH-WSN with a base station and $N$ end device nodes . All the nodes are equipped with a harvested device and a super-capacitor for energy storage. The PM adapts the wake-up period ($T_{WU}$) of the node to respect ENO. The MCU and RF are only wake up by the WUR whenever there is a ready transmission from an ED node.**

## 2. RELATED WORK

A variety of methods and techniques to reduce power consumption and increase energy efficiency are proposed in recent years. Reducing the RF energy consumption of the devices significantly reduces the power consumption so there are a number of novel hardware (e.g. wake-up radio receivers), software (e.g. MAC and routing algorithm) and duty cycle optimization approaches in this field [4][10]. WUR is one of the most promising technology to achieve the goal of power reduction for RF and research in this field was particularly prolific in the past few years. With additional low cost and low power hardware it is possible to switch off instead of idle saving energy.

In [7] and [18], authors present simple architectures for ultra-low power WURs to achieve a reduction of sensor node listening activities (e.g. MAC layer receive checks), drastically reducing the overall network power consumption. The fundamental requirement for a WUR is the ability to continuously listen to a wireless channel and trigger events with negligible latency for significantly (e.g. one or more orders of magnitude) less power than the regular transceiver. This increases network flexibility and reduces the overall power consumption. Many advantages of WUR are presented in [9] where it was estimated that a specialized radio interface could consume as little energy as $1\mu W$. The WUR [13] used in this work is fully featured, with only 300nW (@3.3V) power consumption. Features include addressing and command capabilities, in addition to SPI interfacing with the smart power unit.

Although the consumed energy is reduced, providing a potential improvement on QoS of the system, its main goal is to obey the ENO condition. To achieve this, there are many works adapt the wake-up period of the wireless node to balance the harvested and consumed energy. A low complexity PM in [8] is modelled as a linear program, with the objective to optimize the average wake-up period. Their approach takes advantage of the periodic energy source when photovoltaics (PV) are used in an outdoor environment. Indeed, the harvested energy can be predicted based on previous samples. A cycle lasting for a day is split into slots of the same duration (e.g. 30 minutes) and adaptation calculations are performed at the end of each slot. To ensure the ENO, the residual energy (the difference between predicted energy and real harvested energy) of previous slot is used in future slots. However, the initial wake-up period of slots are determined at the beginning of a day and are only based on the harvested energy of a previous day. Therefore, when there is a change from a sunny to a cloudy day, or vice versa, the PM performs poorly. The ENO concept is extended in [15] by using a class of linear programs to model various constraints such as the sensing rate or the local memory access.

The Opened-Loop and Closed-Loop PM in [6] improve the throughput of a WSN node up to 50% compared to [8]. The harvested energy is approximated by a function of the light intensity from a luminance sensor (expressed in $lux$). Meanwhile, the consumed energy is the average current delivered from the battery during a period and is computed independently for each activity of the WSN node (e.g. sensing, RF transmission). Their approach takes advantage of a dynamic adaptation period to trade-off between the computation overhead and the reactivity of the PM. Simulation results are based on the TI EZ430, a real solar EH-WSN platform with a PV in size of 2.25in x 2.25in.

However, these PMs are applied for rechargeable battery based EH-WSN, which has a limited system lifetime (due to limited recharge cycles of the battery). Super-capacitor (SuperCap), which has virtual recharge cycles compared to the rechargeable battery, is widely used as storage device in EH-WSN [16][11]. Moreover, the remaining energy in a SuperCap can be easily estimated according to its voltage [11]. Unfortunately, the leakage energy of a SuperCap is higher than a battery [20] and therefore, needs to be considered by the PM as a part of total consumed energy.

In our simulations, the PM in [11] is used as it is constructed for the SuperCap based EH-WSN. Moreover, its adaptations are mostly based on the voltage of the SuperCap and therefore, are independent of harvested source and easy to implement. When the consumed energy is reduced by using the WUR, the PM is able to increase the QoS of the node while still satisfying ENO condition. Specifically, the QoS is investigated by using TICER protocol with three widely used RF chips, including CC2420, CC2500 and CC1100.

## 3. EH NODE WITH NANO-WATT WUR

The EH node in this paper is based on the PowWow platform [1] and is shown in Fig. 1. The energy extracted from harvested device is distributed by an energy flow controller to satisfy two different scenarios in EH-WSN. When the harvested energy is greater than the consumed energy, the surplus energy will charge the SuperCap. Otherwise, when the harvested energy is not sufficient to supply the WSN node, the remaining energy will be served by the SuperCap. The improvement in this platform is the use of the WUR to re-

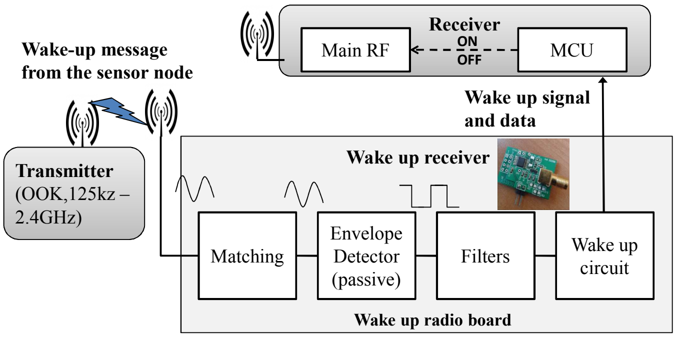

**Figure 2: Multi frequency nano-watt wake-up radio.**

duce idle listening in wireless communications and therefore, reduce global energy consumption.

The main advantage of the WUR is the power consumption reduction of the main radio (MRF). In fact the WUR allows the switching off of the MRF when no data is needed in the idle listening keeping the node ready to react when needed. The WUR can detect wake up signal then it generates an interrupt to wake-up the MRF or other devices. The WUR allows a device to sleep and wake up by an ad-hoc message from another device. Thanks to the ultra low power consumption of the WUR (order of $\mu$W or less) and its fast reactivity ($\mu$s) this technique can almost cancel the energy wasted in the MRF while idle with no data communication.

The wake-up receiver is always on sniffing the channel and can receive wake-up messages sent by a transmitter (the ED in this work, when it wants to wake up the BS node). The Gaussian Frequency Shift Keying (GFSK) modulation is used for data transmission and Gaussian On-Off Keying (GOOK) Pulse Width Modulated (PWM) mode is used for the wake-up packets [9]. The frequency of the WUR can be adapted to every frequency from 125KHz to 2.4Ghz to be flexible with different kind of transmitters. However, this parameter significantly impacts the features of the WUR mainly the communication range. Fig. 2 shows the nano-watt WUR internal blocks and its connection to the ED node. The impedance matching block is needed to provide the maximum power transfer and it needs to be designed carefully since it can drastically decrease the performance. After the impedance matching, the analog signal is rectified by an envelope detector in order to extract the digital signal. The WUR detects the preamble (wake-up signal), then after the filtering and wake-up circuit blocks, generates an interrupt (WUp-Int) which is connected directly to the MCU. The last block provides three pins to read the demodulated wake-up packet as a digital stream on the SPI. This feature is not used in this work. These messages could contain the address and configuration commands for the sensor node. This is important to achieve the radio wake-up addressing and wake up only the right node or to implement various power policies through the command mode. More information on this device can be obtained from [13].

## 4. DUTY-CYCLE POWER MANAGER

In this paper, a low complexity PM in [11] is applied to converge the EH node to ENO. This PM adapts the duty cycle of the node according to the estimation of harvested energy and the consumed energy provided by a simple energy monitor. The time domain is divided into slots $T_S(n)$ and the PM is carried out at the end of each slot. The duration of each slot is different and dependent on current wake-up period as it is a multiple $k$ of current wake-up period ($T_{WU}(n)$). As it has been demonstrated in [11], this dynamic adaptation period provides better convergence to ENO. The architecture of the PM is depicted in Fig. 3. By reading the current voltage of SuperCap ($V_S$) and looking into a table (LUT) characterizing consumed energy of atomic functions, the harvested power ($\tilde{P}_H(n)$) and the consumed energy of the node in an active period ($\tilde{e}_{Active}(n)$) are estimated by an energy monitor. Then, an energy predictor using an Exponentially Weighted Moving Average filter (EWMA) [8] predicts the harvested power and the consumed energy in the next slot ($\hat{P}_H(n+1)$ and $\hat{e}_{Active}(n+1)$). Both of them are used to determine the next wake-up period ($T_{WU}(n+1)$).

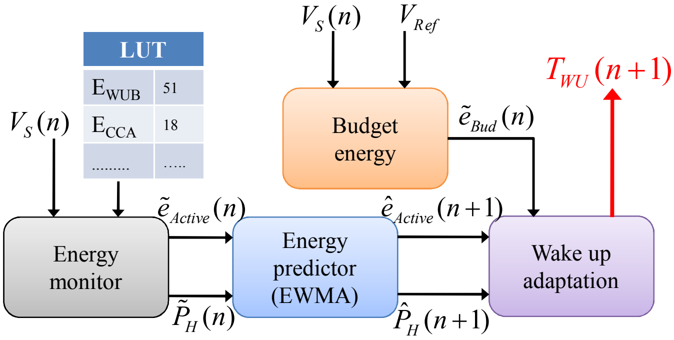

**Figure 3: Duty-cycle power manager for super capacitor based EH-WSN.**

We define $V_{Ref}$ as the desired voltage of the SuperCap in ENO. Therefore, the difference of energy between current state and ENO state can be considered as the budget energy ($\tilde{e}_{Bud}(n)$) for the next slot and is defined as follows:

$$\tilde{e}_{Bud}(n) = \frac{1}{2}C_S(V_S^2(n) - V_{Ref}^2) \qquad (1)$$

where $C_S$ is the capacitance of the SuperCap. Finally,

$$T_{WU}(n+1) = \frac{[\hat{e}_{Active}(n+1) - \eta\tilde{e}_{Bud}(n)]/k}{\eta(\tilde{P}_H(n) - P_{Leak}) - P_{Sleep}} \qquad (2)$$

where $\eta$ is the harvested energy conversion efficiency, $P_{Leak}$ is the leakage power of the system and $P_{Sleep}$ is the consumed power in sleep mode.

## 5. WUR BASED TICER PROTOCOL

In the context of energy efficient MAC, the TICER protocol is widely used in the asynchronous WSN as synchronizations are not required in order to provide optimal energy consumption. Instead of only one RF, the protocol in this work extended from TICER, named WUR-TICER, is implemented from a combination of a MRF and a WUR. The basic communication between two nodes using WUR-TICER is depicted in Fig. 4. When the transmitter has a packet, it broadcasts a wake-up beacon (WUB) which indicates to its receivers that it is ready to send. The receiver, even if in sleep mode with the MRF off, is able to receive an ap-

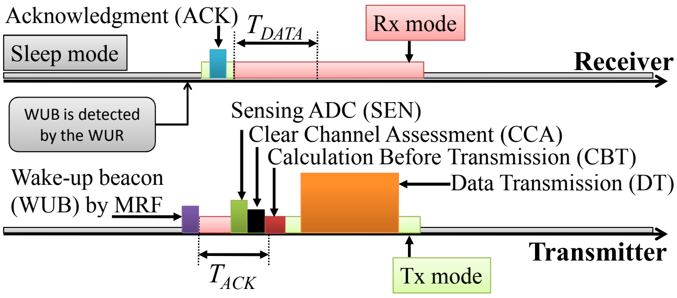

**Figure 4: Communication between two nodes by WUR-TICER protocol.**

propriate WUB by the WUR. Once successfully receiving the WUB, the MRF is wake-up to transmission mode (Tx mode) in order to answer an acknowledgment packet (ACK). Meanwhile, the MRF at the receiver turns into reception mode (Rx mode) and opens a window for idle listening the ACK. The maximum idle time for ACK packet is $T_{ACK}$. As soon as the ACK is received, the receiver performs sensing from its sensor through an ADC channel (SEN), Clear Channel Assessment (CCA) and Calculation Before Transmission (CBT) before transmitting a data packet (DT). Then, the transmitter turns into sleep mode until the next wake-up. At the receiver end, after sending the ACK, the MRF is switched to Rx mode for a data packet (DR). If there is no data signal from the transmitter after a predefined period $T_{DATA}$, the receiver immediately runs into sleep mode. Otherwise, it waits until the reception process is complete before running into sleep mode.

By using the WUR, the idle listening at the receiver by the MRF is not required anymore. This strategy provides a potential solution to reduce the global consumed energy as idle listening is the dominant wasted energy in WSN. It also brings a breakthrough to increase the QoS in EH-WSN.

# 6. SIMULATION RESULTS

In this section we will show the benefits of WUR-TICER and the simulation results of our approach using OMNET++ environment.

## 6.1 Simulation setup

The single-hop EH-WSN shown in Fig. 1 has been implemented in OMNET++ with four nodes ($N = 4$): one BS and three ED nodes. The WUR-TICER protocol depicted in Fig. 4 is used for communicating between an ED and the BS. The maximum idle listening for ACK and DT packet ($T_{ACK}$ and $T_{DATA}$) are set to 10ms. Each node is equipped with the same harvested power profile which is extracted from a real PowWow node in our office with a PV of size 4x6cm is presented in Fig. 5. SuperCap with capacitance $C_S = 0.18$F is used for the energy storage. The leakage power of the system is $P_{Leak} = 53\mu$W and energy conversion efficiency $\eta = 0.85$. These values are characterized on a real PowWow node and are gathered in our simulations.

Our simulations are performed with three popular MRF, including CC2420, CC2500 and CC1100. The consumed energy for each state when communicating is summarized in Table 1. This LUT is used for the duty-cycle PM presented in Fig. 3, which is implemented in each node to respect ENO condition. The resolution of the wake-up period is set to 0.5s. The reference voltage $V_{Ref} = 4$V and $k = 10$. Following metrics are used to evaluate the performance of the system:

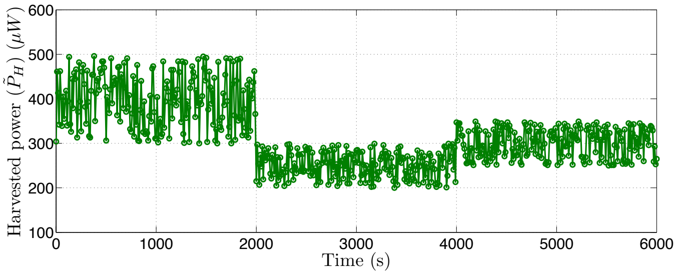

**Figure 5: Harvested power profile in our simulation. In the first 2000s, the light intensity is around 800lux. Meanwhile, in the next 4000s, the light intensity is reduced to 500lux.**

**Table 1: Energy consumption model for MRF CC2420, CC250 and CC1100 in our simulation. These energy values are refered to real measurements in [3].**

| Symbol | CC2420 | CC2500 | CC1100 |
|---|---|---|---|
| $E_{CBT}$ ($\mu$ J) | 9.7 | 9.7 | 9.7 |
| $E_{WUB}$ ($\mu$ J) | 51 | 47 | 42 |
| $E_{ACK}$ ($\mu$ J) | 51 | 47 | 42 |
| $E_{DT}$ ($\mu$ J) | 80 | 98 | 69 |
| $E_{DR}$ ($\mu$ J) | 100 | 73 | 79 |
| $E_{CCA}$ ($\mu$ J) | 18 | 14 | 11 |
| $E_{SEN}$ ($\mu$ J) | 27 | 27 | 27 |
| $P_{Tx}$ (mW) | 66.33 | 69.96 | 57.75 |
| $P_{Rx}$ (mW) | 76.89 | 56.10 | 61.05 |
| $P_{Sleep}$ ($\mu$W) | 85.8 | 21.12 | 22.77 |

- Packet received Data-Rate ($PDR$) (bits/s) : It is defined as the ratio between the size of the packet (128bits) and the average wake-up period.
- Packet Received Rate ($PRR$) (%) : the ratio between the total correctly received packet at the BS node and the total transmitted packet from all ED nodes.
- $IDL_{Tx}$ and $IDL_{Rx}$ (ms) : the average idle listening time at ED nodes and the BS node.
- $E_{Tx}$ and $E_{Rx}$ ($\mu$J) : the average consumed energy at ED nodes and the BS node for one successful packet.
- $E_C$ ($\mu$J): the average consumed energy for one successful packet from both BS and ED nodes.

## 6.2 Performance analysis

First, the simulation is performed on non-WUR platform which uses only the MRF CC2500 for wireless communication. Therefore, whenever the BS wakes up, MRF CC2500

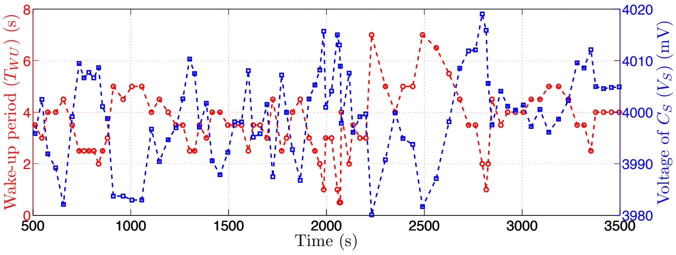

**Figure 6: Wake-up period ($T_{WU}$) and voltage of SuperCap ($V_S$) in non-WUR model. The CC2500 is used as the MRF in this simulation.**

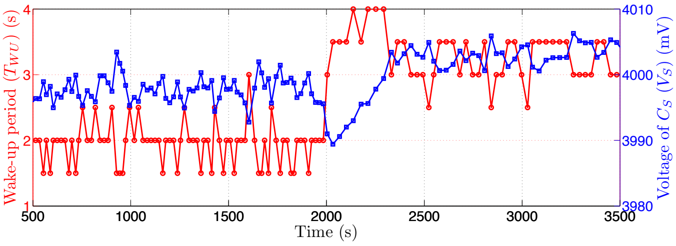

**Figure 7: Adaptations of the ED (Node[1]). At 2000s, the wake-up period is increased 1s in average due to bad harvesting energy conditions.**

is turned into Rx mode and performs idle listening a WUB from an ED. The maximum idle listening time is set to 50ms. During this period, if there is no appropriate WUB, the BS runs into sleep period lasting for $T_{WU}(n)$, which is updated by the PM after $k = 10$ wake-up times. Fig. 6 shows adaptations of the BS from 500s to 3500s. $T_{WU}$ is adapted to keep the voltage of the SuperCap ($V_S$) around 4V that represents the ENO condition. During the first 2000s, the average wake-up period is 3.5s and after, when the harvested energy is lower, it is around 3.8s. The degradation of the harvested energy causes a negligible effect on the wake-up period as the consumed energy has a high ratio compared to $\tilde{P}_H$ ($\tilde{e}_{Active}$ is around 1485$\mu$J for a successful data reception). Meanwhile, Fig. 7 shows the adaptations of Node[1], an ED node in the simulation. In contrast to the BS node, there is a considerable change of $T_{WU}$ at the ED node when the harvested energy is reduced since the consumed energy for a data transmission is only around 693$\mu$J and has a low ratio compared to $\tilde{P}_H$. The average of $T_{WU}$ is 1.9s at the first 2000s and increased to 2.8s in the next 4000s.

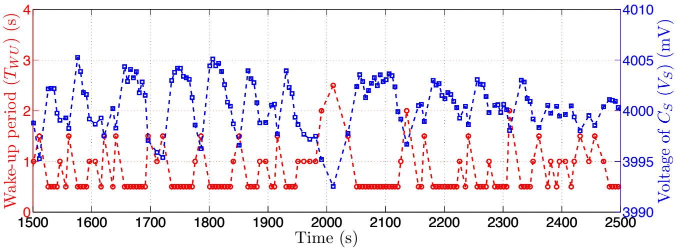

**Figure 8: The QoS of the BS is drastically improved as idle listening for the WUB is not required.**

Second, the WUR is integrated into our simulation. Since the BS node does not require opening the idle listening window by MRF CC2500, it can save up to 85% of the consumed energy. As a consequence, the average wake-up period is only 0.8s, which is much more lower than the non-WUR model (3.7s). Fig. 8 presents adaptations of the BS when the WUR is used. The wake-up period is usually staying at the minimum value (0.5s). However, there is only a small improvement at the ED (1.8s with WUR and 2.4s without WUR). The behaviour of ED in this context is almost similar to non-WUR model as wasted energy issue due to idle listening is handled at the BS node.

Finally, the simulation has been performed on two more radio chips, CC2420 and CC1100, and the results are gathered in Table 2. When considering the traditional EH-WSN platform with only MRF for TICER protocol, there is much more wasted energy due to idle listening at the BS node. The time spent by the ED nodes for a WUB is 28.94ms, 25.88ms and 20.98ms for CC2420, CC2500 and CC1100, respectively. When the WUR is cooperatively used with the MFR, the idle listening time is strongly improved by 75%, 69% and 63%. By using the WUR, the idle listening at the BS (IDL_Rx) is significantly reduced compared to non-WUR model. As a consequence, the QoS is improved by 82%, 74% and 79% while the average consumed energy for one complete communication is reduced to 53%, 45% and 40% for CC2420, CC2500 and CC1100, respectively. The whole networks with WUR is more active than without WUR and therefore, provides better QoS in monitoring applications. However, there is only a small improvement idle listening time and also the consumed energy at the ED node (IDL_Tx and E_Tx) since there is a short idle listening period for ACK packet ($T_{ACK}$ = 10ms) in the WUR-TICER protocol.

Although WUR-TICER can save a great deal of consumed energy and increases the QoS, the PRR is lower than the non-WUR model. As the traffic is busy with a burst of packet transmissions when using the WUR, data collisions are frequent. Moreover, there are also WUB collisions when two or more ED nodes wake up at the same time and try to send a WUB to the BS.

## 7. CONCLUSIONS

In EH-WSN, while the PM keeps the node in ENO mode, reducing the wasted energy due to idle listening is the key to optimize the consumed energy and increase the QoS of the system. In this paper, a nano-watt WUR is applied to provide an ultra low idle listening when considering TICER protocol for wireless communications. This approach can improve up to 82% QoS and 53% energy saving at the BS where a long idle listening window is opened before each data reception. However, there are data and wake-up beacon collisions in a high traffic network that reduces the average data received rate by 5.39%. Future works will concentrate on providing a scheme to reduce these collisions and validate the simulation on a multi-hop EH-WSN.

## 8. ACKNOWLEDGMENTS

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**Table 2: System performance on different radio chips, including CC2420, CC2500 and CC1100. The QoS is improved 82%,74% and 79% while the energy for one successful communication is reduced 53%, 45% and 40%, respectively.**

| | CC2420 | | | CC2500 | | | CC1100 | | |
|---|---|---|---|---|---|---|---|---|---|
| Metrics | Non-WUR | WUR | Gain (%) | Non-WUR | WUR | Gain (%) | Non-WUR | WUR | Gain (%) |
| PDR (bits/s) | 11.39 | 64.00 | 82 | 17.64 | 68.12 | 74 | 12.71 | 62.76 | 79 |
| PRR (%) | 84.23 | 82.53 | - | 88.07 | 76.94 | - | 82.09 | 78.73 | - |
| IDL_Tx (ms) | 9.40 | 7.57 | 19 | 9.35 | 7.70 | 18 | 9.44 | 7.81 | 17 |
| IDL_Rx (ms) | 28.94 | 7.13 | 75 | 25.88 | 8.03 | 69 | 20.98 | 7.74 | 63 |
| E_Tx ($\mu$J) | 959.47 | 818.75 | 15 | 767.24 | 674.67 | 12 | 781.56 | 682.05 | 13 |
| E_Rx ($\mu$J) | 2411.17 | 771.14 | 68 | 1628.48 | 639.47 | 61 | 1462.76 | 657.97 | 55 |
| E_C ($\mu$J) | 3370.64 | 1589.89 | 53 | 2395.72 | 1314.14 | 45 | 2244.33 | 1340.02 | 40 |

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