SNW-MAC: an Asynchronous Protocol Leveraging Wake-up Receivers for Data Gathering in Star Networks

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Abstract. A widespread approach to extend lifetime of battery-powered wireless sensor nodes is duty-cycling, which consists in periodically switching on and off node transceiver. However, energy waste in idle listening periods is still a bottleneck. These periods can be completely removed using emerging ultra-low power wake-up receivers, which continuously listen to the channel with negligible power consumption. In this paper, an asynchronous medium access control protocol is proposed for data gathering in a star network topology. The protocol exploits state-of-the-art wake-up receivers to minimize the energy required to transmit a packet and to make collisions impossible. The proposed approach has been implemented on a real hardware platform and tested in-field. Experimental results demonstrate the benefits of the proposed approach in terms of energy efficiency, power consumption and throughput, which can be up to more than two times higher compared to traditional schemes.

1 Introduction

Wireless Sensor Networks (WSN) constitute a key technology to fulfill the increasing need of interaction between virtual and physical worlds for applications in environmental, healthcare, security, and industrial domains. WSN nodes are made of several subsystems such as processing unit, sensors, wireless communication and energy management to achieve the goal of collecting and processing data from sensors, and wirelessly send information to a remote host [5]. Typical WSNs usually have limited energy resources. As communication is the most power hungry task, great efforts are made to design network protocols at the Medium Access Control (MAC) layer [5] and techniques that rely on duty-cycling [16] turn out to be good candidates that fulfil the energy requirements of WSNs.

In duty-cycling, nodes are periodically powered on and off according to their own specific schedule while establishing on demand *rendez-vous* that can be initiated by the transmitter or the receiver [10]. Because idle listening periods are needed to perform the *rendez-vous* process, these approaches are referred to as *pseudo*-asynchronous in the literature [5]. Employing Ultra Low Power (ULP) Wake-up Receiver (WuRx) circuits allows significant simplification of the MAC protocols, as it enables asynchronous on-demand communication. The energy overhead incurred by the rendez-vous process is therefore eliminated [8].

The main feature of ULP WuRx is to consume power in the micro or nano Watt range, which is negligible when compared with the main radio that consumes milliwatts when active [3,11,13,17]. ULP WuRx can therefore continuously listen to the wireless medium while keeping the main transceiver in sleep state. When the node is in sleep state, the ULP WuRx is the only active component waiting for a specific signal, called Wake-up Beacon (WuB), sent by a neighboring node [3, 11, 13, 14]. Moreover, many ULP WuRx embed address matching features, which allow nodes to wake up only a specific node and not all their neighbors [17, 18].

Specific MAC protocols need to be designed to exploit the new potentiality offered by ULP WuRx. The first contribution of the paper is a novel asynchronous MAC protocol that focuses on star network topology, where all nodes are connected to a central sink that collects the data. SNW-MAC (Star Network WuRx - MAC) leverages ULP WuRx to minimize the energy required to transmit a packet and to make collisions impossible in the context of star networks. The second contribution of the paper is the experimental evaluation. SNW-MAC was implemented and tested in field conditions, using the Powwow platform [4] that embeds energy harvesting capabilities and a state-of-the-art ULP WuRx [11]. A comparison with state-of-the-art has been performed by implementing two traditional low-power MAC protocols on the same hardware.

The remainder of this paper is organized as follows. After giving a state-of-the art of MAC protocols that leverage WuRx, Section 2.1 introduces the star network topology and details the design of SNW-MAC. The experimental setup used to evaluate our approach is exposed in Section 3. Section 4 presents the experimental results with the in-field deployment of six Powwow nodes powered by indoor light. Finally, Section 5 concludes this paper.

2 Star Network WuRx - MAC protocol

2.1 State-of-the-art MAC protocols leveraging WuRx

As ULP WuRx is an emerging technology, only a few research studies were conducted on designing dedicated MAC protocols. WUR-MAC [12] was the first MAC protocol that takes advantage of ULP WuRx, using a multi-channel transmitter-initiated approach based on the request-to-send/clear-to-send handshake mechanism. Each node captures all incoming request-to-send and clear-to-send frames, and therefore has the information about which channel is used by its neighbours. When it wants to communicate, it randomly chooses a free channel and sends a request-to-send frame containing the chosen channel. *Sutton et al.* proposed Zippy [18], a flooding protocol based on ULP WuRx. To the best of our knowledge, this is the only solution that has been implemented on real sensor nodes. In a previous work, we introduced OPWUM [2], an opportunistic forwarding MAC using timer based contention for next hop relay selection and

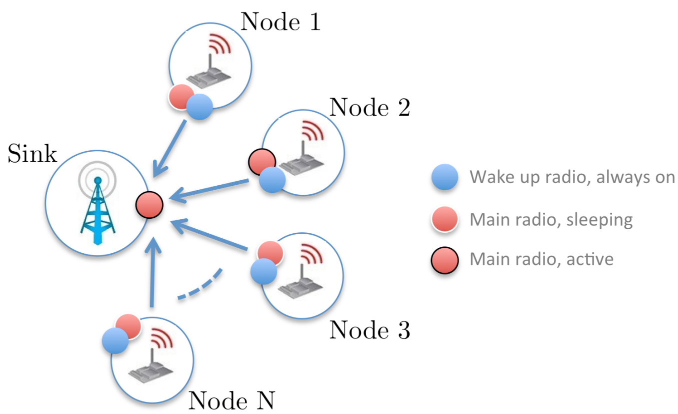


Fig. 1: Star network topology.

leveraging ULP WuRx. The protocol proposed in the present work is specially designed for star networks, and, unlike most of the previously cited protocols, was implemented on sensor nodes and compared to state-of-the-art MAC protocols.

In this section, the proposed SNW-MAC protocol exploiting ULP WuRx for data gathering star networks is presented. SNW-MAC enables asynchronous communication, minimizing the energy required to transmit a packet and making collisions impossible in the context of star networks. It is assumed that a physical layer (PHY) providing an error detection mechanism is used. For example, the widespread IEEE 802.15.4 PHY provides a Cyclic Redundancy Check (CRC) error detecting code.

2.2 Design of SNW-MAC

The target star network topology is illustrated in Fig. 1. The network is composed of two types of nodes. The sink initiates the communication and gathers the data from the nodes. It uses only one main transceiver (IEEE 802.15.4 PHY in our experiments), which is always on. On the other hand, the nodes are equipped with both a main transceiver and an ULP WuRx. The WuRx is always on, while the main transceiver is turned on only on demand from the sink.

SNW-MAC relies on receiver-initiated approach to minimize the energy consumption of WSN nodes. Packet transmission using SNW-MAC is illustrated by Fig. 2. The sink initializes a communication by sending a WuB containing the address of a specific sensor node, and then listens to the channel to receive the data packet. The targeted sensor node is awaken by its ULP WuRx, and starts sending the data packet. Compared to traditional receiver-initiated protocols, this approach reduces the energy consumption of the sink and the nodes as no rendez-vous process is required. The sink energy consumption is further reduced as useless periodic WuBs sending are avoided.

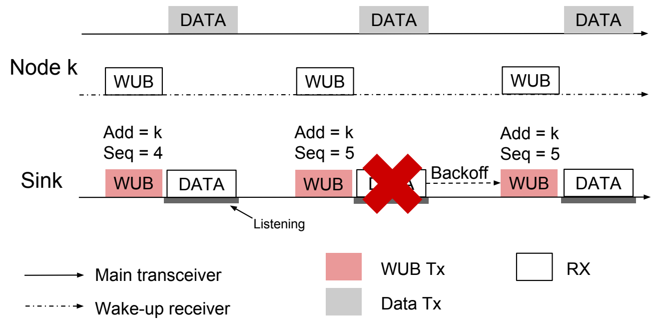


Fig. 2: Packet transmission using the SNW-MAC.

2.3 Error control and retransmission

By coordinating data packet transmission at the sink, SNW-MAC cancels the risk of collisions compared to traditional pseudo-asynchronous schemes as each node is specifically polled. However, wireless channel interferences may lead to corrupted frames, and energy-efficient error control and packet retransmission is therefore an important issue. As the sink is entirely in charge of coordinating the packet transmission, it is responsible for detecting transmission error and scheduling another attempt. To this aim, a 19 bit long WuB is used and its structure is described in Fig. 3. It is composed of 3 synchronization bits, the 8 bit address of the wireless sensor node to be polled and the 8 bit sequence number of the expected data packet.

The sink keeps an updated table that associates for each node the next packet sequence number to poll. When a sensor node ULP WuRx acquires a WuB, it reads both the address and the sequence number. Thanks to the capability of the ULP WuRx to directly recognize the address on the board, it wakes up the node MCU only if the address is valid, and then sends to it the sequence number using the serial port. All the packets, which have sequence number lower than the one received are considered as either successfully received or dropped because of a too high number of transmission attempts, and are thus erased from the transmission buffer. The packet which has the sequence number asked by the sink is then sent. Using this mechanism, when the sink detects a transmission failure, e.g. the received data packet is corrupted, it sets a random backoff and then, when the backoff expires, it initiates a new communication using the same sequence number, as illustrated by Fig. 2. Compared to traditional error-control schemes that use ACK frames, the energy overhead is significantly reduced for sensor nodes as they do not need to listen to ACK frames after each data packet

Sync bits	Sensor address	Sequence number
3 bits	8 bits	8 bits

Fig. 3: Structure of the Wake-up Beacon used in SNW-MAC.

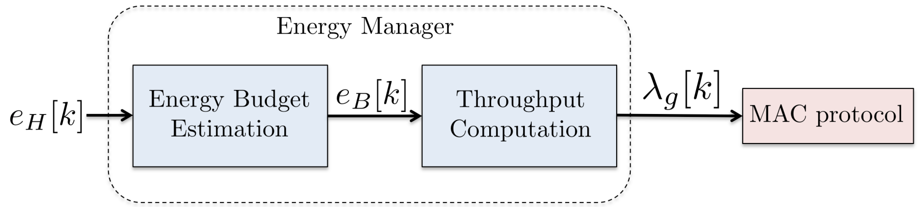


Fig. 4: Software architecture.

transmission. On the sink side, as no ACK frame is sent, energy is also saved. Nonetheless, this energy saving is counterbalanced by longer WuBs sent by the sink due to the sequence number. Using SNW-MAC, only the data frame is sent by the nodes, thus minimizing the per-packet energy consumption.

3 Experimental Setup

SNW-MAC was implemented in a complete WSN platform that embeds energy harvesting mechanisms. This section introduces the software and hardware setups used for the experimentations.

3.1 Software architecture

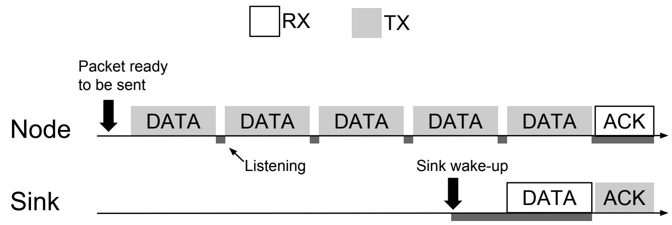
The software architecture of the node is shown in Fig. 4 and is composed of two components: the Energy Manager (EM) and the MAC protocol.

Energy management for energy harvesting sensor node The EM goal is to dynamically adjust the performance of the node according to the time-varying energy that the node can harvest in its environment. Assuming that the time is divided into time slots of equal duration T, the throughput $\lambda_g[k]$ (in packets per second) of the node for the current slot k is set by the EM at the beginning of each slot according to the variation of the harvested energy $e_H[k]$.

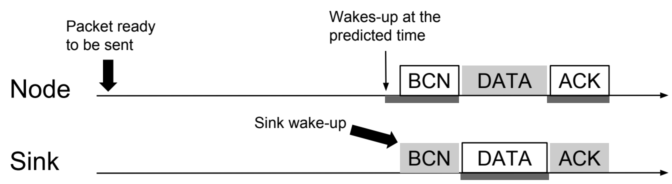
Two submodules compose the proposed EM as shown by Fig. 4. The Energy Budget Estimation (EBE) module evaluates the energy budget $e_B[k]$ that the node can consume during the slot to remain sustainable. The EBE used in our work relies on a simplified version of Fuzzyman [1] and its operating is out of the scope of this paper.

The second module is the Throughput Computation (TC) module, which calculates $\lambda_g[k]$ according to the energy budget. As wireless communications are usually the most consuming task over all the other tasks such as sensing and computing [15], the throughput of the node given an energy budget is strongly tied to the MAC protocol. By denoting e_T and τ_T respectively the energy cost and the total time to transmit a single packet, the energy consumed by the node over one time slot k is:

$$e_C[k] = \lambda_g[k]Te_T + (T - \tau_T\lambda_g[k]T)\,P_S, \tag{1}$$



(a) Packet transmission using XMAC.



(b) Packet transmission using PW-MAC.

Fig. 5: X-MAC and PW-MAC protocols.

where P_S is the power consumption of the node when both the MCU and the radio chip are sleeping. Therefore, in order for the consumed energy $e_C[k]$ to be equal to the energy budget $e_B[k]$, the throughput is set to the following value:

$$\lambda_g[k] = \frac{\frac{e_B[k]}{T} - P_S}{e_T - \tau_T P_S}. \tag{2}$$

This equation is obtained by replacing $e_C[k]$ by $e_B[k]$ in (1).

For SNW-MAC, each sensor node piggybacks its throughput in data packets. The sink keeps an updated table that associates for each node its throughput, and polls each node at the right time. Because the throughput is typically a 16 bit integer, minimal overhead is incurred by the piggybacking of this information. Moreover, the sink can use it to monitor the sensor node activity.

State-of-the-art MAC protocols used for comparison The SNW-MAC protocol is compared to PW-MAC [19] and X-MAC [7], two well-known state-of-the-art pseudo-asynchronous MAC protocols. Fig. 5a illustrates a packet transmission using the transmitter-initiated X-MAC. When a data packet must be sent, the node continuously transmits it, each transmission being followed by a listening period. This process continues until an ACK frame from the sink is acquired. The sink periodically wakes up and listens to the channel. If it detects an activity, it stays awake until it receives a complete data packet, and then acknowledges the received packet.

PW-MAC is a receiver-initiated protocol that focuses on energy efficiency on both the receiver side and sender side. Using PW-MAC, nodes accurately predict the time at which the sink will wake-up by using an on-demand prediction error correction mechanism and by considering clock drift and software and hardware

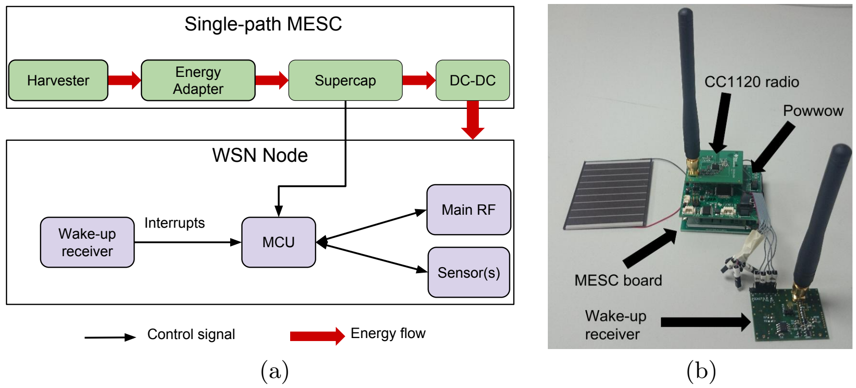


Fig. 6: Hardware architecture of a WSN node using energy harvesting and a WuRx: (a) functional description (b) Powwow node used for experiments.

latency. Moreover, to avoid repeated wake-up schedule collisions while allowing wake-up time prediction, independently generated pseudo-random sequences are used to control each node wake-up time. In this work, we focus on star networks with downlink data gathering. Therefore, using pseudo-random sequences to generate the wake-up schedule is unnecessary as the sink is the only receiver. Instead, the sink uses a periodic wake-up schedule. Fig. 5b illustrates a packet transmission using PW-MAC. When a node needs to send a packet, it computes a prediction of the next wake-up time of the sink and wakes up at this predicted time. It then waits for a beacon from the sink (represented by the BCN frame in Fig. 5b). Once the beacon is acquired, it sends the data packets and then waits for the ACK frame. At each packet transmission, the prediction error is computed, and if it is found to be larger than a fixed threshold, the node requests an update of the prediction state.

3.2 Hardware architecture

The hardware architecture of the node is given in Fig. 6 as well as a picture of the Powwow platform that has been used for experiments [4].

Architecture of energy harvesting Powwow platform Multiple energy harvesting platforms have been proposed by academia and industry over the last decade. Powwow platform relies on a single-path architecture version of the Multiple Energy Source Converter (MESC) architecture proposed in [9]. In single-path architecture, there is only one energy storage device and all the harvested energy is used to charge the storage device which directly powers the node through a DC-DC converter. Fig. 6 shows the block architecture of MESC that can be used with a variety of energy harvesters (e.g. photovoltaic cells, thermoelectric generators and wind turbines). Supercapacitors were chosen as storage devices as they are more durable and offer a higher power density than batteries [6]. In Powwow platform, the energy storage device is a 0.9 F supercapacitor with a maximum voltage of 5.0 V, and the minimum voltage required to power the node is 2.8 V. Powwow platform is also equiped with a CC1120 radio chip and a MSP430 low power micro-controller, both from Texas Instruments.

Ultra-low power wake-up receiver When SNW-MAC is used, each node is equipped with an ULP WuRx presented in [11]. It employs On-Off Keying (OOK) modulation. The receiver operates in the 868MHz transmission frequency band, and with a bitrate of 1 kbps. The sensitivity of the ULP WuRx was measured to be −55 dBm in these conditions. As the power consumption of ULP WuRx has to be orders of magnitude less than the main radio, these devices are usually characterized by low sensitivity and low data rate [11]. For this reason, sending WuBs to an ULP WuRx can be energy-wise costly as it is done at low bitrate and high transmission power to achieve the same range as the main radio.

Moreover, the ULP WuRx embeds an ULP 8-bit microcontroller from Microchip (PIC12LF1552), which was selected for its low current consumption (20nA in sleep mode) and its fast wake-up time (approximately 130μs at 8MHz). The PIC microcontroller is awaken by the analog front-end of the ULP WuRx when a carrier is detected. It then reads the address embedded in the WuB, and performs address matching. If the received address is valid, it wakes up the node MCU using an interrupt. Otherwise, it goes into sleep state, hence minimizing the power consumption of the ULP WuRx.

One of the requirements of an ULP WuRx is the very low power consumption as it is always active, even when all the other components are in sleep state. The power consumption of the ULP WuRx was measured to be 1.83 μW when the radio front-end is active and the PIC is in sleep state and 284 μW when the PIC is active at 3.3 V and is parsing the received data at 2 MHz.

SNW-MAC, X-MAC and PW-MAC protocols were implemented on the Powwow platform, as well as the energy management scheme. The parameters used for experimentations are shown by Table 1.

Parameters		**Values**
MAC	Sink wake-up interval (X-MAC and PW-MAC)	250 ms
	Maximum number of retransmissions	2
PHY	WuB bitrate	1 kbps
	Data/ACK/beacon bitrate	20 kbps
	WuB transmission power	12.5 dBm
	Data/ACK/beacon transmission power	−6 dBm

Table 1: Parameters used for the experimentations.

4 Experimental Results

The evaluated MAC protocols were implemented on a testbed made of 6 Powwow nodes including one sink, in a star topology. The nodes were exclusively powered by indoor fluorescent light, allowing reproducibility of the experiments. Moreover, the nodes were deployed under different lightning conditions, as shown by Fig. 7. Nodes 1, 2 and 5 were located on desks, directly under the ceiling lights while node 3 was deployed in a more shadowed area and node 4 was located on a bookcase, close to the ceiling, thus receiving less light than the others. Each experiment lasted for 3 hours, and the Powwow nodes have been equipped with an ULP WuRx only when the SNW-MAC protocol was evaluated.

The metrics used for comparison are the average throughput, in packets per minute, and the Packet Delivery Ratio (PDR). Fig. 8 shows the obtained results. First, Fig. 8a shows the average energy budget allocated by the EBE. As the amount of harvested energy varies for different nodes, the average allocated energy budget also differs. The results obtained for each node are obviously linked to this energy budget. Fig. 8b presents the throughput achieved with the different MAC protocols. SNW-MAC significantly outperforms the two other protocols, allowing up to two times higher throughput than PW-MAC for the node 2 due to the lower energy cost of packet transmissions. Finally, Fig. 8c shows the PDR achieved by the three protocols. SNW-MAC is the only protocol to achieve a 100 % PDR on all the nodes. These results demonstrate the high reliability that ULP WuRx-based protocols enable.

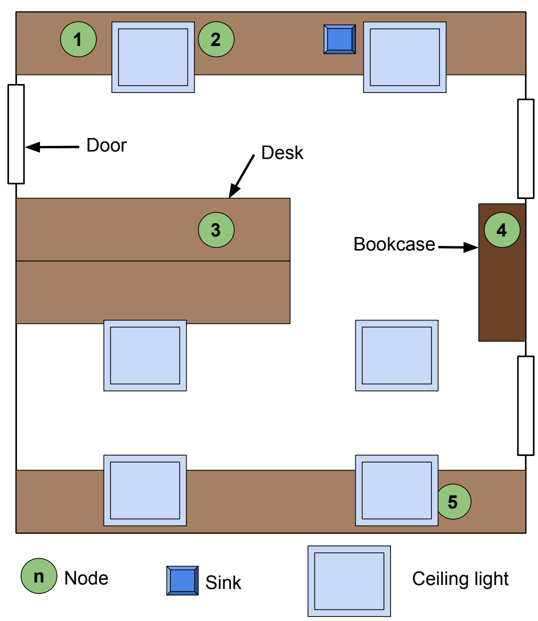
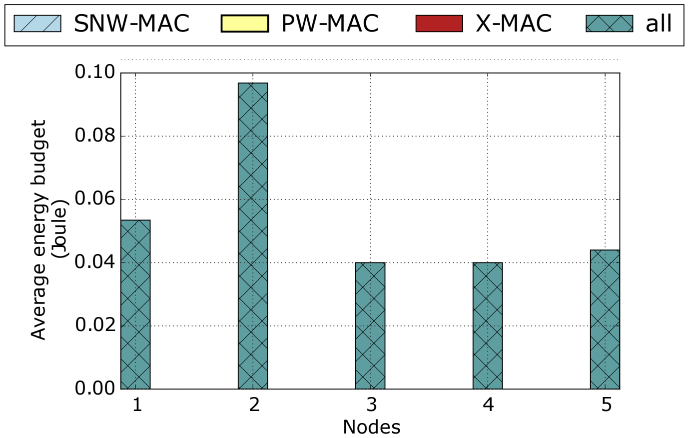
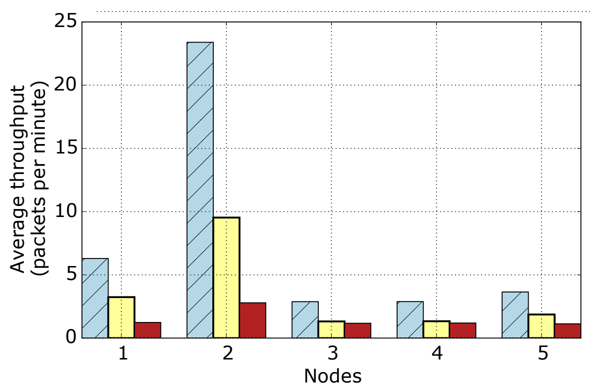


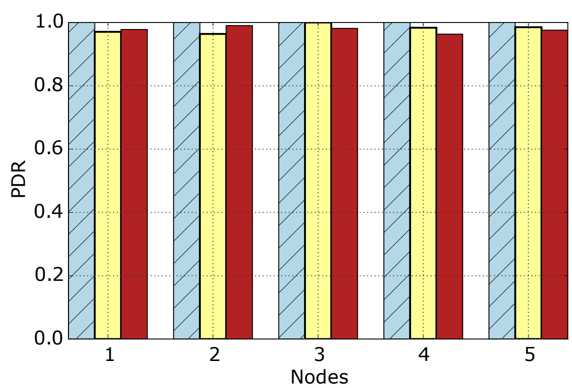
Fig. 7: Setup of the star network.



(a) Average energy budget allocated by the PM for each node.



(b) Average throughput achieved by each node.



(c) PDR achieved by each node.

Fig. 8: Results of the experimentations on a star network.

5 Conclusion

This paper proposes an asynchronous MAC protocol in the context of data gathering sensor networks with a star topology. The proposed solution leverages ultra-low power wake-up receivers to increase the energy efficiency of wireless sensor networks. This new scheme is designed to be implemented on real hardware. Experimental results have shown that the proposed approach concretely permits up to 2 times higher throughput compared with state-of-the-art MAC protocols such as PW-MAC and X-MAC. Future work is to evaluate the scalability of the proposed approach compared to traditional pseudo-asynchronous MAC by analytically computing the packet arrival rate.

6 Acknowledgment

This work was supported by "Transient Computing Systems", a SNF project (200021_157048), by SCOPES SNF project (IZ74Z0_160481) and by "POMADE" project, funded by CD22 and the Brittany region.

References

1. Faycal Ait Aoudia, Matthieu Gautier, and Olivier Berder. Fuzzy Power Management for Energy Harvesting Wireless Sensor Nodes. In *IEEE International Conference on Communications (ICC)*, May 2016.
2. Fayçal Ait Aoudia, Matthieu Gautier, and Olivier Berder. OPWUM: Opportunistic MAC Protocol Leveraging Wake-Up Receivers in WSNs. *Journal of Sensors*, January 2016. Article ID 6263719.
3. Yasmin Ammar, Sadok Bdiri, and Faouzi Derbel. An Ultra-Low Power Wake Up Receiver with Flip Flops Based Address Decoder. In *International Multi-Conference on Systems, Signals and Devices (SSD)*, pages 1–5, March 2015.
4. Olivier Berder and Olivier Sentieys. PowWow : Power Optimized Hardware/Software Framework for Wireless Motes. In *International Conference on Architecture of Computing Systems (ARCS)*, pages 1–5, February 2010.
5. Pei Huang, Li Xiao, Soroor Soltani, Matt W. Mutka, and Ning Xi. The Evolution of MAC Protocols in Wireless Sensor Networks: A Survey. *IEEE Communications Surveys Tutorials*, 15(1):101–120, January 2013.
6. Aravind Kailas, Davide Brunelli, and Mary Ann Weitnauer. Comparison of Energy Update Models for Wireless Sensor Nodes with Supercapacitors. In *Proceedings of the 1st International Workshop on Energy Neutral Sensing Systems (ENSSys)*, 2013.
7. Kevin Klues, Gregory Hackmann, Octav Chipara, and Chenyang Lu. A Component-based Architecture for Power-efficient Media Access Control in Wireless Sensor Networks. In *Proceedings of the 5th International Conference on Embedded Networked Sensor Systems (SenSys)*, November 2007.
8. Trong Nhan Le, Michele Magno, Alain Pegatoquet, Olivier Berder, Olivier Sentieys, and Emanuel Popovici. Ultra Low Power Asynchronous MAC Protocol Using Wake-up Radio for Energy Neutral WSN. In *Proceedings of the 1st ACM*

International Workshop on Energy Neutral Sensing Systems (ENSSys), November 2013.

9. Trong Nhan Le, Alain Pegatoquet, Olivier Berder, Olivier Sentieys, and Arnaud Carer. Energy-Neutral Design Framework for Supercapacitor-Based Autonomous Wireless Sensor Networks. *ACM Journal on Emerging Technologies in Computing Systems (JETC)*, 12(2):19:1–19:21, September 2015.
10. E.-Y.A. Lin, J.M. Rabaey, and A. Wolisz. Power-efficient rendez-vous schemes for dense wireless sensor networks. In *IEEE International Conference on Communications (ICC)*, June 2004.
11. Michele Magno, Vana Jelicic, Bruno Srbinovski, Vedran Bilas, Emanuel Popovici, and Luca Benini. Design, Implementation, and Performance Evaluation of a Flexible Low-Latency Nanowatt Wake-Up Radio Receiver. *IEEE Transactions on Industrial Informatics*, 12(2):633–644, April 2016.
12. Stefan Mahlknecht and M. Spinola Durante. WUR-MAC: Energy efficient Wakeup Receiver based MAC Protocol. In *8th IFAC International Conference on Fieldbuses and Networks in Industrial and Embedded Systems*, 2009.
13. Nafiseh Seyed Mazloum and Ove Edfors. Performance Analysis and Energy Optimization of Wake-Up Receiver Schemes for Wireless Low-Power Applications. *IEEE Transactions on Wireless Communications*, 13(12):7050–7061, December 2014.
14. Joaquim Oller, Ilker Demirkol, Jordi Casademont, and Josep Paradells. Design, Development, and Performance Evaluation of a Low-cost, Low-power Wake-up Radio System for Wireless Sensor Networks. *ACM Transaction on Sensor Networks*, 10(1), 2013.
15. Tifenn Rault, Abdelmadjid Bouabdallah, and Yacine Challal. Energy Efficiency in Wireless Sensor Networks: A Top-Down Survey. *Computer Networks*, 67:104–122, July 2014.
16. Curt Schurge, Vlasios Tsiats, Saurabh Ganeriw, and Mani Srivasta. Optimizing sensor networks in the energy-latency-density design space. *IEEE Transactions on Mobile Computing*, 1(1):70–80, January 2002.
17. Dora Spenza, Michele Magno, Stefano Basagni, Luca Benini, Mario Paoli, and Chiara Petrioli. Beyond Duty Cycling: Wake-up Radio with Selective Awakenings for Long-Lived Wireless Sensing Systems. In *IEEE INFOCOM*, pages 522–530, April 2015.
18. Felix Sutton, Bernhard Buchli, Jan Beutel, and Lothar Thiele. Zippy: On-Demand Network Flooding. In *ACM Conference on Embedded Networked Sensor Systems (SenSys)*, pages 45–58, November 2015.
19. Lei Tang, Yanjun Sun, Omer Gurewitz, and David B. Johnson. PW-MAC: An Energy-Efficient Predictive-Wakeup MAC Protocol for Wireless Sensor Networks. In *IEEE INFOCOM*, pages 1305–1313, April 2011.