Université de Strasbourg

Progress Report

New network protocol suite in heterogeneous wake-up IoT networks

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Context

While low power communication has evolved towards multi-kilometer ranges and low bit-rate schemes in recent years, triggering increasing interests, a trade-off must still be made between power consumption and latency. Pure- asynchronous communication allowed by emerging Ultra-Low-Power (ULP) Wake-Up Receivers (WUR) enables the design of low latency and energy-efficient network architecture composed of heterogeneous radio nodes (long-range communication and ULP short-range WUR) with dedicated access and network protocols. This Ph.D. student position is part of the effort to design such network architecture using heterogeneous radio nodes (long-range communication and ULP short-range WUR). The work will focus on defining a polymorphic network protocol suite, i.e. that it will need to conciliate different communication paradigms and wireless IoT technologies.

First Objective: Wake-Up Radio analysis

The focus of the first academic year was to get to know the state of art regarding Wake-Up Radio technology. We investigated various constraints that must be considered for such kind of technology: short-range (< 50m) and low traffic.
As result, we wrote an analysis article comparing this new technology with traditional solutions to multi-hop Wireless Sensor Networks and we published it in the 14th International Conference on Wireless and Mobile Computing, Networking, and Communications (WiMob 2018).

- **Title:** Is Wake-Up Radio the Ultimate Solution to the Latency-Energy Tradeoff in Multi-hop Wireless Sensor Networks?
- **Abstract:** In Wireless Sensor Networks (WSN), duty-cycled Medium Access Control (MAC) protocols trade-off latency for energy-efficient operation. Over the past few years, Wake- Up Radio (WuR) has been presented as the ultimate solution for this tradeoff, allowing to reduce both at the same time. However, this might not be the general case regarding the large range of network configurations used in WSN. Several previous works have been done comparing WuR to traditional duty-cycled solutions, but no one has investigated before the limitations of this technology. In this article, we analyze the benefits and drawbacks of using WuR in multi-hop WSN. We also identify black spots in WuR that have not been investigated yet. Our study is based on evaluations using COOJA, a simulator for networks of ContikiOS nodes. A traditional duty-cycled MAC protocol is also included in our study for comparative purposes. From our study, we quantify the performances of WuR and provide some guidelines on how this technology can be efficiently used in multi-hop wireless sensor networks.

Second Objective: Cross-layer protocol proposal

During the second year, we explored some challenges of the routing layer and proposed two new cross-layer protocols, LoBaPS, and eLoBaPS. This solution takes advantage of the always-on feature of the Wake-Up Radio to achieve load balancing in Wireless Sensor Networks. As a result, it increases the network lifetime by up to 77 %.
LoBaPS protocol was published in the IEEE Symposium on Computers and Communications (ISCC 2019) and in the national conference CoRes. On the other hand, eLoBaPS was published in the 18th International Conference on Ad Hoc Networks and Wireless (AdHoc-Now 2019).

- **Title:** “LoBaPS: Load Balancing Parent Selection for RPL Using Wake-Up Radios”
- **Abstract:** Wake-Up Radios is an emerging technology, aiming at pushing forward the frontiers of energy efficiency without trading it off for latency nor reliability. Extending the lifetime of the nodes as much as possible is one of the main goals in Multi-hop Wireless Sensor Networks. The Routing Protocol for Low Power and Lossy Networks (RPL) is commonly used in these applications. However, there is still an open problem in its design when it comes to achieving both stability and efficient routing at the same time. In this article, we present Load Balancing Parent Selection (LoBaPS), an algorithm to select opportunistically the next hop, based on RPL. It capitalizes on the Wake-Up Radio and its always-on feature, as well as its Ultra-Low Power consumption. We compare the performance of LoBaPS with that of W-MAC, a reference protocol that uses Wake-Up Radio and supports RPL in its traditional way. The results are obtained through simulations in COOJA for a network of nodes running ContikiOS, and show that the lifetime can be improved up to 55%, while the Packet Delivery Ratio (PDR) can raise a maximum of 20%, keeping a reasonable level of latency. In addition, the network is more robust to node shutdowns and requires less control overhead.

- **Title:** eLoBaPS: Towards Energy Load Balancing with Wake-Up Radios for IoT
- **Abstract:** In an effort to extend the lifetime and reliability of multi-hop wireless sensor networks we recently presented LoBaPS, a protocol to select opportunistic parents and achieve load balancing. This algorithm takes advantage of the wake-up radio for its ultra-low power consumption and always-on feature. Moreover, it overcomes an open problem in the routing layer: achieving both stability and efficient parent selection at the same time. However, the random load balancing strategy and the energy wastage in listening mode still limits the network lifetime. In this article, we present eLoBaPS, a significant modification of LoBaPS that distributes better the energy among the parents improving around 17% the lifetime of the network towards the ideal case. In a nutshell, the next hop is selected in a decentralized way and it is the parent that issues a shorter back-off period before attempting to retransmit. In addition, the nodes overhear all the traffic in the wake-up radio channel and adapt the protocol parameters to the current state of the battery of the neighbors. We perform simulations with a network of ContikiOS nodes running eLoBaPS, LoBaPS and W-MAC, a reference protocol that uses the wake-up radio.

Third Objective: Experimental platform

During the second half of the second year, we worked on an experimental platform to validate our analysis and simulations. We made contact with the people that are working on the state-of-the-art prototypes of Wake-Up Radios at the ETH of Zurich and we received some samples. At the same time, we got some boards from a startup company (Strataggem) that can control multiple radio modules in parallel. We used those boards as the main board to connect the Wake-Up Radio with some other commercial Main Radio such as Zigbee, Bluetooth, or WiFi, through I2C. This study was presented in the workshop AWAKE, and published in the Proceedings of the 2020 International Conference on Embedded Wireless Systems and Networks (EWSN 2020).
The plan in the long term is to integrate these boards into the FIT-IoT Lab so that people all over the world can run experiments remotely.

- **Title:** “A Performance Study of the Behavior of the Wake-Up Radio in Real-World Noisy Environments”
- **Abstract:** Wake-Up Radio (WuR) is a cutting-edge technology for the Internet of Things that is going to change the way end- devices communicate. Asynchronous wireless communications can benefit from WuR to reduce both energy consumption and latency comparatively to well-known duty-cycled solutions. In this article, we present an experimental platform using an existing WuR prototype and analyze its behavior when it is subject to radio interference. We implemented for the first time clear channel assessment capabilities and show that it can improve the packet delivery ratio by up to 10% on average. In particular, it can improve it from 25% up to 85% for internal interference. Besides, we experimentally extract some key physical values of this technology to provide inputs for WuR-based simulations and analytical models. Finally, we analyze the overall current consumption of a simple application to gain new insights into the WuR behavior. In low traffic scenarios, our results show that optimizing further the communication protocol stack will not significantly increase the lifetime of end-devices.

Fourth Objective: Routing protocols proposal

In the third year, we analyzed the routing layer of the wake-up radio addressing the range mismatch problem through exhaustive simulations, based on the measurements of the experimental platform of the previous year. Furthermore, we proposed two routing protocols for wake-up radio networks and showed that the reactive approach presents more benefits compared to the proactive one.
This work was submitted to Computer Networks, the International Journal of Computer and Telecommunications Networking, Elsevier (ComNets), and is pending for review.

- **Title:** “PROPL and REFLOOD: Proactive and Reactive Protocols for Wake-Up Radio Routing in IoT”
- **Abstract:** The Internet of Things and the Wireless Sensor Networks are providing new ways to connect physical variables from the environment to the cybernetic world. As their applications become more ubiquitous, they require better energy efficiency to reduce the size of the batteries or extend their lifetime as much as possible. Traditional solutions to this challenge have used a duty-cycle approach at the medium access control layer of the communication stack trading off latency for energy efficiency. Wake-up radios is a new technology for wireless communications that promises the end of this tradeoff thanks to its ultra-low power consumption. This module is attached to a regular node as a secondary receiver that listens to the channel continuously while the main radio stays sleeping. Un- fortunately, the sensitivity of the wake-up receiver is lower than that of the main radio, creating a range mismatch problem. To address this issue, the packets on the wake-up radio have to be routed through intermediate nodes before waking up the destination. In this article, we provide a comparative analysis of the two main strategies to address the routing of wake-up radio packets: proactive and reactive approaches. We present PROPL and REFLOOD, two examples of the mentioned strategies in ContikiOS, and perform simulations in different scenarios for convergecast traffic. Our wake-up-radio-based protocols show an improvement of 180% of the network lifetime compared to the traditional solutions. The results suggest an advantage of reactive strategies over proactive ones, especially in low traffic applications, where the reliability is around 20% higher in the reactive case.

Publications :

[4-SMN20] S. Sampayo, J. Montavont, T. Noël. A Performance Study of the Behavior of the Wake-Up Radio in Real-World Noisy Environments, dans 1st Workshop on Wake-Up radio technologies for next generation wireless communications (AWAKE), in conjunction with EWSN 2020, Lyon, France, février 2020.

[4-SMN19a] S. Sampayo, J. Montavont, T. Noël. eLoBaPS: Towards Energy Load Balancing with Wake-Up Radios for IoT, dans 18th International Conference on Ad-Hoc Networks and Wireless (AdHoc-Now), Luxembourg, Luxembourg, octobre 2019.

[4-SMN19] S. Sampayo, J. Montavont, T. Noël. LoBaPS: Load Balancing Parent Selection for RPL Using Wake-Up Radios, dans IEEE International Symposium on Computer Communications (ISCC), Barcelone, Spain, juillet 2019.

[5-SMN19] S. Sampayo, J. Montavont, T. Noël. Selecting Parents with Wake-Up Radios for Load Balancing in RPL, dans 4e colloque francophone sur la conception de protocoles, l'évaluation de performance et l'expérimentation des réseaux de communication (CoRes), Saint-Laurent-de-la-Cabrerisse, France, juin 2019.

[4-SMPN18] S. Sampayo, J. Montavont, F. Prégaldiny, T. Noël. Is Wake-Up Radio the Ultimate Solution to the Latency-Energy Tradeoff in Multi-hop Wireless Sensor Networks?, dans IEEE International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), Limassol, Cyprus, octobre 2018.