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Energy Harvesting - Wireless Sensor Networks for Indoors Applications using IEEE 802.11

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Abstract

The paper investigates the feasibility of using IEEE 802.11 in energy harvesting low-power sensing applications. The investigation is based on a prototype carbon dioxide sensor node that is powered by artificial indoors light. The wireless communication module of the sensor node is based on the RTX4100 module. RTX4100 incorporates a wireless protocol that duty-cycles the radio while being compatible with IEEE 802.11 access points. The presented experiments demonstrate sustainable operation but indicate a trade-off between the benefits of using IEEE 802.11 in energy harvesting applications and the energy-efficiency of the system.

Selection and Peer-review under responsibility of the Program Chairs.

Keywords: Wireless Sensor Networks, Energy Harvesting, Medium Access Control, IEEE 802.11

1. Introduction

Advances in energy harvesting technologies have led to the possibility of realizing Energy Harvesting - Wireless Sensor Networks (EH-WSN), making it possible to power wireless embedded devices by small-scale ambient energy [1]. Several sources of environmental energy can be harvested, such as solar power and wind power in outdoor deployments or heat from radiators and artificial light in indoor contexts. The key advantage of EH-WSNs with respect to battery-powered Wireless Sensor Networks (WSNs) is that energy harvesting can continuously produce and provide the system with energy. As a result, the perpetual operation of the system is solely limited by hardware or software failures. Energy harvesting mitigates the need for battery replacements and, therefore, decreases the cost of maintenance that requires human intervention. Furthermore, energy harvesting constitutes an environmentally friendly energy source, as it uses renewable energy and reduces battery wastes. On the other hand, harvested energy is not always available and, therefore, the need for efficient energy management becomes prominent.

The Medium Access Control (MAC) layer plays a key role in wireless sensor networks. It is primarily responsible for the establishment of communication links between nodes, that are vital to form the network infrastructure. The MAC scheme regulates the access to the shared wireless channel by multiple nodes. In addition to that, the MAC protocol plays a key role in the design of energy-efficient WSNs. Since the radio of a sensor node consumes the highest

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amount of power[2], the main method of preserving power is to duty cycle the node. Duty Cycles are materialized by alternating the node between active and sleeping states, where the node is operational in the active state and shut down in the sleeping state. S-MAC[3], X-MAC[4], RI-MAC[5] and the IEEE 802.15.4[6] standard are typical examples of energy-efficient protocols particularly designed for duty-cycling systems. ODMAC[7] is a MAC protocol particularly designed for energy harvesting duty-cycling systems.

IEEE 802.11[8], commonly known as Wi-Fi, defines a MAC protocol that is based on the CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) scheme. The typical topological structure is a star where multiple wireless stations are associated with an Access Point (AP) that connects them to the network infrastructure (e.g. Internet). IEEE 802.11 does not focus on energy-efficiency, as both the wireless nodes and the APs are active continuously. RTX4100[9] is a prototype platform for wireless applications that provides a low-power version of Wi-Fi, marketed as Ultra Low-Power Wi-Fi, which incorporates duty cycling in the operation of the wireless stations. Since the AP is continuously active, the establishment of the link does not constitute a particular challenge. The nodes simply follow a sleep-connect-disconnect-sleep cycle. For instance, the provided operating system supports cycles where the wireless node wakes up, connects to the network after associating with the AP, communicates with a server and goes back to sleep. The key advantage of developing sensing applications using IEEE 802.11, is the compatibility with existing networks and infrastructures. The use of the TCP/IP protocol stack allows the implementation of cloud applications, as the sensor nodes can directly communicate with any computer in the network. Furthermore, the users that have already deployed a WLAN (Wireless Local Area Network) in their building, do not need any additional hardware to support the sensing application. Moreover, the development of plug-and-play sensing applications is possible. On the negative side, IEEE 802.11 and the TCP/IP protocol stack are not optimized for energy-efficiency.

This paper presents the development of a carbon dioxide (CO2) sensor node that is powered by artificial indoors light (Section 2). The CO2 measurements indicate how crowded the room is and are used to automatically control the windows and the ventilation, via a platform that is named NV Comfort[10]. The hardware is based on a prototype circuit developed by WindowMaster A/S. It is composed of an RTX4100[9] Wi-Fi module and a COZIR Ambient CO2 sensor[11]. RTX4100 consist of an Energy Micro EFM32G microcontroller and a Atheros AR4100 802.11n Wi-Fi radio. The circuit is powered by a rechargeable lithium battery that is charged by embedded solar panels through a BQ25504 converter. We evaluate the sustainable performance of the aforementioned system and assess the feasibility of using IEEE 802.11 in energy harvesting sensor applications. The presented experiments (Section 3) demonstrate that sustainable operation is feasible when the application requirements are loose, as the radio communication is significantly less energy-efficient than alternative dedicated solutions (Section 4).

2. Firmware Overview

The firmware is developed with respect to the particular requirements of the application. The system is required to react quickly to a significant change in the CO2 concentration and to operate in a sustainable manner with the available harvested energy. Secondarily, for statistical purposes, the more measurement are collected, the merrier.

The firmware of the sensor node operates on a basic duty cycle. In the beginning of the cycle, the process assesses the available energy. If this assessment is successful, the process continues its operation and activates the CO2 sensor, polling it for a measurement. An assessment of the measurement follows and if it is decided that the specific measurement should be transmitted to the server, the communication procedure begins. At the end, the process puts the hardware into sleep mode until the next cycle.

The energy availability assessment is based on the comparison of the voltage of the lithium battery to a configurable threshold. The microcontroller reads the voltage of the lithium battery through its ADC (Analog-to-Digital Converter) that is wired to the battery. If the voltage is below the threshold, the hardware goes to sleep until the next cycle.

The CO2 sensor implements a digital filter to smooth the noise in the CO2 concentration measurements out. In a nutshell, the digital filter calculates a rolling average on the last measurements. It is empirically found that a rolling average of 24 measurements is required to limit the variation of the measurement to less than 5%, in a constant environment. Similarly, a rolling average of 12 measurements is required to keep the noise less than 10%. The CO2 sensor performs one measurement every 0.5 seconds in active mode. To promote the energy-efficiency and meet the requirement for a quick reaction to significant changes, the firmware transmits the measurement only if it is significantly different than the previously reported measurement. This is implemented as a two-level filtering system

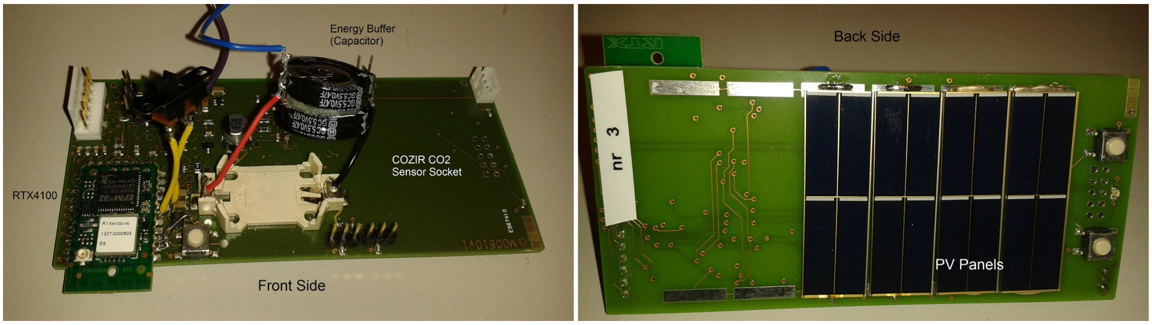


Fig. 1: The prototype Energy Harvesting CO2 Sensor node.

that works with two threshold levels. In particular, the system keeps the level of the previously reported measurement and it compares it with the current one, calculated as the rolling average of 12 actual measurements from the digital filter of the CO2 sensor. If this difference is bigger than the upper threshold (e.g. $> 10\%$), the measurement is reported. If the difference is smaller than the lower threshold (e.g. $< 5\%$), the measurement is dropped. If the measurement is between the upper and lower threshold, the measurement is kept and reassessed in the next cycle. In the next cycle a new measurement is taken. The new measurement is averaged with the held measurement from the previous cycle and it is transmitted if and only if it is above the lower threshold. This way, the system reports fast any big changes to the CO2 concentration, controlled by the upper threshold. Smaller changes, controlled by the lower threshold, are also reported but with a two-cycle delay.

The communication procedure follows the TCP/IP protocol stack. The firmware turns the radio on and associates with the AP that it was previously associated with. It then executes the DHCP protocol to dynamically obtain an IP address. Then, it executes the ARP protocol to find the MAC address of the server (i.e. NV Comfort) which. It then establishes a connection to the server. The server device supports two server applications, a web service and a UDP server. In case the web service is selected, a TCP connection is established and a HTTP request is transmitted over it. In case the UDP server is selected, a datagram is sent. Then, the firmware disconnects from the AP, turns the radio off and goes to sleep. The communication with the AP is encrypted through the WPA2 (Wi-Fi Protected Access II) security protocol that is implemented in Wi-Fi. The initial association to the AP is performed using WPS (Wi-Fi Protected Setup).

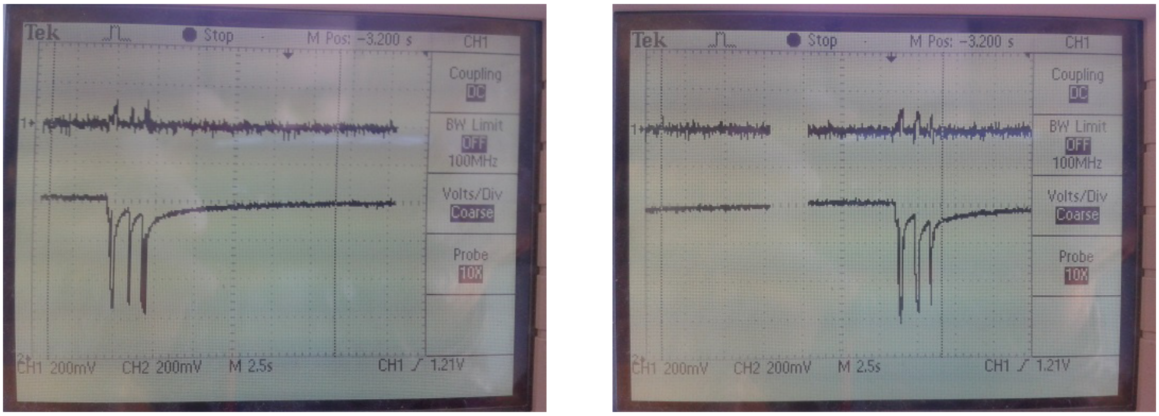
3. Experimental Evaluation

For the experiments presented in this section a capacitor of 2.1 F is used for energy storage, instead of a lithium battery. Figure 1 shows the sensor node used in the experiments.

3.1. Power Consumption and Charging Efficiency

With the transmission power set to 10 dBm, the current consumption, while the radio is active, peaks at approximately 120 mA. In case of UDP, the duration of the active period is approximately 2.5 seconds, which matches the results of the experiments presented in the Application Note[12]. In case of HTTP, the duration of the active period varies between 2.5 and 5 seconds, due to packet retransmissions by TCP. Figure 2 shows the current drain in a typical cycle measured across a 1 Ω shunt resistor, for UDP and HTTP. Figure 3 shows the current drain when the CO2 sensor is activated, measured across a 10 Ω shunt resistor. After the initialization, the current periodically peaks at approximately 14 mA (long-term average at ≈ 3 mA). The measurements experimentally verify that the radio communication dominates the energy consumption.

The idle current drain was measured using two different methods. First, we measure the voltage of the 1 Ω shunt resistor while the sensor node is in idle mode. While sleeping, the constant current drain is measured approximately 6 μA. To verify the instantaneous measurement in a longer period of time, the second method measures the discharge



(a)

(b)

Fig. 2: A typical duty cycle with UDP (a) and HTTP (b). The current drain can be estimated by dividing the voltage of the shunt resistor (upper line) over its resistance (1 Ω). The lower line shows the voltage of the storage capacitor.

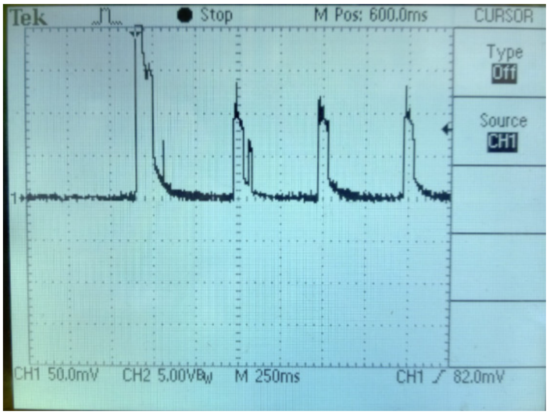


Fig. 3: The activity of the CO2 sensor. The current drain can be estimated by dividing the voltage of the shunt resistor over its resistance (10 Ω).

of the capacitor in a period of 30 minutes. During this period the voltage of the capacitor decreased by 5mV, which translates to a constant current of 5.83 μA or a constant power consumption of 23.5 μW in sleeping mode.

Then, the efficiency of the charging unit is evaluated. A light source was placed at different distances from the solar panels to emulate different levels of power input. The voltage across the solar panels and the input current (measured across a 1 Ω shunt resistor) are used to calculate the power input at the solar panels, i.e. before the charging unit. The system was let to charge the capacitor for 10 minutes. The difference of the voltage of the capacitor is used to calculate the actual charging power after the charging unit. Figure 4 shows the charging efficiency as the ratio of the charging power over the input power for different levels of constant input power. The results indicate an approximately 85% charging efficiency, that falls to approximately 75% when the input power is below 200μW.

3.2. Sustainable Operation

The following experiments aim to evaluate the sustainable performance of data transmission. The cost of using the CO2 sensor does not depend on the communication protocols used. Therefore, the CO2 sensor is deactivated and, instead, dummy data are transmitted to the server. The firmware is set to attempt one transmission every 30 second. The transmission is performed if and only if the voltage of the capacitor is above a threshold. This way, the system automatically finds balance and the sustainable throughput (in packets per minute) is measured. Again, the

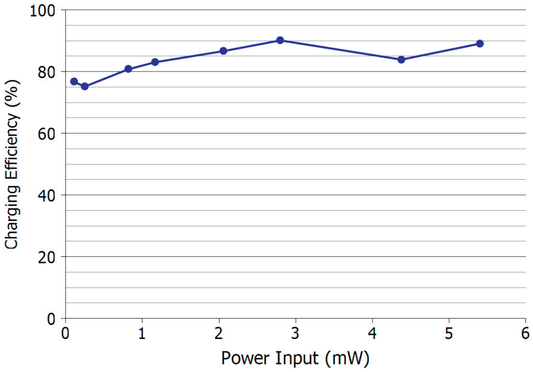
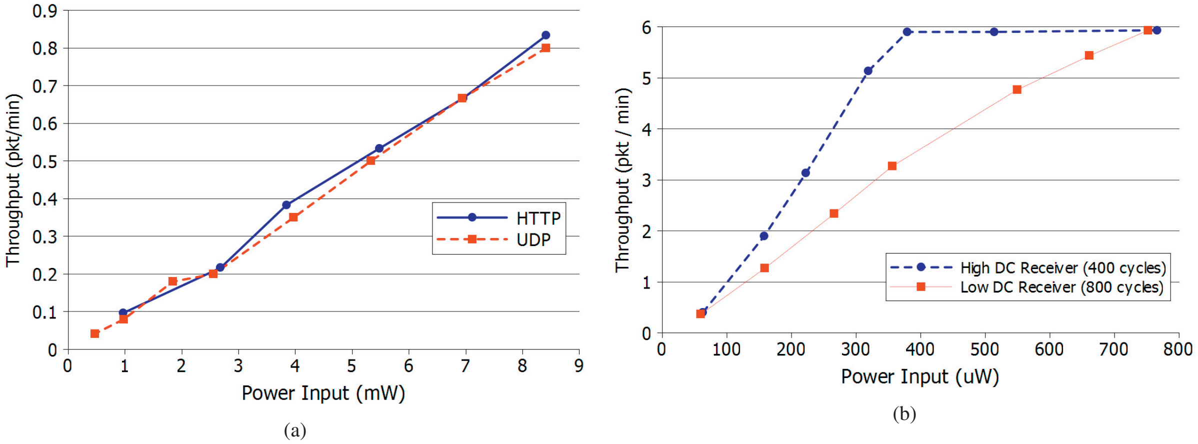


Fig. 4: The efficiency of the charging unit, as the ratio of the charging power over the input power.



(a)

(b)

Fig. 5: Sustainable performance at different levels of power input. The presented IEEE 802.11 system (a) is compared with ODMAC (b)[7], a MAC protocol specifically designed for energy harvesting sensing applications. The harvesting power density of ambient light, which depends heavily on the ambient excitation and harvesting technologies, is approximately 100 $\mu W/cm^2$ in an illuminated office and approximately 100 mW/cm^2 in direct sunlight[13].

power input is controlled by positioning the light source in various distances from the solar cells. Figure 5(a) shows the results of the experiments for different levels of constant input power. All experiments were initiated with the voltage of the capacitor below the threshold. For each power input, the data were collected after 1 hour of continuous operation that demonstrates power balance. The available harvested energy is used to improve the throughput of the application. The throughput increases linearly with the input power. HTTP and UDP seem to perform equally. This phenomenon is attributed to the power consumption of the association to the AP and the overhead protocols (such as DHCP and ARP) which is the same for both schemes and dominates the overall power consumption.

The experiments shown in Figure 5(a) very closely resembles the experiments on ODMAC[14] implemented in the eZ430-rf2500[15] prototype platform by Texas Instruments, as shown in Figure 5(b)[7]. We refer the reader to our previous work[7] for the mechanics of ODMAC and the details of the experiments. Both figures demonstrate a similar linear behavior where the throughput increases with the power input. Yet, ODMAC appears to require one order of magnitude less power for one order of magnitude more throughput. Moreover, our previous work[7] suggests that, in ODMAC, most power is consumed in idle listening in order to synchronize the sender to the duty-cycling receiver. If the receiver did not have energy constraints, like an IEEE 802.11 AP, the difference between the two protocols would be significantly higher. Furthermore, data encryption has a significant effect on the energy-efficiency of IEEE 802.11 sensor node. We experimentally verified the results shown in Application Note[12], which show that data encryption approximately doubles the energy consumption of the association. The additional cost of the association to the AP, which occurs once every duty cycle, drives the overall energy consumption high and makes data encryption significantly less energy-efficient than ODMAC. The two orders of magnitude of difference verify in practice that IEEE 802.11 and the TCP/IP protocol stack are not energy-efficient solutions. Nevertheless, the use of IEEE 802.11 is feasible if the running application has loose performance requirements.

4. Conclusion

In this work, we present the development of a CO2 sensor node that is powered by artificial light. The sensor node uses IEEE 802.11 for wireless communication, which is the protocol commonly used in wireless local area networks. The key advantage of developing IEEE 802.11-based sensing applications is the compatibility with existing networks and infrastructures. The use of the TCP/IP protocol stack allows the implementation of cloud applications, as the sensor nodes can directly communicate with any computer in the network. On the other hand, radio communication is the dominant source of power consumption in a wireless sensing system and IEEE 802.11 and the TCP/IP protocol stack are not optimized for energy-efficiency. The conducted experiments demonstrate that sustainable operation is feasible. However, the comparison of the performance of developed system with ODMAC[7], a MAC protocol specifically designed for EH-WSNs, indicates that data communication with ODMAC is two orders of magnitude more energy-efficient. Therefore, our work demonstrates a trade-off between the convenience of using IEEE 802.11 in EH-WSNs and the energy-efficiency of the network.

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References

1. Seah, W.G., Eu, Z.A., Tan, H.. Wireless sensor networks powered by ambient energy harvesting (WSN-HEAP) - Survey and challenges. In: *Proc. 1st Int. Conf. on Wireless Commun., Vehicular Technology, Inform. Theory and Aerospace Electronic Syst. Technology (VITAE)*. 2009, p. 1–5.
2. Bachir, A., Dohler, M., Watteyne, T., Leung, K.. MAC Essentials for Wireless Sensor Networks. *IEEE Commun Surveys Tutorials* 2010; **12**(2):222–248.
3. Ye, W., Heidemann, J., Estrin, D.. An Energy-Efficient MAC Protocol for Wireless Sensor Networks. In: *Proc. 21st Ann. Joint Conf. IEEE Comput. and Commun. Soc. (INFOCOM)*; vol. 3. IEEE; 2002, p. 1567–1576.
4. Buettner, M., Yee, G.V., Anderson, E., Han, R.. X-MAC: A Short Preamble MAC Protocol for Duty-Cycled Wireless Sensor Networks. In: *Proc. 4th ACM Int. Conf. on Embedded Networked Sensor Syst. (SenSys)*. ACM; 2006, p. 307–320.
5. Sun, Y., Gurewitz, O., Johnson, D.B.. RI-MAC: A Receiver-Initiated Asynchronous Duty Cycle MAC Protocol for Dynamic Traffic Loads in Wireless Sensor Networks. In: *Proc. 6th ACM Int. Conf. on Embedded Networked Sensor Syst. (SenSys)*. ACM; 2008, p. 1–14.
6. IEEE, . IEEE Std. 802.15.4-2003: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low Rate Wireless Personal Area Networks (LR-WSNs) 2003;.
7. Fafoutis, X., Di Mauro, A., Dragoni, N.. Sustainable Medium Access Control: Implementation and Evaluation of ODMAC. In: *Proc. IEEE Int. Conf. on Commun. (ICC) Workshops*. IEEE; 2013, .
8. IEEE, . Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications 2012;.
9. RTX A/S, . Low Power Wi-Fi RTX41xx. `http://www.rtx.dk/LPW/RTX4100`; 2013.
10. WindowMaster, . NV Comfort. `http://www.windowmaster.com/Solutions/NV-Comfort%E2%84%A2.aspx`; 2013.
11. CO2 Meter, . COZIR: Ultra Low Power Carbon Dioxide Sensor. `http://www.co2meters.com/Documentation/Datasheets/DS-COZIR-Ambient-CO2.pdf`; 2012.
12. RTX A/S, . RTX4100 Wi-Fi Module: Application Note AN1 Current Consumption. `http://www.rtx.dk/LPW/RTX4100`; 2013.
13. Paradiso, J., Starner, T.. Energy scavenging for mobile and wireless electronics. *Pervasive Computing, IEEE* 2005;**4**(1):18–27.
14. Fafoutis, X., Dragoni, N.. ODMAC: An On-Demand MAC Protocol for Energy Harvesting - Wireless Sensor Networks. In: *Proc. 8th ACM Symp. on Performance Evaluation of Wireless Ad-Hoc, Sensor, and Ubiquitous Networks (PE-WASUN)*. ACM; 2011, p. 49–56.
15. Texas Instruments, . eZ430-RF2500 Development Tool. SLAU227E; 2009. Available at `http://www.ti.com/lit/ug/slau227e/slau227e.pdf`.