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# Wireless sensor node modelling for energy efficiency analysis in data-intensive periodic monitoring

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ABSTRACT

Data-intensive wireless sensor applications, such as remote visual inspection using high-resolution video sensors, require a special design approach in order to save energy and prolong lifetime of a battery-powered wireless sensor node. This study is motivated by searching for the most efficient communication protocol for high-resolution image transmission in environmental monitoring sensor networks, where data should be transmitted periodically, but relatively rarely (usually once or twice per day). Some previous publications propose ZigBee or Wi-Fi as suitable candidates for data-intensive wireless transmission, but the literature lacks a systematic study that would provide a guidance for designing such systems. We construct a measurement-based model of a wireless sensor node with emphasis on the communication unit. We measured the energy consumption of commercially available wireless ZigBee and Wi-Fi modules, as well as the influence of the interface bandwidth limitation that reduces their energy efficiency. The model includes real-world communication channel properties that at high bit-rates reduce the communication range and increase the energy consumption due to a higher susceptibility to noise.

Our results show that in scenarios when the node sends up to 64kB of data per session once per day, the estimated lifetime of a ZigBee node is up to 10% longer than of a Wi-Fi node. However, when the amount of data per session increases, the Wi-Fi wins due to its higher energy efficiency during data transfer. When the data amount reaches 10MB, the lifetime of a Wi-Fi node using UDP protocol is 5 times longer than that of a ZigBee node. On the other hand, the Wi-Fi node lifetime decreases with increasing number of sessions per day, because the connection establishment with the access point is very energy consuming. As a result, when 5 sessions per day are required the ZigBee node can offer 40% longer lifetime than the Wi-Fi node when 10kB of data is transmitted per session.



## 1. Introduction

Benefits of small embedded devices sensing their surroundings and wirelessly communicating among them have been recognized more than 10 years ago [1]. One of the most widespread applications of such Wireless Sensor Networks (WSNs) is environmental monitoring [2], where wireless sensor nodes are deployed outdoors, often with large distances. Nodes usually comprise sensors for measuring temperature, humidity, pressure, etc. Those sensors are simple, low-power and produce a small amount of raw data. However, nowadays the market offers compact and affordable high-resolution CMOS image sensors enabling new possibilities in WSNs' environmental monitoring applications which benefit from remote visual inspection of monitored phenomena, such as pest monitoring [3], phenological observations [4], etc.

A crucial problem in WSNs is a limited energy budget of wireless sensor nodes, usually powered by batteries. In most common WSNs, energy consumption of the communication unit is a critical component in the total energy consumption of a wireless sensor node [5]. Incorporating a high-resolution image sensor on a wireless sensor node raises a set of new challenges as it has a two-fold effect on the energy consumption: high-consuming data acquisition, and a large amount of data which needs to be processed and transmitted [6]. The energy required for data transmission increases with the amount of data. To lower the energy burden for wireless transmission, image processing can be performed on the node [7]. However, data processing increases energy consumption and introduces a computational energy vs. communication energy trade-off [8] which requires a careful system design. The product of image processing is again an amount of data much larger than the amount of data usually transmitted in WSNs.

Energy efficiency of wireless communication and its effect on WSN lifetime is a topic of many research activities [9]. ZigBee has been the most common protocol in WSNs with requirements

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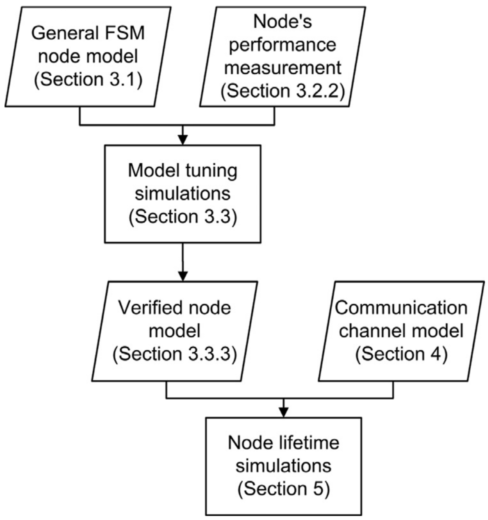


**Fig. 1.** Flowchart of the study presented in this paper.

on large communication range (up to 100 m) and low energy consumption [10,11]. The shortcoming of ZigBee is that it has been designed for small amount of data. However, there have been efforts to modify it and make it more suitable for larger data transmission [12,13]. On the other hand, recent appearance of low-power Wi-Fi modules on the market [14] enables consideration of Wi-Fi as an option for low-power and reliable transmission of large amount of data in WSNs. An initial study comparing the performance of lower level of ZigBee and Wi-Fi protocols (IEEE 802.15.4 and IEEE 802.11, respectively) is presented in [15].

Our research aims at determining whether ZigBee or Wi-Fi is better for energy-efficient communication in periodic data-intensive WSN applications such as high-resolution image transmission. Our contributions are threefold: (i) general measurement-based models for ZigBee and Wi-Fi sensor nodes; (ii) simulations of complete communication cycles (including sleep, idle, connection and transmission states); (iii) comparison of energy efficiency of ZigBee and Wi-Fi in real-world scenarios for different amounts of transmitted data. To the best of our knowledge, there are no such measurement-based models for wireless sensor nodes and networks containing ZigBee or Wi-Fi modules. Moreover, the issue of choosing a convenient communication protocol for energy-efficient transmission of large amount of data over WSNs has still not been resolved.

In order to accomplish our objective, we first explore the related work (Section 2). Afterwards, we use the following approach, as shown in Fig 1:

(a) We design a detailed FSM-based behaviour model of a wireless sensor node that would help us estimate the energy consumption of data-intensive periodic wireless transmission in different scenarios (Section 3.1).
(b) We consider testing the performance of commercially-available ZigBee and Wi-Fi modules. The actual current consumption and time values during node operation are measured on real wireless devices (Section 3.2.2).
(c) We feed our node model with the measured values, and tune some parameters to achieve the best match with the measured node behaviour (Section 3.3).
(d) The verified node model (from Section 3.3.3) is combined with a realistic communication channel model (Section 4) to estimate and compare the lifetime of ZigBee and Wi-Fi nodes for several scenarios of periodic and infrequent transmissions (Section 5).

Conclusions and future work plans are presented in Section 6.

## 2. Related work

The problem of energy efficiency in data-intensive applications has not been tackled thoroughly in the literature. Shahzad and Oelmann [16] compared Wi-Fi, ZigBee and Bluetooth Low Energy in data-intensive applications. They concluded that ZigBee consumes the least amount of energy for data loads of up to 500 B per session, whereas Wi-Fi consumes least amount of energy for data loads of 800kB or more per session. In their simulations they used a simplified model of each protocol, with maximal theoretical throughput and ideal channel conditions. It was not explicitly stated where the parameters for the modelled communication modules come from.

In [15], we compared the energy consumption of the lower levels of Wi-Fi and ZigBee protocols (IEEE 802.11b/g and IEEE 802.15.4, respectively). The results showed that IEEE 802.11b/g protocol is more energy-efficient than IEEE 802.15.4 protocol at intermediate bit-rates (around 6 Mbps). We performed the simulations with the parameters taken from the datasheets and the estimated values for channel disturbances and data transfer rate limitation. The study presented in this paper considers a more realistic scenario. The protocol models include also the higher layers and the simulation parameters are based on the measurements.

Pham [17] performed extensive measurements on IEEE 802.15.4 wireless sensor nodes when transmitting large amount of data. The paper describes the differences between various platforms, as well as hardware and software constraints to throughput in data-intensive scenarios. Energy efficiency was not tackled in that paper. In addition, it does not present any models.

WSNs with large number of nodes are complex systems, with many possible interactions among the nodes and the environment, making lifetime estimation and evaluation a difficult task. To ease the network lifetime estimation and optimization, models are often used. Jung et al. [18,19] presented a statistics-based model of a ZigBee node energy consumption. The model calculates the energy consumed for data capture, processing, and transmission. Zhou et al. [20] focus on modelling energy consumed for data processing in a ZigBee wireless sensor node. Their model is based on energy consumption in different states and state transitions of the microcontroller and the radio module (TI CC2430). However, the origin of the energy and time values is not clear from the paper. Damaso et al. [21] built a measurement-based model of TinyOS, an operating system run on TI CC2420 ZigBee module. They model time and power required for executing tasks in the operating system.

In addition, models and predictions of radio propagation through vegetation in environmental WSNs [22,23] are significant for realistic communication modelling, as well as energy consumption simulations.

As in this paper we will study and compare Wi-Fi and ZigBee communication protocols in data-intensive WSN applications, we briefly present their relevant features.

Wi-Fi is designed for wireless communication between PCs and mobile gadgets. Lower levels of the Wi-Fi (PHY and MAC layers) are defined by the IEEE 802.11 standard. Two most often used IEEE 802.11 protocol versions nowadays are IEEE 802.11 b and IEEE 802.11 g. IEEE 802.11b allows bit rates from 1 Mbps to 11 Mbps, whilst 802.11g allows bit rates from 6 Mbps to 54 Mbps. Both versions typically provide communication range of up to 100 m [24]. The transport layer implements the Transmission Control Protocol (TCP) or User Datagram Protocol (UDP), and the network layer