Experimental Performance Evaluation of IEEE 802.15.4g Applications Using OpenMote-B Devices

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Abstract. *The IEEE 802.15.4 standard has become the backbone of numerous low-power and low cost wireless applications. The IEEE 802.15.4g amendment in 2012 has been created particularly for Smart Utility Network (SUN), as well as for Industrial Internet of Things (IIoT) and machine-to-machine applications. The standard aims to provide interoperability of diverse wireless low-power networks and to enable extended coverage. This paper provides the comparison of the IEEE 802.15.4g physical layer performances in three different test scenarios, operating in sub-GHz and 2.4 GHz frequency bands. For measurement purposes, the OpenMote-B hardware platform implementing the IEEE 802.15.4g and equipped with an Atmel AT86RF215 radio transceiver has been used in experimental testing.*

1 Introduction

Low-Rate Wireless Personal Area Networks (LR-WPANs) are being rapidly developed owing to the growing demands for efficient energy consumption and reducing operational costs, thus having a wide range of applications [1]. The IEEE 802.15.4 standard [2] defines a physical layer (PHY) and a Medium Access Control (MAC) layer of Open Systems Interconnection (OSI) model for LR-WPANs. Due to its simplicity and low-cost, this standard is the basis for multiple low-power wireless communication technologies. Widely usage of the IEEE 802.15.4 among standardization bodies and technologies has encouraged its further upgrades. For example, the IEEE 802.15.4e standard [3] defines the MAC layer based on efficient Time Slotted Channel Hopping (TSCH) mechanism. Recently, Low-Power Wide-Area (LPWA) technologies evolve to support long-range, low-cost, and low-power communications, thus extending the functionalities of LR-WPANs. Similarly, the IEEE 802.15.4g standard [4] has developed a new set of PHYs based on three modulation techniques operating in sub-GHz and 2.4 GHz bands and has been designed for outdoor low data rate wireless SUN applications [5].

Given the raising interest in low-rate low-power wireless networks usage in the industrial domain, its range extension and reliability improvement, in this paper we explore the robustness of the different modulation types. In particular, we focus on experimental testing of the IEEE 802.15.4g based applications in three test scenarios using the OpenMote-B hardware and RIOT software platforms. The overall dataset helps in choosing a proper PHY depending on the application requirements.

The paper is structured as follows: Section II provides an overview of the PHYs defined in the IEEE 802.15.4g standard that are evaluated in this paper. Section III presents the methodology and the setup used to conduct the experimental testing of the IEEE 802.15.4g based applications. Section IV summarizes the results obtained from the measurements. Finally, Section V concludes this paper.

2 Overview of IEEE 802.15.4g

The IEEE 802.15.4g standard [4] initially was an amendment to the IEEE 802.15.4 and has been standardized in 2015. The main features of this standard are [4]: operates in free 700-1000 MHz and 2.4 GHz bands; provides data rates from 40 kb/s to 800 kb/s; maximum length of Physical Service Data Unit (PSDU) is 2047 bytes (B) and a complete IPv6 packet can be transmitted without fragmentation; coexistence with other systems operating in the same band (IEEE 802.11, 802.15 and 802.16). The IEEE 802.15.4g defines three PHYs: Multi-rate Multi-regional Offset Quadrature Phase Shift Keying (MR-O-QPSK), Multi-rate Multi-regional Frequency Shift Keying (MR-FSK) and Multi-rate Multi-regional Orthogonal Frequency Division Multiplexing (MR-OFDM) [4]. In this way, the standard provides communication in multiple bands and use of multiple data rates. MR-FSK is a mandatory PHY, the most common in USA in 902-928 MHz band together with Frequency Hoping Spread Spectrum (FHSS) technique [1]. MR-O-QPSK shares the characteristics of IEEE 802.15.4 modulation and there are already O-QPSK devices commercially available. MR-OFDM provides high data rates, spectrum efficiency and robustness against multi-path fading and external interference in environments with frequency selective fading. This standard aims to enable interoperability of networks with different capabilities and capacities by changing modulation and/or data rate on packet-by-packet basis.

2.1 MR-FSK

Any IEEE 802.15.4g device has to support MR-FSK (2-FSK & 50 kb/s) based on Gaussian FSK (GFSK) modulation with 2 or 4 levels providing constant amplitude of modulated signal [4]. This standard has introduced the novel Mode Switch (MS) mechanism that enables devices to change data rate and/or PHY packet-by-packet basis using MR-FSK PHY. Using MS mechanism, temporary PHY can be changed only for one packet. When communicate, both transceivers have to support desired PHY configuration. MR-FSK supports two Physical Protocol Data Unit (PPDU) formats depending whether MS mechanism is enabled [4]. Additional enhancement is the generic MR-FSK mechanism that provides support to the existing commercial PHY solutions and an adoption of new PHY solutions as a consequence of technological progress or a regulatory change. In other words, this mechanism enables the adoption of changes without the need for standardization.

2.2 MR-O-QPSK

MR-O-QPSK PHY provides multiple data rates by utilization of the Forward Error Correction (FEC), interleaving and frequency spread spectrum technique. There are two frequency spread spectrum techniques depending on the operating band provided: Direct Sequence Spread Spectrum (DSSS) and Multiplexed Direct Sequence Spread Spectrum (MDSSS) [4]. Data transmission with legacy devices is ensured in the following bands: 780, 915, 917, and 2450 [MHz]. O-QPSK-DSSS modulation divides band into 16 orthogonal channels separated by 5 MHz and channel width of 2 MHz. Every symbol presents 4 data bits, so there are 16 possible symbols and each of them is modulated by Pseudo-Random Noise (PRN) chip sequences, which are mutually orthogonal. Data and chip rates provided by MR-O-QPSK PHY are presented in Table 1 [4].

Chip rate [kchip/s]	Rate Mode	PSDU data rate [kb/s]
100	0/1/2/3	6.25/12.5/25/50
200	0/1/2/3	12.5/25/50/100
1000	0/1/2/3	31.25/125/250/500
2000	0/1/2/3/4	31.25/125/250/500/1000

Table 1: MR-O-QPSK data rates.

2.3 MR-OFDM

MR-FSK and MR-O-QPSK are frequently used PHYs in low-power LR-WPANs thanks to its simplicity, low-cost and good performances. Contrary, OFDM modulation is commonly used in systems with strong requirements for signal processing, memory and energy consumption, like xDSL, Long Term Evolution (LTE), WiMAX, Power Line Communications (PLC), and Wi-Fi [6]. OFDM typical application is in security and monitoring systems. MR-OFDM is based on parallel data transmission with orthogonal sub-carriers, each transporting one part of the information in narrow-band channel. This data transmission approach ensures better robustness against multi-path propagation, external interference and improves spectrum efficacy [5]. MR-OFDM provides higher data rates 50-800 kb/s, and the maximum PSDU length of 2047 B [6]. Sub-carrier spacing is constant and equals (31250/3) Hz, and a symbol rate is (23/3) ksymbol/s. OFDM symbol (120 μs) consists of a base symbol (96 μs) and a cyclic prefix (CP). CP presents replication of the last 24 μs of the base symbol and is positioned in front of the base symbol. Cycle feature and the long duration of an OFDM symbol make MR-OFDM PHY more robust against multipath propagation which can cause Inter-Symbol Interference (ISI) [6]. This PHY offers 4 options (numbered from 1 to 4) characterized by the number of active tones (subcarriers), signal bandwidth, channel spacing and the number of channels. The Modulation Coding Scheme (MCS) parameter, numbered from 0 to 6, specifies the following: sub-carrier modulation scheme (BPSK, QPSK, 16-QAM), the FEC coding rate (1/2 or 3/4), data rate and whether frequency repetition is applied [4]. The FEC is mandatory in MR-OFDM. Frequency repetition is a technique where more than one sub-carrier (2 or 4) transport the same information. Even though this technique reduces effective data rate, it improves robustness against multi-path fading. The MR-OFDM header is transmitted using the lowest MCS level provided by the option, which reduces energy consumption. MR-OFDM PHY provides extended data rates for options 1 and 2: 1200, 1600 and 2400 kb/s [4].

3 Experimental Setup

Experimental testing of the IEEE 802.15.4g based applications has been conducted based on three test scenarios using the OpenMote-B hardware and RIOT software platforms. The setup consists of two OpenMote-B devices, a transmitter (TX) and a receiver (RX). The traffic analysis has been performed using the following metrics: packet loss [%], average Received Signal Strength Indicator (RSSI) [dBm], min/avg/max Round Trip Time (RTT) [ms] and PHY configuration. The overall acquired dataset is not presented in the paper due to page limitation. The first scenario has been conducted in a controlled environment, i.e. in a Faraday cage which has ensured idealized conditions. The communication performance has been tested in both frequency bands (FBs): sub-GHz (863-870 MHz) and 2.4 GHz. The purpose of this scenario has been to verify accuracy of applied hardware platform. The second scenario has been carried out in sub-GHz FB and in a real-world environment (inside the building in two neighboring rooms) with 10 m device spacing. The goal of this setup is to analyze PHY configuration performances in real conditions. The last scenario has been tested in sub-GHz FB aiming to assess the PHY resistance to the influence of noise. The experiments in this scenario have been conducted using RF coaxial cables and a coupler. The noise has been generated by the Agilent 33500B signal generator. The test considers the following configurations:

- 16 PHY configurations in sub-GHz FB, namely: [MR-O-QPSK, chip rate = 100 kchip/s, RM (Rate Mode) = 0;1;2;3], [MR-FSK, data rate = 50 kb/s; 100 kb/s, modulation = 2-FSK, modulation index = 1, channel spacing = 200 kHz; 400 kHz], [MR-OFDM, option = 1, MCS = 0;1;2;3], and [MR-OFDM, option = 2, MCS = 0;1;2;3;4;5],

- 28 PHY configurations in 2.4 GHz FB: [MR-O-QPSK, chip rate = 2000 kchip/s, RM = 0;1;2;3], [MR-FSK, data rate = 50 kb/s; 150 kb/s; 200 kb/s, modulation = 2-FSK, modulation index = 1;0.5;0.5, channel spacing = 200 kHz; 400 kHz; 400 kHz], [MR-OFDM, option = 1, MCS = 0;1;2;3], [MR-OFDM, option = 2, MCS = 0;1;2;3;4;5], [MR-OFDM, option = 3, MCS = 1;2;3;4;5;6] and [MR-OFDM, option = 4, MCS = 2;3;4;5;6].

3.1 Hardware platform

The OpenMote-B is an open-hardware platform for the IIoT applications in the field of next generation low-power long-range wireless networks based on IPv6 protocol stack. The second version of this platform, depicted in Fig. 1, was released in March 2018 and consists of a Texas Instruments (TI) CC2538 System on Chip (SoC) and an Atmel AT86RF215 radio transceiver. The CC2538 includes an ARM Cortex-M3 micro-controller (32 MHz, 32 kB RAM, 512 kB Flash) and a radio transceiver compatible with the IEEE 802.15.4-2006 standard. The AT86RF215 completely supports the IEEE 802.15.4g standard and provides data transmission in sub-GHz and 2.4 GHz.

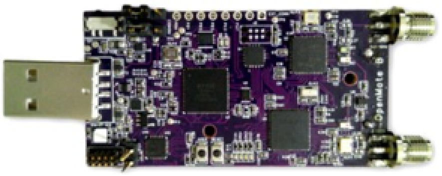

Figure 1: The OpenMote-B hardware platform.

3.2 Software platform

RIOT is a free open-source operating system (OS) for memory constrained systems with focus on the wireless low-power IoT devices [7]. Memory size is around 10 KB and it is based on micro-kernel and modular architecture (8, 16, 32 -bit). RIOT OS provides support to multiple protocol stacks as IPv6, 6LoWPAN, and standard protocols: RPL, UDP, TCP and CoAP. Platforms that RIOT OS supports are: TI MSP430, ARM7, ARM Cortex-M0-M0+-M3-M4, AVR micro-controllers and MIPS32r2 [8]. RIOT OS source code is available on GitHub repository. This OS uses broadly spread IT tools: C and C++ programming, gcc, gdb, valgrind tools, minimal code-hardware dependency, development for Mac and Linux OSs. RIOT aims to implement open standards for the IoT systems featured by connection, security, durability and privacy.

4 Results

4.1 I test scenario

To determine the communication link metrics for a given PHY configuration, the TX sends 50 frames of 28 B to the RX with 1 ms inter-packet delay. The transmit power of both devices has been set to 0 dBm. Overall, this scenario enables 44 experiments. These experiments have confirmed that with increased data rate, the RTT parameter becomes smaller. MR-OFDM PHY is the fastest one, which has met the expectations due to its highest data rates. MR-O-QPSK PHY has up to 10 time larger RTT parameter in comparison with other PHYs. This implies that MR-FSK and MR-OFDM PHYs provide better performances in sub-GHz FB. This result confirms that MR-FSK is the most robust PHY in both FBs based on the RSSI value analysis. Another interesting observation is that the difference in the RSSI value between MR-O-QPSK and MR-OFDM2 is less than 2 dB, -34.25 dBm and -36.5 dBm, respectively. Taking into consideration the signal bandwidth of these PHYs - 5 MHz (MR-O-QPSK) and 0.8 MHz (MR-OFDM2), these results prompt the MR-OFDM usage in low-power LR-WPANs.

4.2 II test scenario

Three measurements have been done in this test scenario. In each of them, the TX sends 100 frames of 88 B to the RX with 1 s inter-packet delay. An 80 dB attenuator has been coupled with the RX's antenna interface, and at the TX it has been used attenuator with selective attenuation. In the first measurement, the TX's attenuation has been set to 0 dB, and in the second one to 27 dB. In the first case, the communication has been established for all PHY configurations (16). Contrary, in the second case, the communication link has been established only for MR-O-QPSK RMs 0 and 1 (6.25 kb/s and 12.5 kb/s). During these measurements, enormous human impact on communication link performances was noticed where packet losses have been varying from 20% to 90%. Obtained results are as expected: the bigger the data rate is, with constant power and position of devices, the greater decline in the communication link quality is. Overall results conclude that MR-O-QPSK provides the longest range, i.e. the most robust propagation waves.

In the third measurement, the relative attenuation at the TX has been measured when the communication link is interrupted [packet losses $> 90\%$]. The attenuation is relative because the communication is full-duplex. The results show that MR-O-QPSK PHY supports the lowest transmit power which is in correspondence with the previous conclusions related to this scenario. Fig. 2 summarizes the estimated relative attenuation at the TX, for all tested PHY configurations. The largest value of transmit power is needed for MR-FSK, MR-OFDM1/MCS3, and MR-OFDM2/MCS5 PHYs. MR-O-QPSK is the most robust PHY, while MR-OFDM and MR-FSK PHYs provide similar results. As expected, the higher the data rate is, the larger transmit power is needed. A large decrease of attenuation is observed for MR-OFDM1 MCS2 and MCS3. This can be partly attributed to the fact that MCS3 data rate (800 kb/s) is reduced by half of MCS2 data rate (400 kb/s). The other reason is the usage of frequency repetition technique in MCS2 configuration which provides extra dB of protection. This result clearly shows the benefit of frequency repetition. The same observation can be noticed between MR-OFDM2 MCS2 and MCS3 PHYs, where MCS2 uses frequency repetition and MCS3 does not. Another interesting result comparing the estimated relative attenuation at the TX of MCS1 and MCS2 for both MR-OFDM options is that it is the same and equals 3 dB. These results show that BPSK modulation

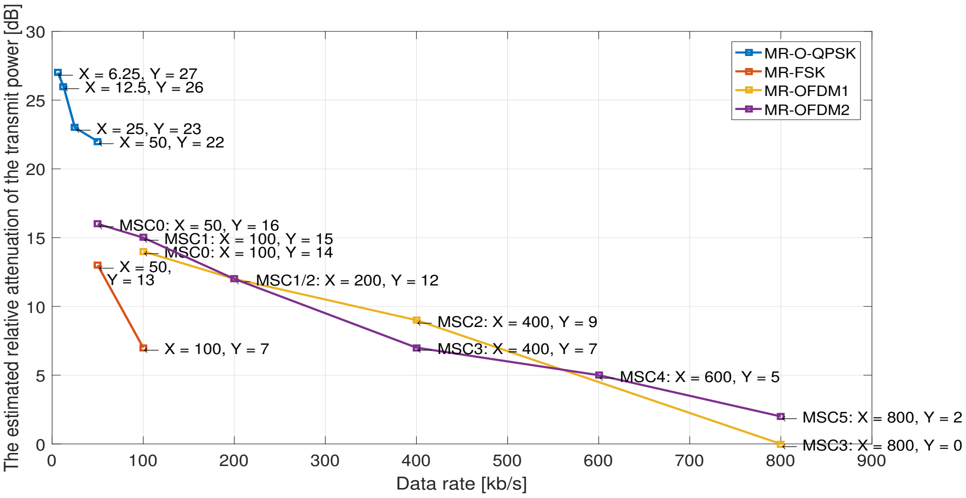

Figure 2: The estimated relative attenuation of TX power when the connection is broken.

provides extra 3 dB over QPSK modulation. Comparing the results of MR-OFDM options, it is concluded that a reduction of the signal's bandwidth makes PHY less robust. This can be attributed to the fact that the Power Spectral Density of the Interference (PSDI) increases as the signal bandwidth is reduced, leading to the increase of Bit Error Rate (BER) (if the signal bandwidth is reduced by half, the PSID increases for 3 dB).

4.3 III test scenario

In this test scenario, the power level of signal and noise have been measured when the connection is interrupted. These values have been measured at the output of a coupler using spectrum analyzer. To determine the communication link metrics for a given PHY configuration, the TX sends 100 frames of 88 B to the RX with 1 s interpacket delay. The results show that the difference between the signal and the noise level is about 15dB in case of MR-O-QPSK PHY RMs 0 and 1, and this difference is reduced to 5dB for RMs 2 and 3. These results imply that as data rate increases, the resistance of PHY to the noise influence reduces. MR-FSK provides noise resistance about 1 dB. MR-OFDM1 configurations have the same value, while MR-OFDM2/MCS0/1/2 provide the difference value of 2 dB, and MCS3/4/5 1 dB. The overall conclusion is that MR-O-QPSK PHY is the least resistant to the noise impact.

5 Conclusions

This paper evaluates the performances and robustness of the PHYs defined in the IEEE 802.15.4g standard, specifically in the sub-GHz FB (863-870 MHz). The experiments were conducted in a controlled setup to evaluate the minimum required TX power by PHY configurations to establish and maintain communication. The results show that MR-O-QPSK provides the longest range in the real conditions, while MR-FSK provides the weakest performances. An interesting observation made from the results is that MR-OFDM PHY is the most resistant to the noise impact. This conclusion is crucial because O-QPSK modulation is widespread in the industry applications, especially when MR-OFDM advantages are taken into account: high data rates, spectral efficiency and an increased level of robustness.

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