Optimal Throughput and Self-adaptability of Robust Real-Time IEEE 802.15.4 MAC for AMI Mesh Network

Hikma Shabani¹, Musse Mohamud Ahmed, Sheroz Khan, Shahab Ahmed Hameed and Mohamed Hadi Habaebi
Department of Electrical and Computer Engineering, Kulliyyah of Engineering, International Islamic University Malaysia, P. O. BOX. 10, Kuala Lumpur, 50728, Malaysia.

E-mail: hikmash@yahoo.fr

Abstract. A smart grid refers to a modernization of the electricity system that brings intelligence, reliability, efficiency and optimality to the power grid. To provide an automated and widely distributed energy delivery, the smart grid will be branded by a two-way flow of electricity and information system between energy suppliers and their customers. Thus, the smart grid is a power grid that integrates data communication networks which provide the collected and analysed data at all levels in real time. Therefore, the performance of communication systems is so vital for the success of smart grid. Merit to the ZigBee/IEEE802.15.4std low cost, low power, low data rate, short range, simplicity and free licensed spectrum that makes wireless sensor networks (WSNs) the most suitable wireless technology for smart grid applications. Unfortunately, almost all ZigBee channels overlap with wireless local area network (WLAN) channels, resulting in severe performance degradation due to interference. In order to improve the performance of communication systems, this paper proposes an optimal throughput and self-adaptability of ZigBee/IEEE802.15.4std for smart grid.

1. Introduction
The legacy electricity grids continuously encounter the challenges of providing reliable electric power to end-users and System breakdown could cause huge economic losses and public concerns [1]. Therefore, the Energy Independence and Security Act of 2007 gave a start for smart grid implementation in the United States [2]. The development of the smart grid provides an efficient and intelligent approach of managing energy supply and consumption in real time. The real time communication capability of smart grid will enable utilities to optimize and modernize the power grid in order to achieve its full potential.

Recently, wireless sensor networks (WSNs) have been widely recognized as a promising technology that can enhance various aspects of today’s electric power systems [3]. Merit to the ZigBee/IEEE802.15.4std low cost, low power, low data rate, short range, simplicity, high reliability and free licensed spectrum that makes wireless sensor networks (WSNs) the most suitable wireless technology for smart grid applications [4].

¹ To whom any correspondence should be addressed
ZigBee/IEEE802.15.4std defines the physical layer (PHY) and Medium Access Control (MAC) sub-layer. In ZigBee physical layer, the radio shall operate at one of the following license-free bands: 868-868.6MHz in Europe, 902-928MHz in North America and 2400-2483.5MHz elsewhere worldwide. However, there is a big issue of interference between various wireless technologies operating at the frequency of 2.4GHz Industrial-Scientific-Medical (ISM) frequency band which reduces the performance of WSNs communication.

This paper develops an optimal throughput and self-adaptability of ZigBee/IEEE802.15.4std for smart grid under WLAN interference. The rest of the paper is organized as follows. Section 2 reviews the RF Link of IEEE802.15.4 PHY layer, section 3 discusses the Zigbee BER Analysis Under WLAN interference. Section 4 proposes the IEEE 802.11b/IEEE 802.15.4 Simulation Models and presents the simulation results. Finally, in section 5, the conclusion and suggestions are presented.

### 2. RF Link of IEEE 802.15.4 standard

IEEE802.15.4std specifies 27 channels spread across three different ISM frequency bands as presented in ‘figure 1’ [5].

| Frequency  | Bit rate | Symbol rate |
|------------|----------|-------------|
| 868.3MHz   | 20kb/s   | 20ks/s      |
| 902MHz     | 40kb/s   | 40ks/s      |
| 928MHz     |          |             |

**a) 868/915MHz (PHY)**

**b) 2400MHz (PHY)**

**Figure 1:** IEEE802.15.4std channels and frequency band [5]

Hence, the radio shall operate at one of the following available license-free ISM bands: 868-868.6MHz in Europe, 902-928MHz in North America and 2400-2483.5MHz elsewhere worldwide. Furthermore, IEEE802.15.4std uses the BPSK (Binary Phase Shift keying) modulation for both 868 and 915MHz bands, and OQPSK (Offset Quadrature Phase-Shift Keying) modulation for 2.4 GHz ISM bands. Finally, as shown in ‘figure 1’, ZigBee has channel 0 in the 868MHz band, 10 channels in 915MHz band, each with 2MHz of bandwidth and 16 channels in the 2400 GHz band, each with
5MHz of bandwidth and the transmission power capability of 1mW is typically specified in the standard. In order to limit the power consumption, IEEE802.15.4 standard is designed for very low duty cycle (≤ 0.1%) and the nominal transmitter power output specified is 0.5mW (−3dBm) [6]. However, the output power can be increased through external amplifiers to whatever the regional regulatory limits are. The nominal receiver sensitivity is specified by Packet Error Rate (PER). The specification requires 1% PER at -85dBm receive power level for the 2400 MHz band and -92dBm for the sub-GHz bands (as measured at the chip’s antenna terminals). This represents a receiver with a noise figure substantially worse than 20dB, though most radios in production are between 7 and 9 dB better than this.

3. Zigbee BER Analysis Under WLAN
This developed bit error rate (BER) analysis model is the extension of the model developed in [7] from which the interference and noise are included. The PHY of IEEE 802.15.4 at 2.4 GHz uses OQPSK modulation. For an additive white Gaussian noise (AWGN) channel, the BER can be calculated by the following equation [8]:

\[
BER = Q\left(\frac{E_b}{N_0}\right) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \exp\left(-\frac{u^2}{2}\right) du
\]

Where \(E_b/N_0\) is the normalized signal-to-noise ratio (SNR) and \(Q(x)\) is the Q-function of Gaussian distribution:

\[
Q(x) = \frac{1}{\sqrt{2\pi}} \int_{x}^{\infty} \exp\left(-\frac{t^2}{2}\right) dt
\]

When a Zigbee channel overlaps with a WLAN channel, WLAN signal can be considered as partial band jamming noise for the Zigbee signal [9] and the SNR is replaced by signal-to-interference-plus-noise ratio (SINR) which can be defined as

\[
\text{SINR} = \frac{P_{\text{signal}}}{P_{\text{noise}} + P_{\text{interference}}}
\]

Where \(P_{\text{signal}}\) is the power of the desired signal at Zigbee receiver, \(P_{\text{noise}}\) is the noise power, and \(P_{\text{interference}}\) is the received interference power from WLAN signal at Zigbee receiver. The path loss model represents the power loss between transmitter and receiver, and can therefore be used in conjunction with the transmission power to enable the calculation of \(P_{\text{signal}}\) and \(P_{\text{interference}}\.

The maximum transmission power of Zigbee is defined as 1 mw (0 dBm). Considering that Zigbee and WiFi are most frequently deployed in the indoor environments, a simplified indoor path loss model is adopted in this paper [7]. For self-adaptability, as suggested in [10], the frequency dependency is incorporated in the developed indoor path loss model as Zigbee and WLAN are most frequently deployed in the indoor environments

\[
L_p(d,f) = \begin{cases} 
20\log_{10}\left(\frac{4\pi d}{\lambda}\right) + 20\log_{10}\left(\frac{f}{f_p}\right), & d \leq d_0 \\
20\log_{10}\left(\frac{4\pi d}{\lambda}\right) + 20\log_{10}\left(\frac{f}{f_p}\right) + 10\log_{10}\left(\frac{d}{d_0}\right), & d > d_0 
\end{cases}
\]

Where \(d_0\) is a break point. And \(n\) and \(d_0\) are set to 3.3 and 8m respectively [11].

Therefore, considering that the power spectrum of IEEE 802.11b is 11 times wider than Zigbee (‘figure 2’) and is not uniformly distributed, in-band interference power of IEEE 802.11 cannot be simply calculated by dividing by 11 [12]. An amendment parameter of in-band power factor \(r\) is added to \(P_{\text{interference}}\). Therefore, (3) is modified to:

\[
\text{SINR} = \frac{P_{\text{signal}}}{P_{\text{noise}} + rP_{\text{interference}}}
\]
To obtain the power factor $r$, the power spectral density of the IEEE 802.11b and offset frequency between the central frequency of Zigbee and WLANs are considered. Since the power is concentrated around the central frequency, $r$ increases as the offset frequency decreases.

![IEEE 802.11b and IEEE 802.15.4 channels in the 2.4GHz bands](image)

**Figure 2:** Zigbee and WLAN channels in the 2.4GHz bands [11]

### 4. IEEE 802.11b/IEEE 802.15.4 Simulation Model and Results

According to theoretical model the simulation model based on the IEEE 802.15.4 standard is shown in ‘figure 3’.

![IEEE 802.11b /IEEE 802.15.4 coexistence simulation model](image)

**Figure 3:** IEEE 802.11b /IEEE 802.15.4 coexistence simulation model
In accordance with IEEE 802.15.4 standards document, every four bits are mapped into a symbol and each symbol spreads to a 32-chip almost orthogonal PN sequence, thus a spreading table is set in a spreading block. Data is packed into frames, with a maximum frame size of 128 bytes as defined in the standard. The transmission rate is 250 kbps at 2.4 GHz for Zigbee, while 11 Mbps for WLAN. The IEEE 802.11b simulation module provided in NS2 is utilized. The IEEE 802.15.4 and IEEE 802.11b signals are added together before being passed through AWGN channel. Both signals must be sampled and filtered at the same sampling rate [13]. The frequency band for both simulation systems was set from -44 to +44 MHz to satisfy the Shannon theorem. The BER is calculated based on minimum Hamming distance between data before modulation and after demodulation [8]. Measurements were taken in a screen room, enabling the elimination of all external signals and interference.

Theoretical analysis and simulation of BER are shown in ‘figure 4’. The solid line represents theoretical values while the dotted lines represent the values obtained via simulation. Except for a few channels that are far away from the WLAN central frequency, most of channels overlapped with the WLAN channels have 2 MHz, 3 MHz, 7 MHz, and 8 MHz offsets from the WLAN channel frequency. Therefore, the simulations were performed in these four scenarios. From both the simulation and theoretical results, we find that the BER drop drastically as the offset frequency increases. For the same offset frequency channel, the BER decreases when the separation distance increases. BER is higher when the offset frequency is 2 MHz and 3 MHz in the simulation compared to theoretic results; when the offset frequency is 7 MHz and 8 MHz, the BER is lower than theoretical result. That is because the frequency band of the IEEE 802.11b simulation model is narrower than the theoretical one, with more power concentrated on the effective band frequency. Both graphs prove that most interference power is around the central frequency of WLAN. “Safe Distance” and “Safe Offset Frequency” are two critical parameters, which guide the Zigbee deployment in order to mitigate the WLAN interference. If the offset frequency is less than 2 MHz, the distance needs at least 8 m to efficiently minimize the effect of the IEEE 802.11b. If the offset frequency is larger than 8 MHz, safe distance can be decreased to 2 m.
5. Conclusion
In this paper, Zigbee performance under WLAN interference for AMI mesh network was evaluated. A theoretical model has been introduced, followed by a corresponding simulation model which completely reflects the Zigbee and WLAN coexistence features via NS2. Both analysis and simulation results show that Zigbee may be severely interfered by WLAN and that a “Safe Distance” and “Safe Offset Frequency” can be identified to guide Zigbee deployment. It is shown that 8 m between Zigbee and WLAN is a “safe” distance which can guarantee the reliable Zigbee performance regardless of the offset frequency, while 8 MHz is a “safe” offset frequency even when the distance is just 2 m. These results have been verified by means of empirical analysis and experimentation. It was shown that in general, Zigbee provides satisfactory performance when the WLAN interference is not significant. In the event of significant WLAN interference, the proposed model provides an effective and efficient means of providing reliable data service.

Acknowledgment
The authors wish to thank the International Islamic University Malaysia and the Renewable Energy Research Group (RERG), Faculty of Engineering.

Appendix A. ZIGBEE FREQUENCY BANDS AND DATA RATES [8]

| PHY (MHz) | Frequency band (MHz) | Channel Number | Spread parameters | Data parameters |
|-----------|----------------------|----------------|-------------------|-----------------|
|           |                      |                | Chip rate (Kchip/s) | Modulation | Bit rate (Kb/s) | Symbol          |
| 868       | 868-868.6            | 0              | 300               | BPSK         | 20             | Binary          |
| 915       | 902-928              | 1-10           | 600               | BPSK         | 40             | Binary          |
| 2450      | 2400-2483.5          | 11-26          | 2000              | OQPSK        | 250            | 16-ary orthogonal |

Appendix B. IEEE 802.11b DATA RATES SPECIFICATIONS [7]

| Data rate | Code length | Modulation | Symbol rate | Bits/symbol | System  |
|-----------|-------------|------------|-------------|-------------|---------|
| 1 Mbit/s  | 11 (Barker C)| DBPSK      | 1           | 1           | DSSS    |
| 2 Mbit/s  | 11 (Barker C)| DBPSK      | 1           | 2           | DSSS    |
| 5.5 Mbit/s| 4 (CCK)     | DBPSK      | 1.375       | 4           | HR/DSSS |
| 11 Mbit/s | 8(CCK)      | DBPSK      | 1.375       | 8           | HR/DSSS |

6. References
[1] Joo S K, Kim J C and Liu C C 2007 Empirical analysis of the impact of 2003 blackout on security values of US utilities and electrical equipment manufacturing firms *IEEE Trans. Power Systems* vol. 22 no. 3. pp. 1012-18
[2] Erol-Kanterci M and Moufta H T 2011 Wireless Sensor Networks for Cost-Efficient Residential Energy Management in the Smart grid *IEEE Trans. Smart Grid* vol. 2 no. 2. pp. 314-25
[3] Gungor V C, Akan O B and Akylidiz 2008 A Real-Time and Reliable Transport (RT)2 Protocol for Wireless Sensor and Actor Networks *IEEE/ACM Trans. Network* vol. 16 no. 2. pp. 359-70
[4] Callaway E et al. 2002 Home Networking with IEEE 802.15.4: A developing Standard for Low-Rate Wireless Personal Area Networks *IEEE Communications Magazine* vol. 40 no. 8. pp. 70-7
[5] IEEE std 802.15.4-2006 Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs) *IEEE Standard for Information Technology* pp. 1-32
[6] Gandotra N, Bijalwan V and Panwar M 2012 Coexistence Model of ZigBee & IEEE 802.11b (WLAN) in Ubiquitous Network Environment *International J. Adv. Research in Computer Engineering & Technology (IJARCET)* vol. 1 no. 4. pp. 680-84
[7] Shin S Y, Park H S, Choi S and Kwon W H 2007 Packet Error Rate Analysis of ZigBee Under WLAN and Bluetooth Interferences *IEEE Trans. Wireless Comm.* vol. 6 no. 8. pp. 2825-30
[8] Peizhong Y, Iwayemi A and Zhou C 2011 Developing ZigBee Deployment Guideline Under WiFi Interference for Smart Grid Applications *IEEE Trans. Smart Grid* vol. 2 no. 1. pp. 110-20
[9] Peterson R L, Borth D E and Ziemer R E 1995 *An Introduction to Spread-Spectrum Communications* (Upper Saddle River, NJ: Prentice-Hall)
[10] Pagani P and Pajusco P 2006 Modeling the Space-and Time-Variant Ultra-Wideband Propagation Channel *IEEE Int. Conf. on Ultra-Wideband* pp. 201-206
[11] Yoon D G, Shin S Y, Kwon W H and Park H S 2006 Packet Error Rate Analysis of IEEE 802.11b under IEEE 802.15.4 Interference *Proc. 63rd IEEE Veh. Tech. Conf.* pp. 1186-90
[12] Shin S Y, Park H S and Kwon W H 2007 Mutual Interference Analysis of IEEE 802.15.4 and IEEE 802.11b *International J. Computer Networks* vol. 51 no. 12. pp. 3338-53
[13] Mikulka J and Hanus S 2007 Bluetooth and IEEE 802.11b/g Coexistence Simulation *RadioEngineering* vol. 17 no. 3. pp. 66–73