Coexistence of Smart Utility Networks and WLAN/ZigBee in Smart Grid

Ruofei Ma and Weixiao Meng
The Communication Research Center
Harbin Institute of Technology, China
Email: {maruofei, wxmeng}@hit.edu.cn

Hsiao-Hwa Chen and Yu-Ren Huang
The Department of Engineering Science
National Cheng Kung University, Taiwan
Email: {hshwchen, n96984171}@mail.ncku.edu.tw

***Abstract*—IEEE 802.15.4g defines smart metering utility networks (SUNs) to enable system control and information transfer in smart grid. However, sharing operation on unlicensed bands makes most SUN channels to overlap with wireless local area network (WLAN) or ZigBee channels in a heterogeneous communication environment. Thus, coexistence of SUNs and WLANs/ZigBees is a crucial issue, which is the focus of this paper. In particular, we will find a solution to mitigate WLAN and ZigBee interferences on SUNs operating in the same band. Analytical model is applied to evaluate bit error rate (BER) performance of a SUN in different interference scenarios. The simulation shows that frequency offset and separation distance play important roles in coexistence situations. We then use a packet error rate (PER) calculation model to analyze the PER performance in order to determine the minimum separation distances between a SUN receiver and WLAN/ZigBee transmitters. Finally, a coexistence solution based on multiple gateway wireless mesh topology is proposed for SUNs to mitigate WLAN/ZigBee interferences.**

***Index Terms*—Smart grid, SUN, WLAN, Zigbee, coexistence**

I. Introduction

Smart grid is a sophisticated power system which connects a large number of distributed energy networks and devices using various advanced power, control, communication, and networking technologies [1]. By adding communication architecture to the power grid, two-way transmission of real-time information can be realized in a grid and the operation of all interconnected units from power stations to customers can be monitored and optimized in a timely manner. More specifically, in a smart grid, the power consumption and real-time monitoring information are collected from customers and directed to utility centers, while control and pricing messages are delivered in the reverse direction, based on which a balance of power supply and demands can be achieved.

Wireless communication and networking technology play a critical role to achieve the goals of smart grid. Smart grid devices are distributed in large geographical areas, and some are deployed in a complex environment. In such conditions, multi-hop wireless networking technologies, such as wireless sensor networks (WSNs) and wireless mesh networks (WMNs), are suitable for smart grid communications, while wired communication networks may not meet the coverage and cost-effective requirements of smart grid. With respect to different domains of power systems, the communication networks of smart grid are usually divided into three segments, i.e., wide area networks (WANs), neighborhood area networks (NANs), and home area networks (HANs) [2]. A conceptual model for hybrid wireless communication networks of a smart grid is depicted in Fig. 1, in which various wireless communication networks are deployed in different domains of smart grid.

To promote the applications of wireless communication networks for smart grid, IEEE 802.15.4g task group defines wireless smart metering utility networks, which is a modified version of physical (PHY) and medium access control (MAC) layers of IEEE 802.15.4 (ZigBee) [3]. The SUN is defined as an outdoor low rate, multi-hop wireless network which is relevant to smart grid applications. A SUN implementation scenario is illustrated in Fig. 1, from which we can see that SUN is used primarily in NANs. However, SUN was developed to operate on the license-exempt bands, on which other wireless networks also exist, such as WLANs and ZigBees used for implementing smart grid HANs. Therefore, the coexistence issues between SUNs and the other wireless networks must be investigated. Accordingly, this paper focuses on the coexistence performance of SUNs under WLAN and ZigBee interferences, as well as the solution for SUNs to coexist with WLANs and ZigBee networks.

Coexistence performance of two wireless systems is usually evaluated in terms of bit error rate (BER) and packet error rate (PER). In [4], coexistence performance of IEEE 802.15.1 and IEEE 802.11b was studied based on an analytical BER model, but noise was omitted. BER performances of IEEE 802.15.4 under IEEE 802.11 interferences were evaluated in [5]. Shin *et al.* [6] analyzed PER of ZigBee under WLANs and Bluetooth interferences using a packet collision model, in which PER was obtained from BER and packet collision time. On-demand channel agility schemes are normally used for resolving the coexistence problems between different systems in the unlicensed bands. Thus, the desired system can dynamically detect the interferers appearing in the same bands and change channel to mitigate interference according to the detection results. Coexistence mechanisms for SUNs were surveyed in [7], including multi-PHY management, clear channel assessment, and link quality indicator algorithms, which can be used in both heterogeneous and homogeneous systems. The author stated that more efficient on-demand coexistence algorithms are needed to protect SUNs from the interferences of heterogeneous systems in the same unlicensed

978-1-4673-0911-0/12/$31.00 ©2012 IEEE

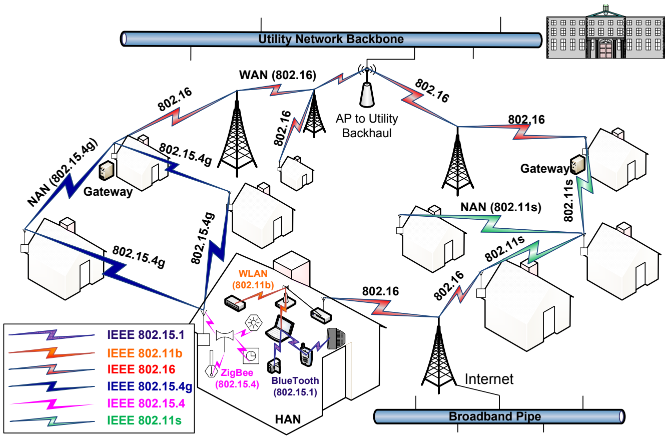


Fig. 1. A conceptual model for hybrid wireless communication networks in smart grid.

bands. Yi *et al.* [8] also studied PER characteristics of ZigBee interfered by WLANs on 2.4 GHz unlicensed bands, based on which a channel agility scheme was proposed. The proposed algorithm can select clear channels adaptively to avoid WLAN interferences.

Unfortunately, none of the existing studies addressed particularly the coexistence issues of SUNs and the other wireless networks in the same unlicensed bands. In this paper, first we analyze the coexistence performance of SUNs under WLANs and ZigBees interferences on 2.4 GHz license exempt band in terms of BER using a BER calculation model. we also want to evaluate PER performance of SUNs to determine the minimum separation distances between SUN and WLAN/ZigBee devices. A simple PER calculation model is used to compute PER from the known BER, and the minimum separation distances are obtained according to PER performance and the required PER level. Then, we will propose a coexistence solution for SUNs with a tree-like multiple-gateway mesh topology, in which SUNs can avoid the interferences from WLANs and ZigBees.

The rest of this paper is outlined as follows. Section II provides a brief introduction of SUNs and other related standards. In Section III, we present a BER calculation model for performance evaluation of SUNs under WLAN and ZigBee interferences. Section IV discusses coexistence performances of SUNs, and summarizes the minimum separation distances between SUNs and WLANs/ZigBees. A coexistence solution for SUNs is proposed in Section V, followed by the conclusion of the paper in Section VI.

II. Preliminaries for SUN and Related Standards

A. SUN/IEEE 802.15.4g

IEEE 802.15.4g specifies the principal requirements of outdoor low rate wireless smart metering networks. SUNs were designed to operate on shared network resources to provide control and monitoring of the metering systems distributed in very large areas. Usually, SUN devices need peer-to-peer and multi-hop technologies to connect to access points. In

TABLE I
Major parameters of three SUN PHYs in 2.4 GHz band.

System	PHY specification	Receiver bandwidth	Transmit power	Receiver sensitivity	PHY mode
SUN	MR-FSK	200 kHz	0 dBm	-90 dBm	FSK Mode 1
WLAN	DSSS	22 MHz	17 dBm	-76 dBm	CCK 11 Mbps
ZigBee	DSSS	2 MHz	0 dBm	-85 dBm	OQPSK 250 kbps

order to meet different application requirements, the standard provides three alternative PHYs to support its key objectives, including scalability to many users, large packets and long ranges, high availability, highly reliable data delivery, and ease of commissioning.

SUNs operate on unlicensed bands, and the number of channels on each band depends on the PHY mode adopted [3]. In this paper, the industrial, scientific, and medical (ISM) band at 2.4 GHz is the band of interest, and multi-rate and multi-regional frequency shift keying(MR-FSK) mode 1 is the selected PHY for SUNs. In this mode, data rate is 50 kbps, modulation type is filtered binary FSK, modulation index is 1, and channel spacing is 200 kHz. The other parameters are listed in Table I. The channel allocation of SUN FSK mode 1 in 2.4 GHz band is illustrated in Fig. 2. There are totally 416 channels for SUN FSK mode 1 and the central frequency of the first channel is 2400.2 MHz.

The basic network topology of a SUN is a peer-to-peer structure. A centralized coordinator is used for network management to facilitate communications amongst network devices. Two kinds of devices, full function device (FFD) and reduced function device (RFD), are included in SUNs. The FFD, which provides all MAC functions, can be used as a coordinator, router, or an ordinary end device. The RFD with a reduced set of MAC functions is used as an end device only. If a FFD acts as a network coordinator, it will play the role of gateways for information exchange with external entities.

B. WLAN/IEEE 802.11b

The PHY and MAC of WLANs are specified by IEEE 802.11b which supports high rate data transmission. There are totally 14 channels available for WLANs in 2.4 GHz ISM band, as shown in Fig. 2. The WLAN channels are separated by 5 MHz in most cases with a bandwidth of 22 MHz. It is possible to find a maximum of three non-overlapping channels. The channel set #1, containing non-overlapping channels 1, 6, and 11, is the most widely used set in the US. IEEE 802.11b standard can work at variety of data rates, i.e., 1, 2, 5.5, or 11 Mbps. Carrier sense multiple access with collision avoidance (CSMA/CA) is the media access scheme for WLANs. In this paper, we assume that Barker code and complementary code keying (CCK) serve as the modulation scheme of WLANs.

C. ZigBee/IEEE 802.15.4

IEEE 802.15.4 specifies connection protocols of low power, low data rate, and low complexity short distance wireless personal area networks (WPANs), also known as ZigBee, which is used for smart grid HAN connectivity. As shown

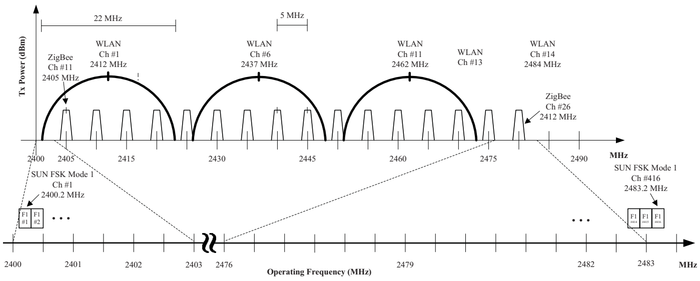


Fig. 2. Channel allocations of SUN FSK mode 1, WLAN, and ZigBee in 2.4 GHz band.

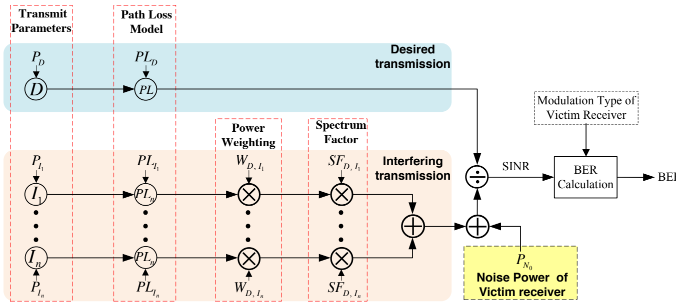


Fig. 3. BER calculation model for two or more different systems coexisting in the same frequency bands.

in Fig. 2, channels 11 to 26 of ZigBee are located in the 2.4 GHz band, each with a bandwidth of 2 MHz and a 5 MHz spacing between the central frequencies of adjacent channels. Moreover, the primary channel access scheme for ZigBee is also CSMA/CA. According to deployment conditions, communication distance of ZigBee devices can be 1 to 100 meters [8]. Besides, the topology of ZigBee is similar to the SUN.

The major parameters for WLANs and ZigBee PHY used in this paper are provided in Table I, in which DSSS and OQPSK are short for direct sequence spread spectrum and offset quadrature phase shift keying, respectively.

III. BER Calculation Model for SUNs

In this section, we describe in detail how to evaluate and model the coexisting interference. An analytical model for BER calculation when different systems coexist in the same band is depicted in Fig. 3. This model is derived from BER calculation model described in [4], and the difference is that noise power is considered in the new model. This new model will be used for BER analysis of a SUN under WLAN and ZigBee interferences.

In this work, the desired signal is from a SUN and the interferences are WLAN and/or ZigBee signals. The desired transmission to a receiver is attenuated by path loss, while each interfering transmission is subject to its path loss attenuation weighted by a spectrum factor to account for the combined effect of transmitter and receiver masks and frequency offsets. The power weighting indicates how much interfering power impacts on a victim receiver according to their bandwidth allocations. The signal to interference and noise ratio (SINR) at a receiver is calculated as

$$SINR = \frac{P_D/PL_D}{\sum_{k=1}^{n} SF_{D,I_k} W_{D,I_k} P_{I_k}/PL_{I_k} + P_{N_0}}. \quad (1)$$

For the received signal power, we need to know the transmitting power P_D of the intended signal and the attenuation caused by path loss PL_D. For received interference power, we need to calculate transmitting power P_{I_k} of interferer, attenuation caused by path loss PL_{I_k}, spectrum factor SF_{D,I_k}, and power weighting W_{D,I_k}. For received noise power P_{N_0}, we assume that the noise at a victim receiver is additive white Gaussian noise (AWGN), and thus noise power can be expressed as $P_{N_0} = B_{\mathbf{Rx}_v} \times N_0$. $B_{\mathbf{Rx}_v}$ is the required bandwidth of the victim receiver, and N_0 is the noise spectral density given by $N_0 = kT$, where k is Boltzmann constant in joules per kelvin, and T is receiver noise temperature in kelvins. The following subsections will describe how to calculate path loss, spectrum factor, power weighting, and BER.

A. Path Loss Model

Let us consider a deployment scenario of SUNs, WLANs, and ZigBees in smart grid applications. IEEE breakpoint path loss model is adopted here. This model stipulates a two-segment function with a path loss coefficient of 2.0 for the first 8 meters and path loss coefficient of 3.3 thereafter. Therefore, the path loss follows free-space propagation, while the distance of transmitter and receiver is within eight meters, and then it attenuates more rapidly with distance. But this model is not suitable for the situation where the distance is below 0.5 meter due to near-field and implementation effects. For the carrier frequency of 2.4 GHz, the formula of path loss in decibels is given by

$$PL = \begin{cases} 40.2 + 20\log_{10}(d), & 0.5 \le d \le 8 \text{ m}, \\ 58.5 + 33\log_{10}\left(\frac{d}{8}\right), & d > 8 \text{ m}. \end{cases} \quad (2)$$

B. Spectrum Factor

The spectrum factor considers the combined effects of transmitter and receiver masks and frequency offset between the interfering and wanted signals. In the calculation, transmitter mask must be normalized first to ensure that the entire area under the curve is one. The non-normalized receiver mask is then obtained. The spectrum factor is just to calculate the integral under the curve by multiplying all these masks together at a particular frequency offset. The spectrum factor will be unity for the receiver and transmitter with the same modulation type and zero frequency offset.

In our previous work, the frequency offsets between interferences and the wanted signals are always zeros, and thus there is no attenuation caused by the masks of interfering transmitter(s) and victim receiver(s). In this paper, we will take the frequency offsets into account. Assume that there is no frequency offset for SUN signals at the transmitter and receiver, and the SUN receiver mask is ideal such that there is no attenuation within receiver bandwidth, while the signal

TABLE II
SPECTRUM FACTORS FOR WLANS AND ZIGBEES IN SUNS.

Frequency offset (MHz)	Spectrum factor (dB)	
	WLAN to SUN	ZigBee to SUN
0-3	-13.2	-8.5
4-10	-13.2	-28.5
11-21	-43.2	-28.5
22-40	-63.1	-28.5
41-50	-80.0	-79.6

power attenuates to zero outside the bandwidth. The frequency offsets between interferences, i.e., WLAN and ZigBee signals, and the SUN signals exist. The transmitter masks of WLANs and ZigBees can be found in [9]. Based on the aforementioned calculation model, the spectrum factors can be calculated as

$$SF_{D,I_k} = \int_{-A}^{A} M_{\mathbf{Rx}}^{(D)}(f - \Delta f_k) \frac{M_{\mathbf{Tx}}^{(k)}(f)}{\int_{-\infty}^{\infty} M_{\mathbf{Tx}}^{(k)}(u)\, du} df, \quad (3)$$

where $M_{\mathbf{Tx}}^{(k)}(f)$ is transmitter mask of the kth interfering signal, and $M_{\mathbf{Rx}}^{(D)}(f)$ is receiver mask of the desired signal, and Δf_k is the absolute frequency offset of the desired signal and the kth interfering signal. Note that the integration limit A is not critical, but it must be large enough to cover the required frequency range. The spectrum factors for WLAN and ZigBee transmitters to a SUN receiver are obtained and listed in Table II, from which it is seen that the spectrum factors for WLAN and ZigBee transmitters to SUN receivers are decided mainly by WLAN and ZigBee transmitter masks. This is reasonable for the cases that the bandwidth of a SUN receiver is much smaller than the bandwidths of WLAN and ZigBee transmitters.

C. Power Weighting

The effect of the kth interfering signal on the desired signal is assumed to be similar to AWGN in the same bandwidth, and it is averaged over the bandwidth of a victim if the bandwidth of an interfering signal B_{I_k} is smaller than the required bandwidth of the desired signal B_D; otherwise, the interfering transmission power will have a power weighting equal to the required bandwidth of the victim system divided by the bandwidth of the interfering signal [10]. Thus, the power weighting can be expressed as

$$W_{D,I_k} = \begin{cases} 1, & \text{if } B_{I_k} \le B_D, \\ \dfrac{B_D}{B_{I_k}}, & \text{if } B_{I_k} > B_D. \end{cases} \quad (4)$$

D. BER Calculation

In the BER calculation model, the final BER can be obtained when modulation type and SINR are given, meaning that BER is a function of modulation type and SINR at a receiver. For SUN FSK mode 1, we assume that PHY employs ideal coherent detection in AWGN channels, and a coherent binary FSK (BFSK) transceiver is adopted. Thus, the BER formula of BFSK coherent detection can be written as

$$P_b = Q\left(\sqrt{SINR}\right), \quad (5)$$

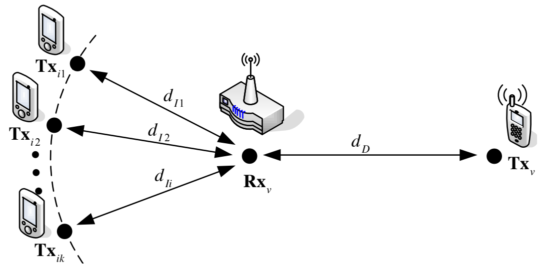


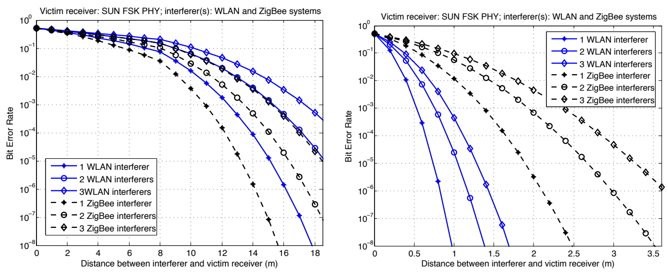
Fig. 4. System model for the coexistence performance analysis of a SUN.

where P_b denotes BER, and $Q(x)$ represents the Q-function. If non-AWGN channels are considered, we can simply employ the corresponding BER functions according to modulation type and propagation channel model.

IV. COEXISTENCE PERFORMANCE FOR SUNS

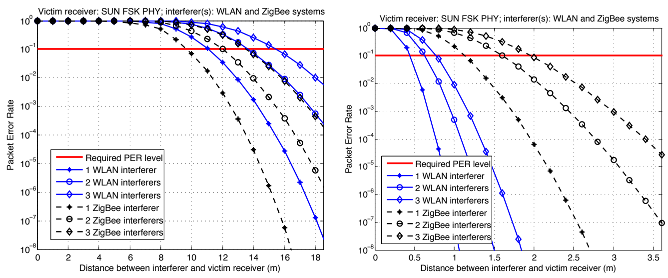
Based on the BER calculation model, this section analyzes performance of a SUN under WLAN and ZigBee interferences in the 2.4 GHz band. The network topology of interfering and victim systems used in the analysis is depicted in Fig. 4, in which the distance between a victim receiver $\mathbf{Rx}_v$ and a victim transmitter $\mathbf{Tx}_v$ is fixed at d_D, and the distances between victim receiver and k interfering transmitters (i.e., $\mathbf{Tx}_{im}$, $m \in [1 \sim k]$) are $d_{I1},\ d_{I2},\ \cdots, d_{Ik}$, respectively. Assume that distances between a victim receiver and k interfering transmitters are the same, i.e., $d_{I1} = d_{I2} = \cdots = d_{Ik}$ without losing generality.

The BER performance of a SUN with different numbers of WLAN and ZigBee interferences is evaluated first. Fig. 5 illustrates the relationship between BER performance of a FSK SUN victim receiver and the distances between the victim receiver to the interferer(s). The list of interferers is given in the legend of Fig. 5. The distance between SUN receiver and transmitter is set to 20 meters, and two typical frequency offsets between the central frequencies of a SUN receiver and the interference transmitters, i.e., 2 MHz and 11 MHz, are used for analysis. The reason to choose these values is that we want to set the same frequency offset values for WLAN and ZigBee, and 2 MHz represents the case in which SUN channel is completely covered by WLAN/ZigBee channels, while 11 MHz indicates that SUN channel is outside WLAN/ZigBee channels. The BER performance with 2 MHz frequency offset is shown in Fig. 5(a), from which it is observed that with the same number of interferences WLAN induces higher interference to SUN than ZigBee due to its relatively high transmission power. When the distance between interferer and victim receiver is 15 meters, we can see that BER of SUN FSK PHY under one ZigBee interferer can be 10^{-7}, whereas it achieves only 10^{-5} under one WLAN interferer. But the situation is different when the frequency offset increases to 11 MHz. Fig. 5(b) shows that with the same number of interferences, ZigBee induces higher interference than WLAN at 11 MHz frequency offset, because WLAN signal attenuates much faster than ZigBee signal at the same



(a) (b)

Fig. 5. BERs of a SUN in different interference scenarios: (a) Frequency offset is 2 MHz; (b) Frequency offset is 11 MHz.



(a) (b)

Fig. 6. PERs of a SUN in different interference scenarios: (a) Frequency offset is 2 MHz; (b) Frequency offset is 11 MHz.

transmission distance according to different spectrum factors of the two systems at the 11 MHz frequency offset.

Apparently, BER of SUN FSK PHY becomes worse as the number of WLAN and ZigBee interferers increases. Meanwhile, comparing Figs. 5(a) and 5(b), we know that when a SUN channel is separated far away from WLAN or ZigBee channels, i.e., the frequency offset is large, BER performance of the SUN FSK PHY will be better.

To explain the findings of coexistence evaluation, parameter $\mathcal{D}$ is defined as the critical distance of minimum separation between a SUN receiver and WLAN/ZigBee transmitters, beyond which the interferers may cause a performance degradation greater than the required PER of the SUN standard. Therefore, PER performance and the default PER required by SUN must be found out to verify the minimum separation. PER can be theoretically calculated by the following equation, i.e.,

$$P_p = 1 - (1 - P_b)^L, \tag{6}$$

where P_p denotes PER of a SUN, P_b is BER obtained by (5), and L represents the default packet length of SUNs. In (6), forward error correction (FEC) is not taken into consideration, and thus a SUN data packet is considered as an error packet if there exists at least one error bit. This means here we consider the worst case of a SUN.

With the help of (6), PER of a SUN FSK victim receiver in terms of the distances between SUN receiver to interferer(s) was simulated, and the results are depicted in Fig. 6. The bold horizontal line represents the required PER of the SUN standard, i.e., 10^{-1}. The trend of PER curves is similar to the BER curves in the same interference scenarios. It can be observed that the more the interferers exist, the longer the minimum separation distances are required. Fig. 6(a) shows that, with a 2 MHz frequency offset, to achieve a required PER level, the minimum separation distances between a SUN receiver and WLAN transmitters should be 11, 13.7, and 15.5 meters, corresponding to 1, 2, and 3 WLAN interferers, respectively. The minimum separation distances between a SUN receiver and ZigBee transmitters should be 9.7, 12.0, and 13.5 meters, corresponding to 1, 2, and 3 ZigBee interferers, respectively. When frequency offset is 11 MHz, to meet the PER requirement, the minimum separation distances between a SUN receiver and WLAN transmitters should be 0.44, 0.63, and 0.77 meters, corresponding to 1, 2, and 3 WLAN interferers, respectively, and the minimum separation distances between a SUN receiver and ZigBee transmitters should be 1.13, 1.6, and 1.97 meters, corresponding to 1, 2, and 3 ZigBee interferers, respectively.

V. SUN and WLAN/ZigBee Coexistence

According to the analysis, we can observe that frequency offset and separation distance are two important factors determining coexistence performance of SUNs. The separation distance offers a physical isolation for a given system, and it must be considered when SUN and WLAN/ZigBee devices are deployed in smart grid. Once a system deployment is finished, the separation distances between devices are fixed. Frequency offset is a soft isolation as a basis for more flexible and effective on-demand coexistence solutions, e.g., channel agility schemes. Accordingly, a coexistence solution is proposed from the aspect of frequency offset for SUNs coexisting with WLANs and ZigBees in the same band. We present our idea from three aspects, including network topology, interference detection, and interference avoidance as follows.

1) Network Topology for SUNs: Considering the fact that SUNs are used mainly in NANs, a tree-based multiple gateway WMN topology might a good choice for its characteristics of reliability and stability [11]. In such a network, multiple gateways (coordinators) exist to manage the communications between backbone access points and home meters, and these gateways are managed by the local grid centers and their locations are well selected. The entire network is clustered into multiple tree-based subnetworks, each having one gateway as its root node. The gateway establishes its tree via periodical announcements of root information, and each meter has a tree-table to record the tree information. Each meter is connected with its root node in a single-hop or multiple-hop manner; meanwhile, it also maintains the routing information to each of the other gateways. Furthermore, we suggest that each gateway is assigned a particular SUN channel, and all its child nodes operate in this channel. Besides, a separate SUN channel is assigned as a public channel for all gateways to transmit control information. Such design can also mitigate interferences within a SUN.

2) Interference Detection: Each SUN gateway checks its link quality indicator (LQI) between its child nodes and itself for every received packet. Once LQI is lower than a designed threshold x, it indicates that a packet loss caused by poor link quality has occurred. In such a case, the gateway will scan the current channel using energy detection (ED) to verify that the interference causes link quality degradation. If the ED result, i.e., received signal strength indicator (RSSI), is above a threshold y, the SUN gateway assumes that the interference has been detected and it will send a control information to all its child nodes through the public channel to trigger their corresponding interference avoidance procedures. At the same time, the gateway continues to make ED scans on the current channel within a time threshold. Note that the public channel is a carefully chosen channel which should not be overlapped by any WLAN and ZigBee channels.

3) Interference Avoidance: Once the meter nodes in a victim tree receive the control information originated from a gateway to start interference avoidance procedure, each node will take necessary action to avoid interference. First, it will check its tree-table for routing information to the other gateways and find out a path to one of the gateways, which has the best routing metric. Meanwhile, the node will ensure the availability of channel according to the control information sent by the candidate gateway. Then, if channel is available, the node will select the candidate gateway as its new root gateway and join the new tree by refresh its tree-table according to the root announcement; otherwise, the node will check the tree-table to find out a suboptimal path. This procedure is repeated until the node joins to a new tree. Moreover, if a time threshold expires and the interference still exists in the victim channel, the gateway will stop ED on the victim channel and scan the entire SUN band to find a new clear channel.

Compared with the channel agility scheme suggested in [8], this work suggests that the interference detection is carried out by the coordinators and LQI is checked for every received packet. Moreover, a public channel is used for control information transmission. These differences can make SUN to respond to WLAN/ZigBee interferences in a much more timely way. The overall approach has a high stability because of the mesh topology and existence of the public channel. But simulations are needed to validate the performance. The expense is that this solution consumes more SUN frequency resources. Furthermore, a traffic balancing scheme should be proposed and investigated for the interference avoidance procedure to balance the traffic amongst all gateways.

VI. Conclusions

This paper studied the coexistence issues of SUN and WLAN/ZigBee in license-exempt band at 2.4 GHz. An analytical model for BER calculation was derived to evaluate the performance of a SUN under various interference conditions. Particularly, we showed the importance of spectrum factor which was obtained for WLAN and ZigBee transmitters to SUN receivers. It was shown that the frequency offset and separation distance between SUN and WLAN/ZigBee have a great impact on the coexistence performance. A larger frequency offset and a longer separation distance lead to a better coexistence performance. We also evaluated PER performance of SUNs, and minimum separation distances between SUN and WLAN/ZigBee in various scenarios were obtained. It was observed that a larger frequency offset and fewer interferers can result in shorter minimum separation distances. From the perspective of frequency isolation, we proposed a coexistence scheme for SUNs based on a tree-like multiple gateway WMN topology. Theoretically, this solution allows SUN devices detect and avoid WLAN/ZigBee interferences timely in its operation channels. Some further studies such as traffic balancing amongst gateways are needed to evaluate its performance.

Acknowledgments

This work was supported partially by the Program for China's New Century Excellent Talents in Universities (NCET-08-0157), and Taiwan National Science Council research project (NSC99-2221-E-006-016-MY3).

References

[1] Y. X. Wenye Wang and M. Khanna, "A Survey on the Communication Architectures in Smart Grid", *Computer Networks*, vol. 51, no. 15, pp. 3604–629, 2011.

[2] R. Yu, Y. Zhang, S. Gjessing, C. Yuen, S. Xie, and M. Guizani, "Cognitive Radio Based Hierarchical Communications Infrastructure for Smart Grid", *Network, IEEE*, vol. 25, no. 5, pp. 6–14, Sep.-Oct. 2011.

[3] "*Physical Layer Specifications for Low Data Rate Wireless Smart Metering Utility Networks*", IEEE Std. P802.15.4g/D4 part 15.4, Apr. 2011.

[4] "*Coexistence of Wireless Personal Area Networks with Other Wireless Devices Operating in Unlicensed Frequency Bands*", IEEE Std. 802.15.2-2003 part 15.2, Aug. 2003.

[5] I. Howitt and J. A. Gutierrez, "IEEE 802.15.4 Low Rate-Wireless Personal Area Network Coexistence Issues", in *Proc. IEEE Wireless Communications and Networking Conf.(WCNC)*, 2003, pp. 1481–1486.

[6] S. Y. Shin, H. S. Park, S. Choi, and W. H. Kwon, "Packet Error Rate Analysis of ZigBee Under WLAN and Bluetooth Interference", *IEEE Trans. Wireless Commun.*, vol. 6, no. 8, pp. 2825–2830, 2007.

[7] C.-S. Sum, F. Kojima, and H. Harada, "Coexistence of Homogeneous and Heterogeneous Systems for IEEE 802.15.4g Smart Utility Networks", *New Frontiers in Dynamic Spectrum Access Networks (DySPAN), 2011 IEEE Symposium o*n, May 2011, pp. 510–520.

[8] P. Yi, A. Iwayemi, and C. Zhou, "Developing ZigBee Deployment Guideline Under WiFi Interference for Smart Grid Applications", *IEEE Trans. Smart Grid*, vol. 2, no. 1, pp. 110–120, 2011.

[9] "*Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs)*", IEEE Std. 802.15.4-2006 part 15.4, Sep. 2006.

[10] Q. Pang and V. C. M. Leung, "Channel Clustering and Probabilistic Channel Visiting Techniques for WLAN Interference Mitigation in Bluetooth Devices", *IEEE Trans. Electromagn. Compat.*, vol. 49, no. 4, pp. 914–923, 2007.

[11] H. Gharavi and B. Hu, "Multigate Communication Network for Smart Grid", *Proceedings of the IEEE*, vol. 99, no. 6, pp. 1028–1045, Jun. 2011.