Analysis, Simulations and Improvement Proposals of IEEE 802.15.4g-2012

Master's thesis in Communication Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

IEEE 802.15.4g-2012 is a new amendment of the communication standard IEEE 802.15.4-2011. IEEE 802.15.4g-2012 enables multiple applications to operate in the same location and share the same frequency band.

In this thesis we analyze the MAC layers and PHYs of both standards and discuss about the major differences between them. Then we show the simulation results of IEEE 802.15.4-2011 O-QPSK PHY and IEEE 802.15.4g-2012 MR-O-QPSK PHY, where the simulation performance is measured with the BER.

By analyzing the simulation results we draw the conclusion that in AWGN channel without burst errors or unpredicted inverse of the bit streams, IEEE 802.15.4-2011 O-QPSK PHY performs better than IEEE 802.15.4g-2012 MR-O-QPSK PHY when the data rate keeps the same.

We propose a spreading map switching mechanism that may improve the performance of the IEEE 802.15.4-2011 O-QPSK PHY in different application scenarios. We also propose a dynamic mode switching mechanism to choose the optimal PHY mode in different application scenarios to make better use of the MR-PHYs in IEEE 802.15.4g-2012.

Keywords: IEEE 802.15.4-2011, IEEE 802.15.4g-2012, MAC, PHY, O-QPSK, AWGN

Contents

1 Introduction

1.1 Purpose

In industrial applications it takes a lot of resources to implement a new communication standard so it is important to test if this new standard is worthy enough to be implemented. The purpose of this thesis is to gather information to analyze IEEE 802.15.4g-2012 and test the performance of IEEE 802.15.4g-2012 multi-rate and multi-regional offset quadrature phase-shift keying (MR-O-QPSK) Port Physical Layer (PHY) compared with IEEE 802.15.4-2011 O-QPSK PHY. After analyzing the standards documents and the simulation results we propose two mechanisms to improve the performance of IEEE 802.15.4-2011 O-QPSK PHY and IEEE 802.15.4g-2012 PHYs.

1.2 Outline

- In chapter 1, we explain the purpose and the outline of this thesis.
- In chapter 2, we analyze the Media Access Control (MAC) layer and PHYs of IEEE 802.15.4-2011. We focus on MAC functions and O-QPSK PHY in this chapter.
- In chapter 3, we discuss the major differences between IEEE 802.15.4g-2012 and IEEE 802.15.4-2011 in MAC layer. Then we analyze the three PHYs of IEEE 802.15.4g-2012 while MR-O-QPSK is mainly discussed.
- In chapter 4, we present the mathematical description of the simulation procedures of IEEE 802.15.4-2011 O-QPSK PHY and IEEE 802.15.4g-2012 MR-O-QPSK PHY. We take the 2450MHz band which is world-widely used in industry [1] as the frequency band in simulations. The BER performance is displayed according to the simulation results.
- In chapter 5, based on the analysis and simulation results, we propose a spreading map switching mechanism for IEEE 802.15.4-2011 O-QPSK PHY and a dynamic mode switching mechanism for IEEE 802.15.4g-2012 PHYs to make improvements.
- In chapter 6, we draw our conclusions.

2

Analysis of IEEE 802.15.4-2011

2.1 General description

IEEE 802.15.4-2011 is a communication standard defined by IEEE 802.15 working group in 2003. IEEE 802.15.4-2011 is the basis of some upper applications such as the ZigBee, WirelessHART and MiWi. [2] It specifies the physical layer and MAC for LR-WPANs (low-rate wireless personal area networks). An LR-WPAN is an energy-efficient communication network. LR-WPAN provides easy installation, reliable data transmission and low energy cost, which make it suitable for wireless communications in limited-energy applications. In this paper the IEEE 802.15.4-2011(hereinafter referred to as IEEE 802.15.4-2011), which was released in 2011, is mainly discussed.

2.2 Devices and topologies

Two kinds of devices can be implemented in an IEEE 802.15.4-2011 network. A full-function device(FFD) is a device that can operate as a personal area network (PAN) coordinator or a normal network coordinator. The other one is the reduced-function device(RFD) which can not serve as a coordinator. An RFD can only associate with one FFD at a time and is usually used to send small amount of data. The RFDs are mainly implemented in simple applications.
There are two typical network topologies implemented in IEEE 802.15.4-2011 LR-WPANs: the star topology and the peer-to-peer topology, as shown in Figure 2.1. In a star topology a PAN coordinator, which serves as a central controller, is in charge of the initiation, termination or route communications of the network. In a peer-to-peer topology, each device is able to communicate to all its neighbor devices. The peer-to-peer topology can be used in some complex applications, such as wireless sensor networks and industrial control.

2.3 MAC layer functions

The media access control (MAC) sublayer in IEEE 802.15.4-2011 is responsible for the following tasks:

- **Generating the network beacons for the PAN coordinators**
  A superframe structure can be used by a coordinator in a PAN to bound the channel time. As depicted in Figure 2.2, a superframe may contain an active

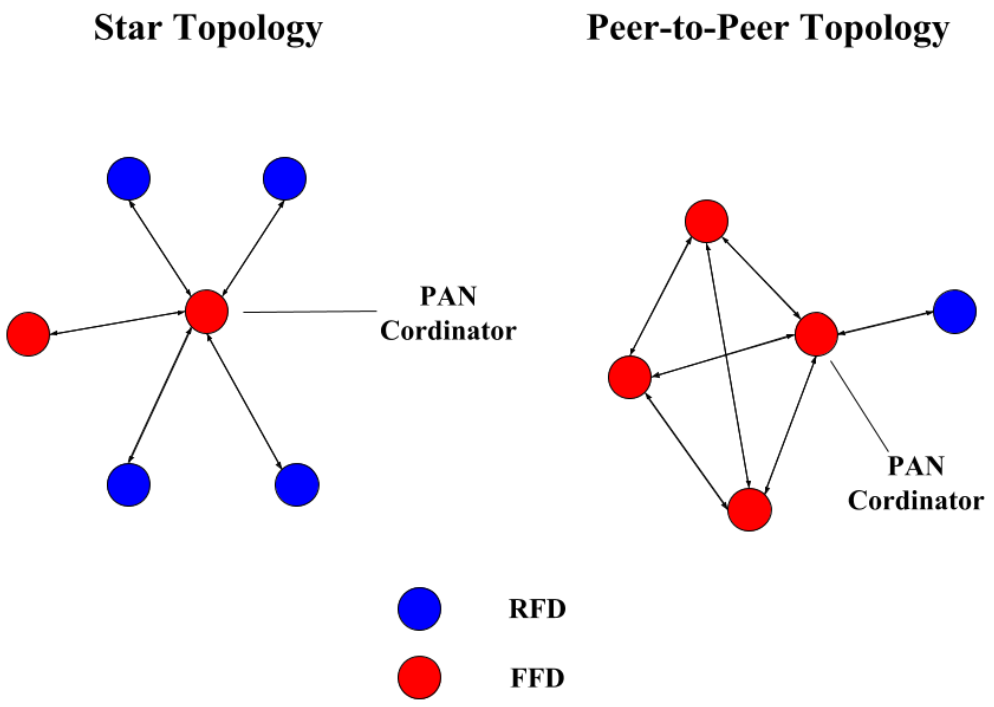

Figure 2.1: Network topologies

portion and an inactive portion. In some applications where the nodes do not need to keep awake all the time, the coordinator will be switched to the low-power mode (sleep mode) during the inactive portion.

The active portion of a superframe may contain 3 parts: 1) a beacon frame that bounds the superframe; 2) a contention access period (CAP) where CSMA/CA algorithm is used by nodes in the network to contend for channel access; 3) a collision free period (CFP) where the channel is reserved but the reserving nodes are able to use the channel with a guaranteed time slot (GTS). The CFP is optional and usually can be used in applications with specific data transmission bandwidth or low latency. [3]

- **Synchronizing to the network beacons**
  There can be two kinds of PANs depending on if network beacons can be supported in the PAN. In a beacon-enabled PAN, the synchronization is performed by decoding the beacon frames. For nonbeacon-enabled PANs, the synchronization is achieved by polling the coordinator for the information.
- **Supporting the association and disassociation in PANs**
  When a device is about to associate with a PAN, the next higher layer above the MAC layer will perform a MAC layer reset then scan the channel. A suitable PAN is selected according to the results of the channel scan. The next higher layer then requests association through MAC sublayer management entity (MLME)-ASSOCIATE.request primitive.

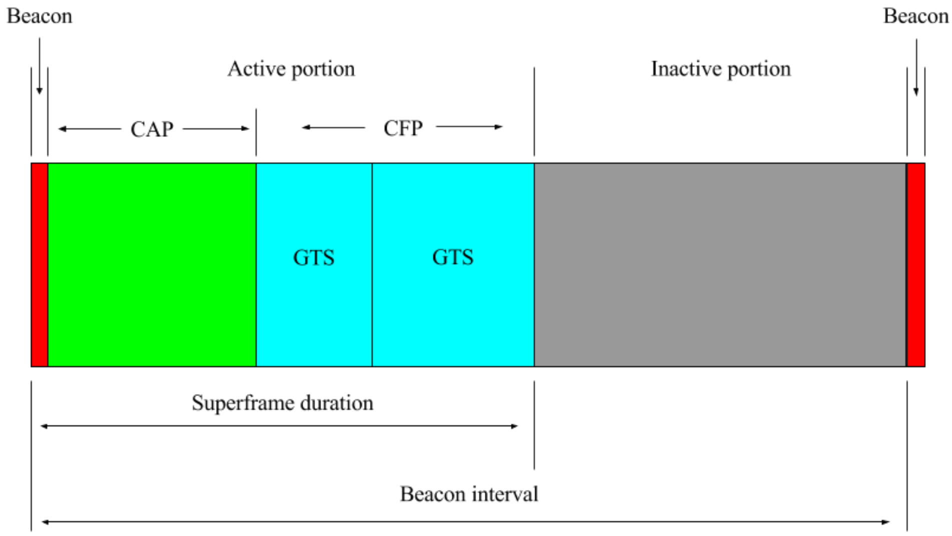

Figure 2.2: Superframe structure

The device instructed to associate with a PAN is ordered to try to associate with an existing PAN and not to start its own PAN. The association attempt will be ignored by the PAN coordinator if the coordinator does not permit association.
The MLME of the coordinator will send a disassociation command to a device with indirect or direct transmission if the coordinator wants the device to leave the PAN. When an associated device is about to leave the PAN, its MLME will also send a disassociation command to the PAN coordinator. In both cases, the MAC layer should notify the next higher layer if the disassociation command is not successfully sent due to the channel access failure.

- **Employing the CSMA-CA mechanisms**
  Two kinds of carrier sense multiple access with collision avoidance (CSMA-CA) channel access mechanisms are employed in IEEE 802.15.4-2011 LR-WPAN. In nonbeacon-enabled PANs the unslotted CSMA-CA mechanism is used. Every time a device in nonbeacon-enabled PANs is about to transmit data except for acknowledge frames, the device waits for a random back-off. If the device finds the channel idle after the back-off the device transmits its data. If the device finds the channel busy after the random back-off, it shall wait for another random period then tries to access the channel again.
  In beacon-enabled PANs the slotted CSMA-CA mechanism is employed where back-off periods of all devices in the same PAN are aligned to the coordinator and the back-off periods are aligned with the beacon transmission start time. The MAC layer in beacon-enabled PANs is responsible to make sure that PHY starts all transmissions on the boundary of one fixed back-off period.
- **Processing and maintaining the GTS mechanism**
  The GTS is an optional mechanism which offers a device in PAN one dedicated portion of the superframe. In one PAN only the PAN coordinator can manage the GTSs and the coordinator is able to allocate seven GTSs at most when sufficient capacity is available in the superframe.

2.4 PHY descriptions

Five different PHYs are supported in IEEE 802.15.4-2011: ASK, BPSK, O-QPSK, CSS and UWB. We focus on the O-QPSK PHY as a similar modulation scheme is also used in MR-O-QPSK PHY in IEEE 802.15.4g-2012. The PPDU (Presentation Protocol Data Unit) of O-QPSK PHY includes three fields: SHR which consists of the preamble and synchronization field; PHR which shows the frame length; PHY payload(PSDU) which contains data.
The O-QPSK PHY Implements the following modulation process shown in Figure 2.3. In every symbol period, 1 symbol containing 4 information bits will be mapped to 1 of 16 pseudo-random noise (PN) sequences according to a spreading map. In the spreading map the PN sequences are quasi-orthogonal, which means each PN sequence is nearly orthogonal to other 15 PN sequences. Then the consecutive PN sequences will be modulated with O-QPSK scheme and transmitted.

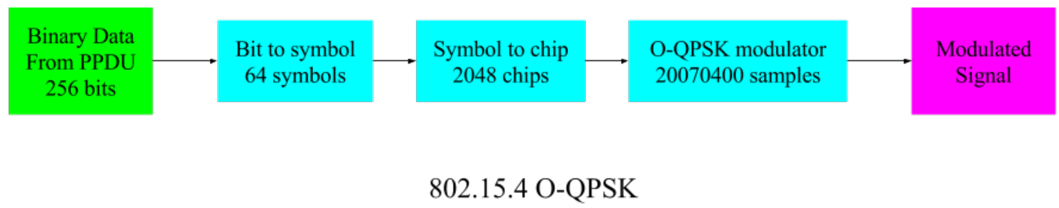

Figure 2.3: Modulation diagram of the O-QPSK PHY

In the 2450 MHz band, each data symbol (four bits) will be mapped into a 32-chip PN sequence according to the spreading map. The half-sine pulse is used as the baseband shape. The chip sequences will then be divided into 2 parts. The in-phase carrier (I-phase carrier) will carry the even-indexed chips while the quadrature-phase carrier (Q-phase carrier) will carry the odd-indexed chips. An offset is added between the I-phase carrier and Q-phase carrier in O-QPSK to make phase shift no more than 90 degrees. [4] So the Q-phase chips will be transmitted Tc seconds later than the I-phase. Tc is the transmission period of one chip and it is also the inverse of the chip rate. Figure 2.4 shows an example of the modulated chip sequences on I-phase and Q-phase. The details of the modulation and demodulation of O-QPSK PHY will be explained in chapter 4.

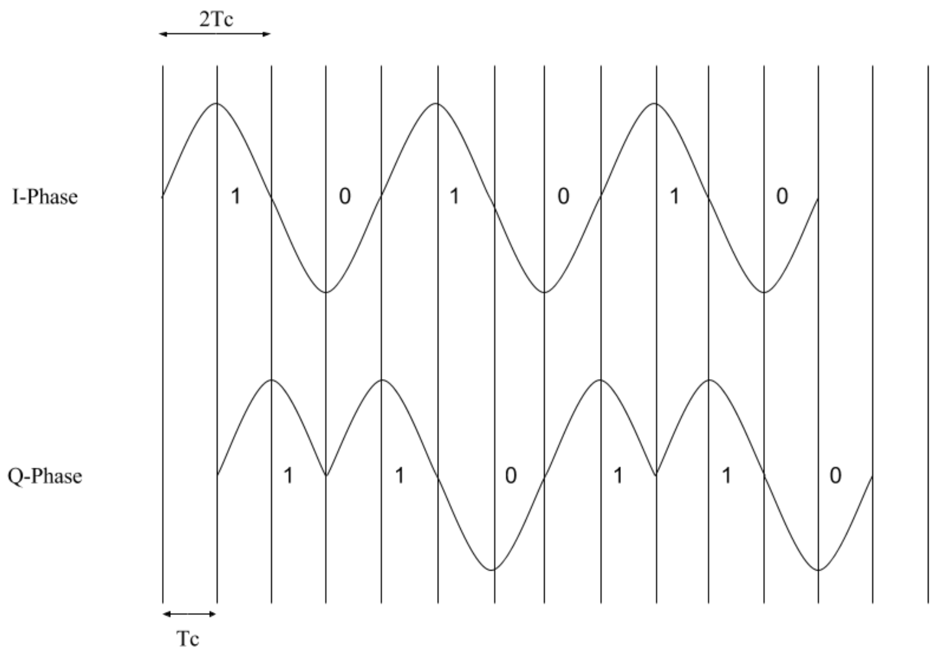

Figure 2.4: Modulated chip sequences

3

Analysis of IEEE 802.15.4g-2012

As an amendment of the IEEE 802.15.4-2011, IEEE 802.15.4g-2012 implements the smart utility networks (SUNs) which enables multiple applications to work with shared network resources and provides control of a utility system. [5] These networks are usually large and diverse, with a big number of outdoor devices inside. So new management methods and functional blocks are introduced to MAC layers and PHYs in IEEE 802.15.4g-2012g. We will discuss about the differences between IEEE 802.15.4g-2012 and IEEE-802.15.4-2011 in this chapter.

3.1 Differences in MAC layers

In this section we analyze the MAC layer of IEEE 802.15.4g-2012 by discuss the differences between its MAC layer and the MAC layer of IEEE 802.15.4-2011.

3.1.1 MPM procedure

Three alternative PHYs are provided in IEEE 802.15.4g-2012 for the SUN devices to support the applications in different conditions:

- **MR-FSK**
  Multi-rate and multi-regional frequency shift keying (MR-FSK) PHY provides remarkable transmission power efficiency because of the constant envelope of the signal.
- **MR-OFDM**
  Multi-rate and multi-regional orthogonal frequency division multiplexing (MR-OFDM) PHY provides the high data rates as well as high spectral efficiency.
- **MR-O-QPSK**
  Multi-rate and multi-regional offset quadrature phase-shift keying (MR-O-QPSK) PHY results in less cost in the multi-mode systems and makes the system easier to design. It is the PHY mode on which we focus in this thesis.

The IEEE 802.15.4g-2012 aims to make it possible that multiple, different SUN PHYs can operate in the same location and in the same frequency band. In order to mitigate the interference among different PHYs a multi-PHY management scheme (MPM) is specified for SUNs. The MPM scheme is introduced to facilitate the interoperability and negotiation among potential PAN coordinators working with different PHYs. In this process the MPM shall permit a coordinator to detect an existing working network during its discovery phase, using the common signaling mode (CSM). The CSM discussed here is a common physical layer mode used between SUN devices implementing MPM scheme.

3.1.2 Enhanced beacon

The enhanced beacon (EB) is a new MAC frame that is introduced in IEEE 802.15.4g-2012 to support the work of the MPM procedure. In a beacon-enabled PAN, unlike the usual periodic beacon which is located in front of the CAP, the enhanced beacon is designed to be transmitted at a fixed interval in CAP and can only be sent in CAP. [5]
The transmission of EBs should be processed in all the channels that are defined for CSM and overlap with other channels in operation. Also, the scanning for EBs and the transmission of the enhanced beacon requests (EBRs) should be processed in all the channels that are defined for CSM and overlap with the channel of interest. There can be several different schemes for the transmissions and scanning of the EBs in beacon-enabled PANs and nonbeacon-enabled PANs:

- In a beacon-enabled PAN, a coordinator which is currently operating a network shall always transmit an EB at a fixed interval using CSM. If another coordinator is intending to start a separate network, it shall scan for an EB until the expiration of the enhanced beacon interval (EBI) or till an EB is detected. When an EB is detected by the intending coordinator, the intending coordinator shall take the methods depending on the specific conditions. These methods are:
    1. The intending coordinator could try to occupy another available channel.
    2. The intending coordinator could try to achieve synchronization with the existing PAN which is operating a network. The timing information applicable for synchronization purposes will be specified in the EB while specific mechanisms to achieve synchronization between two PANs utilizing different PHY modes are implementation-dependent.
    3. The intending coordinator could just stop communication and wait for another chance.
- In a nonbeacon-enabled PAN, the same scheme discussed above can be used for transmitting and scanning the EBs as in beacon-enabled PAN. Optionally, an EB can be obtained in an on-demand way where an EBR containing the ID, which is in the list of IE IDs, will be sent by the intending coordinator to demand an EB from the existing working coordinator. And the existing coordinator will send an EB to the intending coordinator as a response when receiving the EBR. The intending coordinator should transmit at least one EBR in every EBI, while the existing coordinator should periodically scan for the EBR in CSM to increase the probability of detecting the EBR.

3.1.3 Information element

The information element (IE) is a new field which is introduced to the IEEE 802.15.4g-2012 MAC frames for the implementations of different functions. There are four types of IE in IEEE 802.15.4g-2012:

- Coexistence specification IE is used to convey the parameters that define the EB. This kind of IE is included in the enhanced beacon frame to indicate the important information of EBs such as beacon order, enhanced beacon order, channel page, etc. The length of coexistence specification IE is 9 octets.
- SUN PHY capability IE is used to declare the PHY capabilities of the SUN device.
- MR-FSK generic PHY descriptor IE is used to declare one MR-FSK generic PHY descriptor.
- Mode switch parameter entry IE is defined to declare one mode switch parameter entry.

3.1.4 FCS fields

Due to the longer payload of the IEEE 802.15.4g-2012 MAC frame, the frame check sequence (FCS) field contains a 32-bit cyclic redundancy check (CRC) while in IEEE-802.15.4-2011 the FCS field usually contains a 16-bit ITU-T CRC. Devices operating with one or more of the SUN PHYs shall implement the 4-octets FCS and the default FCS length for these devices is 4 octets.

3.1.5 Channel pages

A greater channel numbering capability is required due to the addition of the SUN PHY specifications. The definitions of the channel pages nine and ten have been modified for the SUN PHYs to provide the larger number of channels. The existing channel assignment schemes are still maintained at the same time. Channel page nine specifies each standard-defined SUN PHY operating mode supported by the device. These specifications are frequency band(s), modulation scheme(s) and PHY mode(s). Channel page ten defines the specifications of the MR-FSK Generic-PHY-defined PHY modes.

3.1.6 Packet size and PER tolerance

The receiver sensitivity is defined as the lowest input power for which the packet error rate (PER) conditions are met. To meet the PER conditions the PSDU length should be more than 250 octets for SUN PHYs with data rates 50 kb/s and greater while the PSDU length should be more than 20 octets for all other PHYs. The PER should be less than 10% for SUN PHYs while the PER should be less than 1% for the other PHYs. [5] These specifications indicate that the packet size for SUN PHYs is over ten times larger than other PHYs and the PER that can be tolerated in SUN PHYs is much higher than it is in other PHYs.

3.2 SUN PHYs descriptions

3.2.1 MR-FSK

3.2.1.1 Description

Frequency-shift keying (FSK) is a digital modulation scheme which is commonly used in high-frequency communication spectrum. [6] In FSK, the information is carried by the frequency changes of the carrier waves. In IEEE 802.15.4g-2012 different data transmission rates can be supported by the MR-FSK PHY.

3.2.1.2 PPDU format

The MR-FSK PPDU includes the synchronization header (SHR), PHY header (PHR), and PHY payload. These components are treated as bit strings of length n, numbered b_0 on the left and b_{n-1} on the right. When transmitted, they are processed b_0 first to b_{n-1} last, without regard to their content or structure.

3.2.1.3 Mode switch mechanism

The most impressive feature about the MR-FSK is the mode switch mechanism. This mechanism enables the a device using MR-FSK PHY to change its symbol rate and/or modulation scheme on a packet-by-packet basis (i.e. different modes could be applied in different single packets).
An MR-FSK mode switch PPDU will be transmitted on $phyCurrentChannel$ by the device which has changed its PHY mode. When this PPDU is received by another device which supports the mode switching, the device shall change its operation mode to the new mode defined in the PPDU in order to receive the coming packets. There will be a setting delay when changing the current operating mode to a new mode. The delay depends on the specific mode switch types.
With the mode switch mechanism the nodes in wireless sensor networks are able to change the symbol rates and modulation schemes according to the environment and needs. Also, this mechanism permits two devices using FSK PHY to establish the communication in a different PHY mode.

3.2.2 MR-OFDM

3.2.2.1 Description

In IEEE 802.15.4g-2012 the MR-OFDM PHY provides the high data rates, ranging from $50kb/s$ to $800kb/s$. The signal bandwidth ranges from 1.2 MHz to less than 200 kHz.

3.2.2.2 Frame format

The frame of the MR-OFDM includes SHR, PHR and payload fields. The SHR field consists of short training field (STF) and long training field (LTF).

3.2.2.3 Bit-to-symbol mapping

Three conventional mapping are available in MR-OFDM: BPSK, QPSK and 16-QAM.

3.2.2.4 FEC

The data field shall be encoded with a convolutional code of coding rate $R = 1/2$ or $3/4$, according to the desired data rates.

3.2.3 MR-O-QPSK

3.2.3.1 Description

Multiple PSDU data rates within each supported frequency band can be supported in MR-O-QPSK. The FEC coding, interleaving, and spreading are employed in MR-O-QPSK to improve the transmission performance.

3.2.3.2 PPDU format

The MR-O-QPSK PPDU includes the synchronization header (SHR), PHY header (PHR), and PHY payload. These components are treated as bit strings of length n, numbered b_0 on the left and b_{n-1} on the right. When transmitted, they are processed b0 first to b_{n-1} last, without regard to their content or structure.

3.2.3.3 FEC

In DSSS mode the FEC(Forward Error Correction) will be applied in both PHR and PSDU fields. A 1/2 rate convolutional code with the constraint length $k = 7$ will be employed as the FEC. The generator polynomials are:
$G_0(x) = 1 + x^2 + x^3 + x^5 + x^6$
$G_1(x) = 1 + x + x^2 + x^3 + x^6$
The convolutional codes are working based on information bits in memories and the coming information bit. So the burst error can be corrected when it is employed. In the simulation the Viterbi hard decoding is used to recover the data.

3.2.3.4 Interleaving

Interleaving is employed together with the FEC mechanism in PSDU code-bits in order to improve robustness against burst errors.
The consecutive bits will be less correlated after interleaving so some problems caused by the burst errors can be corrected by FEC. In MR-O-QPSK PSDU the interleaving degree λ is 7 while the interleaving depth is $N = 7 * 18 = 126$. For instance, an indexed code-bits stream $1, 2, 3, 4, ..., 126$ will be interleaved into $1, 19, 37, 55, 73, 91, 109, 2, 20, ..., 126$ after procedure. So when a burst error occurs at $1, 19, 37$ their real consecutive symbols $2, 20, 38$ are not influenced and the original data can be recovered by FEC.

3.2.3.5 BDE

The Bit Differential Encoding (BDE) is employed to correct the errors caused by the unpredicted inverse of the bit streams when data is transmitted through the communication channels in reality. This encoding can be simply described by an equation:
$E_n = R_n \oplus E_{n-1}$
So even if the coded bit streams became inverted (0 turned into 1 or 1 turned into 0) the differences between consecutive bits stay the same. So the information is protected by introducing BDE.

3.2.3.6 Processing diagrams

The data bits of the PSDU field are processed by different signal flows depending on spreading mode. The PSDU processing diagram for (16,4)-DSSS is shown in Figure 3.1 while the processing diagram for (32,1)-DSSS is shown in Figure 3.2.

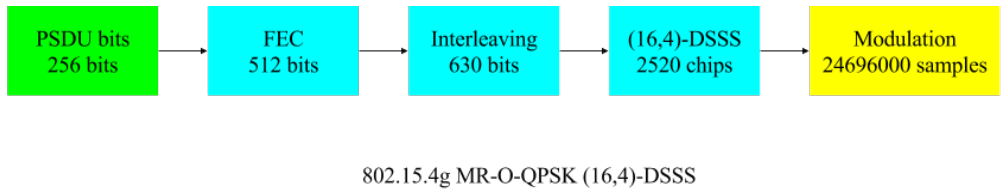

Figure 3.1: PSDU processing diagram for (16,4)-DSSS

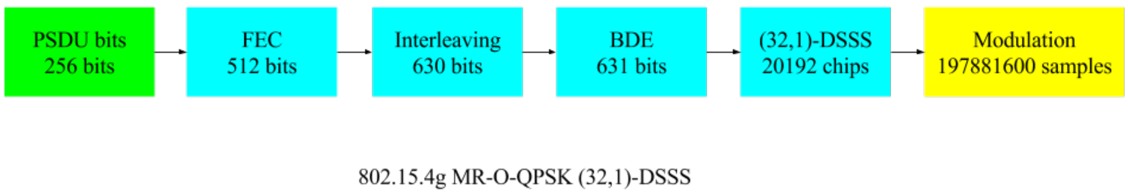

Figure 3.2: PSDU processing diagram for (32,1)-DSSS

4

Simulations

4.1 Simulation process of IEEE 802.15.4-2011 O-QPSK PHY

We run the simulation of IEEE 802.15.4-2011 O-QPSK PHY with a 256-bit original packet by taking following steps:

1. $Symbols = f_1(Packet\ data); Chip\ sequences = f_2(Symbols)$
   Here f_1 is a function that converts every 4 bits to a hexadecimal symbol. f_2 is a function that maps each symbol to a 32 chips.
2. $Symbol\ rate = Data\ rate/4; Chip\ rate = Symbol\ rate * 32;$
3. $Number\ of\ samples = N_s = 2 * S * F_c/R_c = 16 * F_c/R_c$
   F_c is the carrier frequency which is 2450 MHz here and R_c is the chip rate. S is the sampling factor which is 8 in the simulations. So N_s is the number of samples in each chip on the I-phase or Q-phase. Let N_c be the number of chips and $V(n)$ be the value of each chip, $n = 0, 1, 2, ..., N_c - 1$.
   Discrete samples in each chip on the I-phase and Q-phase carriers can be explained as follows.
4. $Sample_I(t, n) = \sqrt{(2)} * sin(\pi * t/N_s) * cos(2 * \pi * t/8) * V(n)$,
   $t = 1, 2, 3, ..., N_c * N_s/2; n = 0, 2, 4, ..., N_c - 2$.
   $Sample_Q(t, n) = 0, t <= N_s/2$.
   $Sample_Q(t, n) = \sqrt{(2)} * sin(\pi * (t - N_s/2)/N_s) * sin(2 * \pi * (t - N_s/2)/8) * V(n)$,
   $t = N_s/2 + 1, N_s/2 + 2, N_s/2 + 3, ..., N_c * N_s/2; n = 1, 3, 5, ..., N_c - 1$
5. $Modulated\ signal = S(t) = Sample_I(t) + Sample_Q(t)$.
6. Then we add AWGN to the modulated signal with the function provided by MATLAB. SNR is the signal-to-noise ratio for each sample:
   $Signal\ with\ AWGN = S_n = AWGN(S(t), SNR, measured);$
7. We do the demodulation with the low-pass-filter (LPF):
   $Demodulated_I(t) = LPF(S(t) * \sqrt{(2)} * cos(2 * \pi * t/8))$.
   $Demodulated_Q(t) = LPF(S(t) * \sqrt{(2)} * sin(2 * \pi * t/8))$.
8. The values of the demodulated chips can be determined by:
   $V(n)_I = f_3(Demodulated_I(n * N_s/2 + \pi/2)), n = 0, 2, 4, ..., N_c - 2$
   $V(n)_Q = f_3(Demodulated_Q((n + 1) * N_s/2)), n = 1, 3, 5, ..., N_c - 1$
9. $Demodulated\ symbols = f_4(Chip\ sequence)$.
10. $Decoded\ data = f_1^{-1}(Symbols)$
    f_3 is a function which translates positive values to 1 and negative values to 0. f_4 is a function that maps a 32-chip sequence to a sequence in the spreading

map with the minimum Hamming distance and translates the chip sequence to a symbol.

4.2 Simulation process of IEEE 802.15.4g-2012 MR-O-QPSK PHY

4.2.1 MR-O-QPSK (16,4)-DSSS

We run the simulation of IEEE 802.15.4g-2012 MR-O-QPSK (16,4)-DSSS with a 256-bit original packet by taking following steps:

1. First we apply the FEC to the packet with a 1/2 rate convolutional code with constraint length $k = 7$. As we have explained in 3.2.3.3, the convolutional codes are generated with the information bits in memory registers and the coming information bit. Every coming bit u_k will be coded into 2 bits: a_{k0} and a_{k1}. At the beginning information bits in all 6 memory registers are 0. The convolutional coding diagram is as follows:

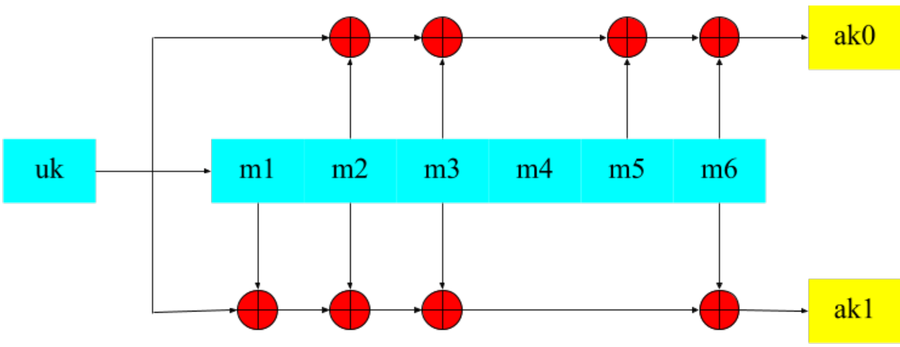

Figure 4.1: convolutional encoder

2. For every coming u_k:
   $a_{k0} = u_k \oplus m_2 \oplus m_3 \oplus m_5 \oplus m_6$.
   $a_{k1} = u_k \oplus m_1 \oplus m_2 \oplus m_3 \oplus m_6$.
   Then $m_n = m_{n-1}, n = 2, 3, 4, 5, 6; m_1 = u_k$.
3. Then the codes generated by convolutional encoder will be sent to the interleaver. Interleaving of PSDU code-bits is employed in MR-O-QPSK to break correlation of consecutive bits and improve the transmission robustness against burst errors. In MR-O-QPSK PSDU the interleaving degree λ is 7 while the interleaving depth is $N = 7 * 18 = 126$. The whole PSDU code-bits will be divided into $C = ceiling(N_b/N)$ blocks, where N_b is the number of the code-bits. The block with less than N bits will be zero-padded to N bits so each block contains N bits.
4. In each block the procedure shown in Figure 4.2 will be performed to interleave the code-bits. For instance, an indexed code-bits stream $1, 2, 3, 4, ..., 126$ will be interleaved into $1, 19, 37, 55, 73, 91, 109, 2, 20, ..., 126$ after procedure. So when a burst error occurs at $1, 19, 37$ their real consecutive symbols $2, 20, 38$ are not influenced and the original data can be recovered by FEC.

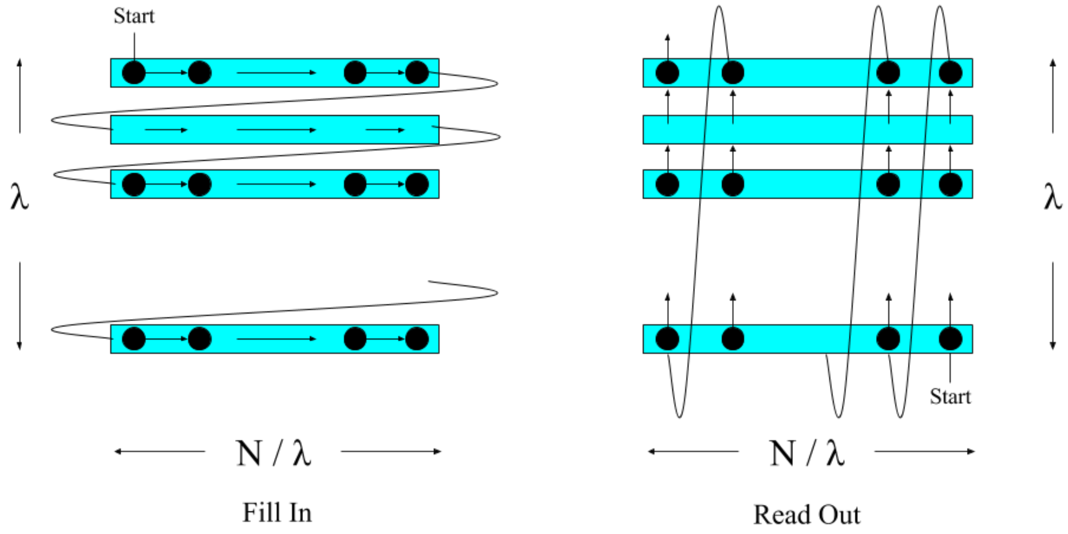

Figure 4.2: interleaver

5. $Chip\ sequences = f_5(Interleaved\ code\ bits)$
   Here f_5 is a function that converts every 4 bits to 16 chips according to the (16,4) spreading map.
6. The step 2 to step 8 as described in 4.1 will be taken.
7. $Demodulated\ code\ bits = f_6(Chip\ sequences)$ where f_6 is a function that maps a 16-chip sequence to a sequence in the spreading map with the minimum Hamming distance and translates the chip sequence to 4 code-bits.
8. $Deinterleaved\ code\ bits = deinterleaver(demodulated\ code\ bits)$. The deinterleaver performs the reverse function of the interleaver.
9. $Decodedpacketbits = Viterbi(Deinterleaved\ code\ bits)$. In the end we implement the Viterbi hard decoder to decode the convolutional codes and get the decoded packet data.

4.2.2 MR-O-QPSK (32,1)-DSSS

We run the simulation of IEEE 802.15.4g-2012 MR-O-QPSK (32,1)-DSSS with a 256-bit original packet by taking following steps:

1. The step 1 to step 5 as described in 4.2.1 will be taken.
2. Together with the (N,1)-DSSS, the The BDE is employed to correct the errors caused by the unpredicted inverse of the bit streams when data is transmitted through the communication channels in reality. The mechanism is to protect the information by reserving the information in the difference between two successive bits: $E_n = R_n \oplus E_{n-1}$ where R_n is the raw bit; E_n is the corresponding differentially encoded bit and E_{n-1} is the previously differentially encoded bit.
3. $Chip\ sequences = f_7(BDE\ code\ bits)$
   Here f_7 is a function that converts every single bit to 32 chips according to the (32,1) spreading map.
4. The step 2 to step 8 as described in 4.1 will be taken.

5. $Demodulated\ code\ bits = f_8(Chip\ sequences)$ where f_8 is a function that maps a 32-chip sequence to a sequence in the spreading map with the minimum Hamming distance and translates the chip sequence to 1 bit.
6. We can do the inverse function of the BDE to get the data before differential coding: $R_n = E_n \oplus E_{n-1}$.
7. The step 8 and step 9 as described in 4.2.1 will be taken.

4.3 Simulation results

The parameters of our simulations are shown in Figure 4.3.

	Packet size	Packets number	Passband frequency	Spreding map	Chip rate	Data rate
802.15.4-2011 O-QPSK	256 bits	500	2450 MHz	(32,4)	2000k chip/s	250 kb/s
802.15.4g-2012 MR-O-QPSK (16,4)-DSSS	256 bits	500	2450 MHz	(16,4)	2000k chip/s	250 kb/s
802.15.4g-2012 MR-O-QPSK (32,1)-DSSS	256 bits	500	2450 MHz	(32,1)	2000k chip/s	31.25 kb/s

Figure 4.3: Simulation parameters

For each PHY simulation we transmit 500 packets with different SNR values. A packet containing 256 bits is considered to be successfully received if all bits in it are correctly recovered. Depending on the successfully received packets ratio we can decide the range of the SNR values in our simulations, as shown in Figure 4.4.

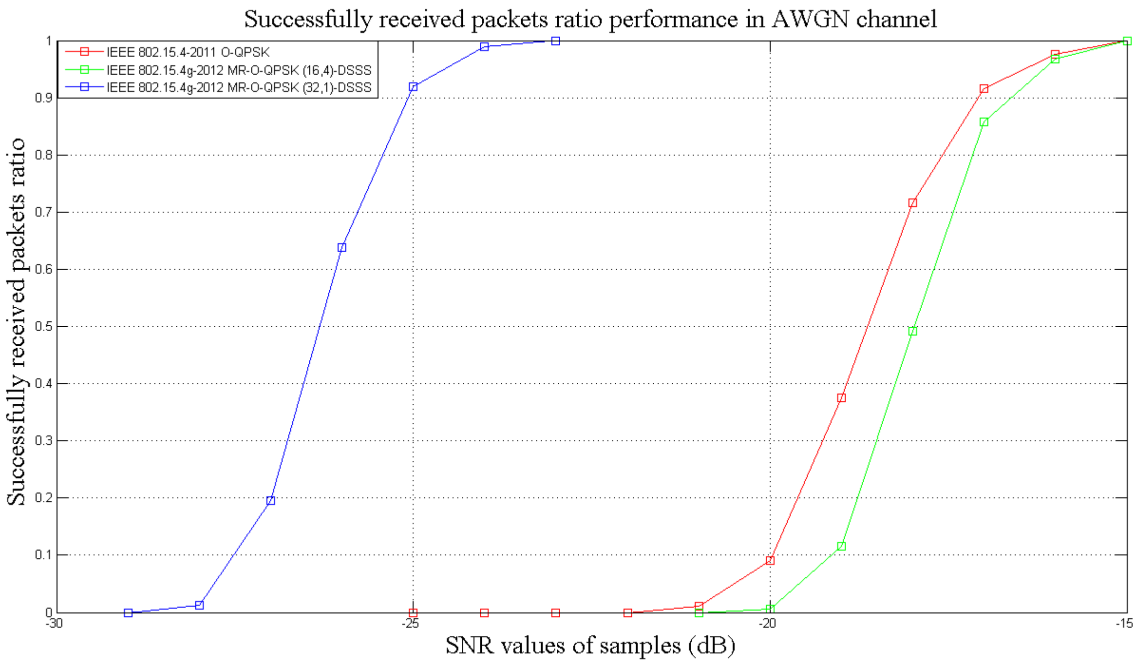

Figure 4.4: Successfully received packets ratio performance in AWGN channel

To analyze the Bit error rate (BER) performance together with the ratio of bit energy to noise power spectral density ($EbN0$) we introduce the following equations:

1. $E_c/N_0(dB) = 10log_{10}(0.5T_{Chip}/T_{Sample}) + SNR(dB)$
   where $T_{Chip}/T_{Sample} = Sample\ rate/Chip\ rate$.

2. $E_c/N_0(dB) = E_b/N_0(dB) + 10log_{10}(k)$
   where k is the number of information bits per chip.

According to the simulation results and the parameter shown in Figure 4.3 we can get the BER performance in AWGN channel, which is shown in Figure 4.5.

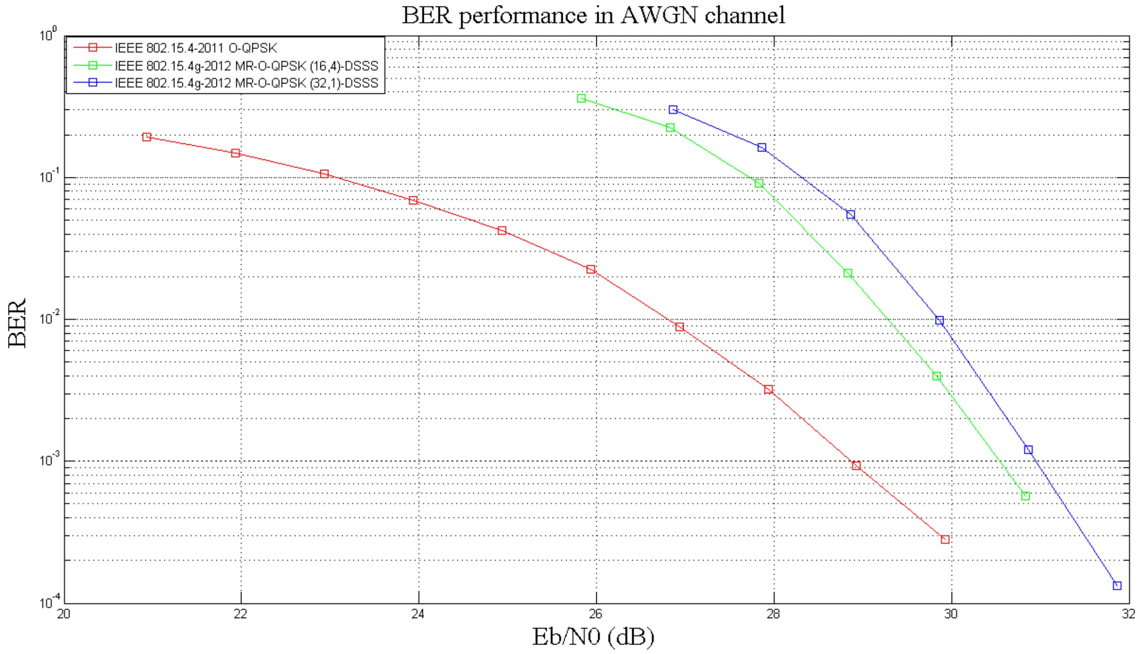

Figure 4.5: BER performance in AWGN channel

5

Improvement Proposals

5.1 Improvement proposal for IEEE 802.15.4-2011

According to the analysis and simulations of IEEE 802.15.4-2011, we have discussed a mechanism to improve the performance of the IEEE 802.15.4-2011 O-QPSK PHY in different application scenarios. We can introduce multiple spreading maps to IEEE 802.15.4-2011 O-QPSK PHY and a switching method to choose the optimal spreading map according to the specific application. This can be done by taking 4 steps:

1. A counter keeps working in the PAN coordinator to calculate the PER during a fixed interval.
2. If the PER is higher than the threshold, the PAN coordinator shall broadcast a notification packet (as shown in Figure 5.1) to inform all devices in the PAN to increase the complexity of the spreading map (from (16,4) to (32,4) for instance). If the PER is much lower than the threshold the sink shall broadcast a notification packet to inform all the devices in the PAN to decrease the complexity of the spreading map.
3. Re-do step 2 until a satisfying PER is achieved or there is no more (or less) complex spreading map. Keep this spreading map for a fixed period.
4. After the fixed period, re-do step 1, 2 and 3.

5.2 Improvement proposal for IEEE 802.15.4g-2012

As we discussed before, the most valuable point provided by the IEEE 802.15.4g-2012 is that multiple PHY modes can be managed to serve in one PAN and mode switch mechanism becomes possible in IEEE 802.15.4g-2012. So a dynamic mode switch mechanism can be added to IEEE 802.15.4g-2012 to improve the performance of the PAN in different application scenarios. Figure 5.2 shows the brief description of this mechanism.

This mechanism works as the following steps:

1. The PAN coordinator shall inform the neighboring devices that PHY test starts by send a special notification packet. All devices that receive the notification packet should switch the PHY to the specified one in the notification packet. Then the devices will send back a feedback packet, which is known by the coordinator. This step will be repeated for three times and in each turn one of the three PHYs will be tested.

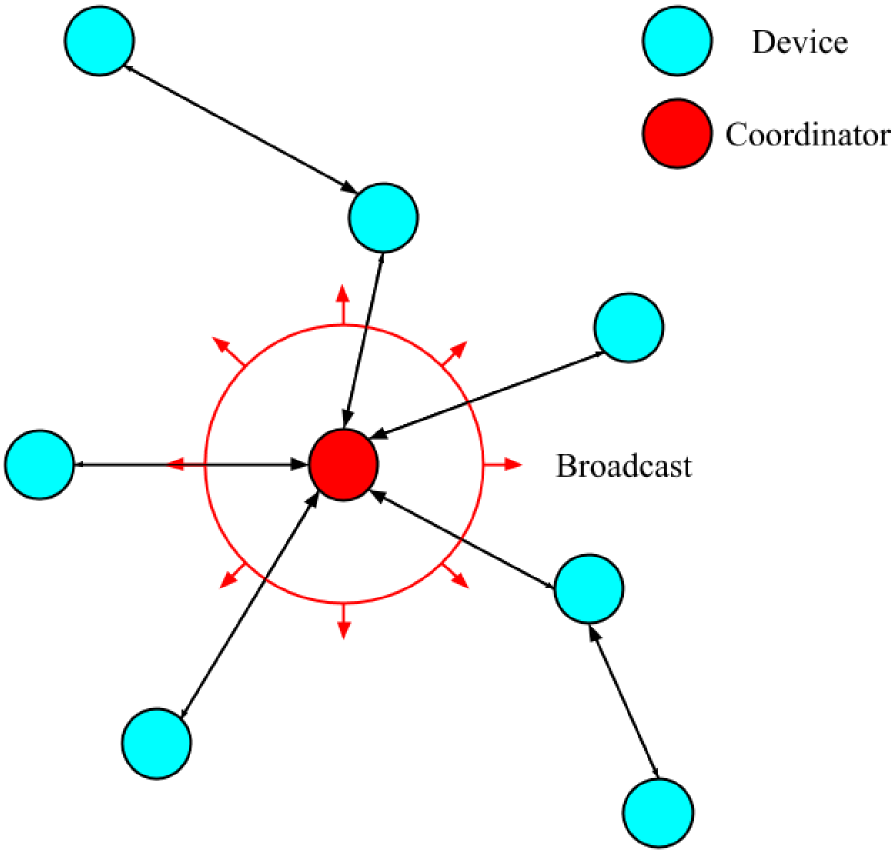

Figure 5.1: Spreading map switching mechanism

2. The coordinator determines the optimal PHY mode according to the PER performance of the feedback packets.
3. The coordinator shall broadcast a message to all devices in the PAN to switch the PHY mode to the optimal one.
4. When the PER becomes higher than a threshold (or after a fixed period), do step 1, 2 and 3 again.

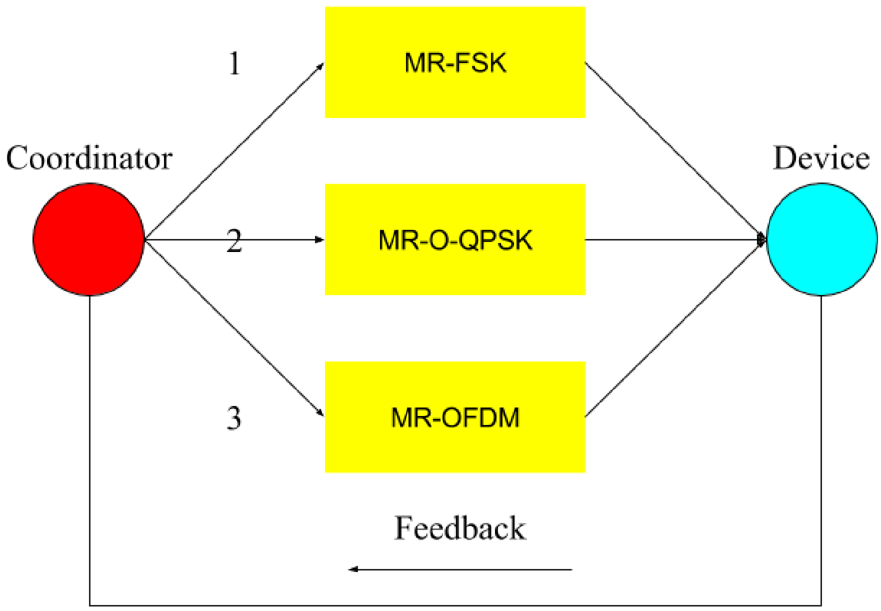

Figure 5.2: Dynamic mode switching mechanism

6
Conclusions

After analyzing IEEE 802.15.4-2011 and IEEE 802.15.4g-2012, we draw the conclusion that the most impressive difference between them is that three multi-rate and multi-regional SUN PHYs are supported in IEEE 802.15.4g-2012. SUNs are designed to enable multiple applications to operate in the same location and share the same frequency band. The MPM scheme is specified in IEEE 802.15.4g-2012 for SUNs to facilitate the inter-PHY coexistence. The enhanced beacon and information elements are introduced in MAC layer to support the MPM scheme.
From the Figure 4.4 and Figure 4.5 we can see that the IEEE 802.15.4-2011 O-QPSK performs better than the IEEE 802.15.4g-2012 MR-O-QPSK (16,4)-DSSS and (32,1)-DSSS measured with BER performance in AWGN channel. The interleaving and BDE are introduced to the IEEE 802.15.4g-2012 to improve transmission robustness against the burst errors and unpredicted inverse of the bit streams. In pure AWGN channels (like AWGN channels in our simulations) these functions contribute quite little to transmission robustness improvements, but decrease the information bits in chips because of zero-padding and differential coding. The FEC increases the transmission robustness while the increasing complexity of the spreading map (from (16,4) to (32,4)) results in similar or even better effect.
So we can draw the conclusion that in AWGN channel without burst errors or unpredicted inverse of the bit streams, IEEE 802.15.4-2011 O-QPSK performs better than IEEE 802.15.4g-2012 MR-O-QPSK when the data rate keeps the same. But under the circumstances where every turn of data transmissions takes considerable energy consumption or the channel condition is really poor, IEEE 802.15.4g-2012 MR-O-QPSK (32,1)-DSSS can be employed to ensure the probability of the successful transmission. In some emergency applications where the chances to send out information are very valuable (fire alert, for instance) the IEEE 802.15.4g-2012 MR-O-QPSK (32,1)-DSSS is more suitable than IEEE 802.15.4-2011 O-QPSK to prevent the transmission failure.
By analyzing the simulation results we propose a spreading map switching mechanism that may improve the performance of the IEEE 802.15.4-2011 O-QPSK PHY in different application scenarios. Multi-rate and multi-regional PHYs are supported in IEEE 802.15.4g-2012. We propose a dynamic mode switching mechanism to choose the optimal PHY mode in different application scenarios. For instance, the MR-O-QPSK can be switched to MR-OFDM when faced with a multi-path fading channel. MR-OFDM can be switched to MR-FSK to decrease the influence caused by Doppler effect when the device starts to move fast. This mechanism could make better use of the MR-PHYs in IEEE 802.15.4g-2012.

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