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Multi-band OFDM and *p*-Persistent CSMA/CD-based Indoor Power Line Communication (PLC) Systems

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Abstract

In this thesis, we propose a novel multi-band Orthogonal Frequency Division Multiplexing (OFDM) indoor power line communication (PLC) system. The physical layer of the proposed system consists of multi-band OFDM, convolutional encoding, Viterbi decoding, and interleaver. A *p*-persistent Carrier Sense Multiple Access/Collision Detect (CSMA/CD) is adopted as the MAC layer protocol. A PLC channel model proposed by OPERA (Open PLC European Research Alliance) is considered. Taking account of the characteristics of the power line noises, an efficient Noise Detection and Multi-band Switch Scheme (DNDMS) is applied to dynamically choose among multiple OFDM bands. A multiple-point sliding DFT (SDFT) is employed in DNDMS. System performance is evaluated by extensive simulations and the results show that the proposed system can reach a low Bit Error Rate (BER) and high system throughput.

Keywords— PLC, Multi-band OFDM, dynamic noise detection, CSMA/CD

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ACRONYM

PLC: Power Line Communication

WLAN: Wireless Local Area Network

CP：Cyclic Prefix

ISI：Inter-Symbol Interference

SNR：Signal Noise Ratio

BER：Bit Error Ratio

QPSK: Quadrature Phase Shift Keying

UWB：Ultra Wide-Band

FFT：Fast Fourier Transform

DFT：Discrete Fourier Transform

DSP: Digital Signal Processing

SDFT: Sliding Discrete Fourier Transform

IFFT：Inverse Fast Fourier Transform

IDFT: Inverse Discrete Fourier Transform

OFDM：Orthogonal Frequency Division Multiplexing

DSL：Digital Subscriber Line

CSMA/CD: Carrier Sense Multiple Access/ Collision Detect

MAC: Medium Access Control

SGC: Spectrum Gravity Center

DNDMS: Dynamic Noise Detection and Multi-band Switch

Chapter 1

INTRODUCTION

1.1 Topic Background

The essence of Internet access is to solve the delivery between the network service provider and the subscriber, known as "The Last Mile Problem" [1]. Only through such a link distance of less than one mile, can normal subscribers get access to the wide area network of telecommunication companies, and further to the Internet.

At present, the most popular access media are cable (such as Digital Subscriber Line (DSL) and optical cable) and radio (such as Wireless Local Area Network (WLAN)). For cable access, although its bandwidth is relatively broad (compared with wireless channel and dial-up connection), it is comparatively expensive in cost and a lack of Access Point (AP). AP is a device or interface that allows communication devices to connect to a network via certain media. The number of DSL and optical interfaces is limited in a house, which causes inconvenience for users, and extra extension cords boost the cost as well.

An alternative is wireless connectivity. Wireless access is ubiquitous, thus avoids the problem of limited AP. However, it is relatively unreliable, likely to influence other devices nearby, and has large attenuation as a function of distance. Is there any other technology that can be adopted to improve the current network services? In the past few years, a third medium for signal transmission other than Ethernet cable and wireless has been attracting more and more attentions. That is power line.

Power-line networking depends on electrical power lines to transmit data, and no extra lines or devices are needed. To get access to Internet, a user only needs to connect a Power Line Communication (PLC) modem to an electrical outlet. Power lines are distributed across urban area and countryside, in almost every room and every corner where people are living. Therefore, PLC boasts of an advantageous coverage compared with other means of network access. Furthermore, no more cable or wire needs to be installed, and residents will not have to destroy the household structure and decorations. A comparison of different access solutions are given in Table 1.1 [2].

Table 1.1 Comparison of different access solutions

Features	**ADSL**	**Cable**	**Wireless**	**PLC**
Plug and play	N	Y	N	Y
Enables home networking	N	N	Y	Y
Requires extra in-house installation	Y	Y	N	N
Requires upgrade of existing infrastructure	Y	Y	Y	N
Geographical coverage	Limited	Limited	Full	Full

1.2 The Development of PLC

The first PLC can be traced back to 1920's, when the first carrier frequency system began to work over high-tension lines for telemetry purposes around the year 1922 [3]. Before 1980's, power line was utilized only as a low-rate pulse control system for streetlights and meter reading [4]. During the 1990's and 2000's, the development of modulation techniques and integration circuits have enormously increased the transmission rate of PLC and expanded the bandwidth to 50 MHz [5]. Along with the telecommunication act of 1996 which relieved the regulation [6], the power department of America began to engage in communication services. High transmission rate has enabled it to be a competitive option in home networking in America.

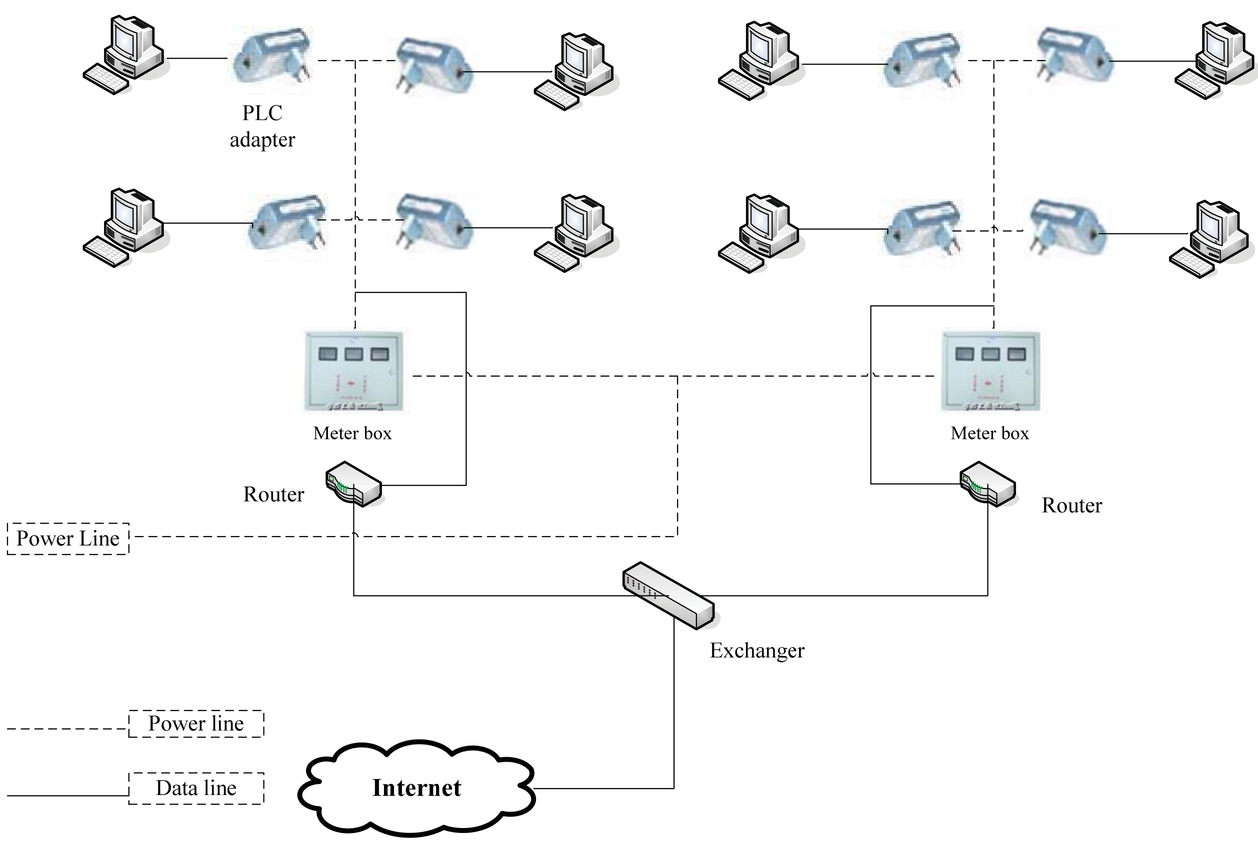

Fig. 1.1 An example of an in-house PLC network topology

1.3 The Status Quo of PLC Technologies in America

Currently, the PLC companies in America are focused on two major schemes of solutions to PLC: *In-premise Networking* and *Outdoor Accessing* [32]. In-premise networking is a low-voltage solution, which sets up a local area network through indoor power lines and electrical outlet within a single building. Outdoor accessing is a solution that includes medium-voltage and low-voltage. This method builds a backbone broadband network via medium-voltage line that connects substation and low-voltage transformer, and the low-voltage line below the transformer serves for data transmission and has access to a user's computer.

The In-premise networking scheme is represented by Intellon Inc., which developed a 14 Mbps chip for indoor low-voltage PLC networking in 2001 [33]. Based on that, the PLC alliance HOMEPLUG released HOMEPLUG 1.0 standard [7]. Dozens of PLC networking products have been put into American markets, and have set up a reliable platform for indoor working and entertainment.

The Outdoor Accessing scheme is represented by NS2, which is an emerging Research and Development corporation in Spain in the new century. This corporation has been devoted to the medium-voltage PLC market, and it conducted a series of experiments of broadband service, including high-speed Internet access, Voice over Internet Protocol (VoIP) telephone and electrical meter reading [32].

1.4 The Challenges and Motivations

However, since power line was not originally designed to transmit data, the channel environment is very severe. Frequent turning on/off of surrounding devices generates numerous noises of large amplitude; on the other hand, the time-variant characteristics and multiple branches give rise to multipath during transmission of high-frequency signals. Consequently several kinds of fading were brought in, including frequency selective fading and fading due to Intersymbol Interference (ISI) [8]. The existence of severe fading and noises combined has resulted in a high BER on the receiver end.

Many researches are focused on solving the aforementioned obstacles in high-speed PLC by advanced modulation and demodulation techniques, such as narrowband Frequency Shift Keying (FSK) [9] and Spread Spectrum (SS) [10]. FSK is known for its low transmission rate and inefficient resistance to noise in spite of the narrow band it occupies; SS have higher rate and noise resistance, however, it occupies broad bandwidth and has to have complicated equalization. Then OFDM (Orthogonal Frequency Division Multiplex) is proposed to address these problems [11]. OFDM techniques have offered great advantage in countering interference across signals, and are helpful for high-speed transmission in an environment of multipath and fading channels. When selective fading occurs due to multipath, only the subcarrier and the information it carries that falls within subsided frequency band will be affected, allowing the rest of subcarriers intact. Consequently, the general Bit Error Rate (BER) of system is greatly improved.

Extensive studies were dedicated to different layers for PLC system. In [12], the authors presented a Reed-Solomon coded OFDM system for PLC channel, which addressed a physical layer design. In [13], a PLC MAC protocol based on Korea standard (KS X 4600-1) was embodied, which was focused on MAC layer design. In [14], the authors provided a system design that combines physical and MAC layers. Research in this thesis is based on previous work. Furthermore, a more advanced multi-band OFDM (MOFDM) scheme is proposed, extending the conventional single-band OFDM to multi-band OFDM. Although multi-band OFDM approach is widely used as a leading method in the IEEE 802.15.3a standard for Ultra-Wide Band (UWB) communications [15], this thesis for the first time adopts and transplants this scheme to the field of PLC. We further propose a dynamic noise detection scheme to control the multi-band switch. Simulation results show that our proposed MOFDM can achieve better throughput for broadband signal transmission.

1.5 Organization of thesis

The rest of this thesis is organized as follows. In Chapter 2, the principle of OFDM and the CSMA/CD protocol as preliminary background knowledge is briefly introduced. In Chapter 3, a single-band OFDM PLC system is discussed. We introduce a proposed structure of multi-band OFDM PLC system and a dynamic noise detection scheme in Chapter 4. Chapter 5 presents the simulation results and shows the advantage of our proposed schemes over existing schemes. Finally, we conclude this research work and describe our future work in Chapter 6.

Chapter 2

PRELIMINARIES

2.1 Introduction

Normally, research on PLC systems are concentrated on two layers: Physical Layer and Medium Access Control Layer. In this research work, we adopt OFDM as the modulation/demodulation technique in the Physical Layer, and select CSMA/CD as our MAC layer protocol. To better understand the structure and benefit of our proposed system, we firstly go over some preliminary knowledge before introducing our proposed PLC system.

2.2 OFDM Techniques

In Chapter 1 we have talked about the FSK and SS techniques and their limitations. Actually as early as 1960's, OFDM was put forward in pursuit of solving this problem [34]. However, no great importance was attached to this technique due to technical obstacles in that period. At this period, OFDM was mainly used for military applications, such as in KINEPLEX [35], ANDEFT [36], KATHRYN [37]. Along with the development of Digital Signal Processing (DSP) and microelectronic technologies, large-scale utilization of OFDM has been made possible.

OFDM is a multi-carrier transmission technology. It utilizes N subcarriers to divide the whole channel into N subchannels and a high-speed serial data stream is transformed into multiple low-speed data streams in parallel [16], as is shown in Fig. 2.1. Consequently, this multi-channel transmission elongates the duration period of the signal to be transmitted, thus alleviates the ISI caused by multipath propagation. When the total number of subchannels is sufficient, every subchannel can be considered as a one without ISI, thus the receiver end can enable a non-ISI transmission without complicated equalization techniques. In addition, OFDM provides strong resistance against frequency-selective fading. Each subchannel can choose different modulation methods in response to channel characteristics, which maximizes the influence of the channels that have low Signal to Noise Ratio (SNR) to other channels [24]. The system performance in transmission is then ensured.

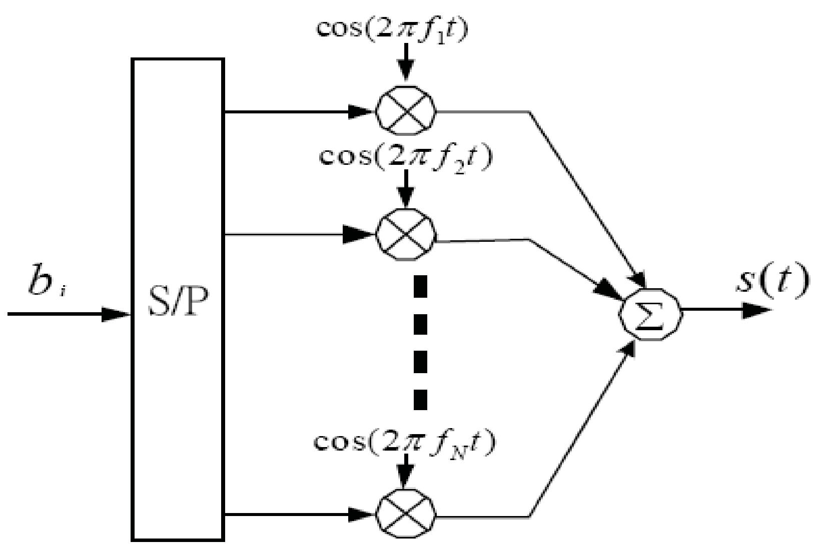

Fig. 2.1 The structure of OFDM modulator

In OFDM modulation, the interval between two adjacent subcarrier waves is required to meet the orthogonality, namely, the product of two subcarrier waves is zero during a symbol period. Normally, we set the interval to be equal to the reciprocal of one symbol period, as is shown in Fig. 2.2. We can find that the peak of each subcarrier wave is located at the zero point of other subcarrier waves, thus the othogonality is satisfied.

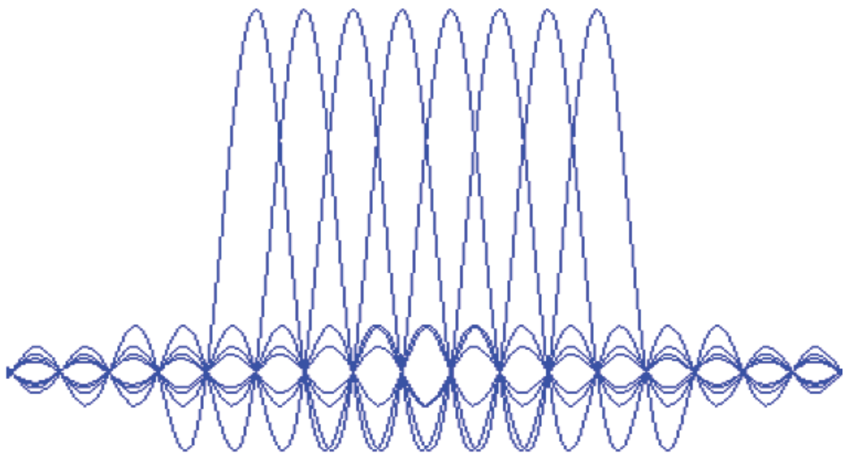

Fig. 2.2 The othogonality of sub-carrier waves

The implementation of Frequency Division Multiplex (FDM) is not completed by segregating the transmission band with filters; instead, engineers cope with this process via Discrete Fourier Transform (DFT) of the baseband signals. In an OFDM system, the frequency spectrums of each subcarrier are orthogonal. As a result, the signals on each subcarrier can be recovered without any distortion.

The disadvantages of OFDM include:

1. Sensitive to frequency offset and phase noise. Orthogonality is the yardstick by which an OFDM system differentiates each subchannel. Frequency offset and phase noise will deteriorate the orthogonality, and an 1% offset will reduce the SNR by 30dB [17].
2. High Peak to Average Power Ratio (PAPR) leads to a low efficiency of Radio Frequency (RF) Amplifier [18]. Since an OFDM signal is a sum of multiple modulated signals from subcarriers, it may produce a high peak power. Take an OFDM system of N subchannels as an example, when all N subchannels with the same phase are summed up, the PAPR will reach N. High PAPR will demand strict requirement of RF amplifier, and will lower its efficiency.

2.3 Introduction of CSMA/CD

To solve the interconnection issue between networks of different structures, the International Standardization Organization (ISO) established the Open System Interconnection Reference Model (OSI/RM). This model consists of seven layers of network protocols: Physical Layer, Data Link Layer, Network Layer, Transport Layer, Session Layer ,Presentation Layer and Application Layer [19].

The second layer of OSI model is Data Link, which is composed of two sublayers: Logical Link Control (LLC) at the upper part and Media Access Control (MAC) at the lower part. MAC layer is mainly responsible for controlling the physical medium that connects Physical Layer. Our system deals with PLC, therefore, the physical medium is power line.

The major function of MAC protocols is to relay data between Physical Layer and LLC sublayer. Before it picks data from Physical Layer, the MAC sublayer firstly checks the existence of signals sent from different stations across the same channel. If no collision occurs during the transmission, the MAC sublayer forwards the signals up to the LLC sublayer.

MAC protocols are widely used in both wired LAN and Wireless LAN (WLAN). PLC network belongs to wired LAN，which adopts IEEE 802.3 MAC layer protocol with CSMA/CD as the access control scheme.

In a PLC network, all of the nodes share the same channel. Consequently, the MAC layer needs a protocol that can handle the delivery service among multiple nodes in an orderly and effective fashion. Hereby we consider CSMA/CD.

CSMA/CD is a contention-based MAC protocol, which was developed from the ALOHA protocol proposed by University of Hawaii in the 1970's [19]. CSMA/CD outperforms ALOHA in the utilization of channel. Unlike ALOHA, CSMA/CD keeps sensing each of the nodes, and once a collision is detected, the current packets being sent are terminated immediately. Since packets usually takes a long time to be totally transmitted, this termination will save a large amount of time and thus increase the throughput of the system.

The process of CSMA/CD consists of four steps [19]:

a. Channel Sensing

If an arriving packet is ready to be transmitted, the terminal firstly senses if the medium is busy, namely, if any packet is being transmitted. If the medium is busy, the terminal keeps sensing until the medium becomes idle. If the medium is idle, we go to Step b.

b. Transmission

The terminal transmits all available packets immediately. As soon as the transmission sets out, we go to Step c.

c. Collision Detection

When a node is transmitting a packet, the node will send notification signals to all other nodes. During the process of receiving a packet, if any such notification signal arrives, the node will detect the collision and then terminate the transmission immediately. After that, we go to Step d.

d. Retransmission

The node whose packet is terminated will wait a random number of time and will attempt to transmit a new incoming packet. The procedure will go all the way back to Step a.

2.4 Summary

In this chapter, the mechanisms for the core techniques in this research work: OFDM modulation/demodulation and CSMA/CD protocol were briefly introduced. The advantages of

OFDM and CSMA/CD in physical layer and MAC layer respectively can give an edge in constructing the overall PLC networking system.

In next chapter, we will go further to present a PLC system design that adopts OFDM as the physical layer modulation scheme.

Chapter 3

PREVIOUS WORK

3.1 Introduction

Since our system structure is based on [14], which proposed an single-band OFDM system design for PLC network, we will focus on the authors' work in this chapter. Understanding the single-band OFDM scheme will help grasp the novelty and benefits brought by our proposed schemes.

3.2 Previous work on OFDM system

3.2.1 General review of studies on PLC system

We have briefly introduced some studies dedicated to different layers for PLC system in Chapter 2. These studies can be categorized into three classes: physical layer designs, PLC channel modeling, and MAC layer protocols. Next, we will have an overview of the current research of each of the classes.

(a) Studies focused on physical layer design

Studies focused on physical layer design normally discuss one or more modules in the transmitter and receiver of a PLC system. Hot research topics during the past few years are mainly in coding/decoding method, such as in [28], the authors apply a Low Density Parity Check (LDPC) code in the PLC system. In [12], the authors presented a Reed-Solomon coded OFDM system for PLC channel. Simulation results show in these works show that these two coding method do not win an edge in the environment of an SNR under 30dB, so convolutional coding might as well be selected in the system.

(b) Studies focused on PLC channel modeling

In [26], the authors put forward a PLC model for indoor environment and outdoor environment respectively. In their model, the emission of radiations via the electric power line and interference from surrounding devices connected to the network are examined.

In [27], the authors use Numerical Electromagnetic Code to predict signals radiation for near field and far field. Interference to high antenna gain, low noise floor, and HF ground side are also analyzed.

In [5], a theoretical postulation of PLC channel model is proposed. This official document is approved by Open PLC European Research Alliance (OPERA), which provides mathematical models to measure the attenuation of signal transmission according to different environment of indoor and outdoor locations. Furthermore, channel noises are precisely analyzed and modeled considering the unique characteristics of their own.

(c) Studies focused on MAC layer protocols

Most of the current approaches for MAC in PLC networks deal with centralized methods of data access. In [13], a PLC MAC protocol based on Korea standard (KS X 4600-1) was embodied, which was focused on MAC layer design. In [29], a distributed approach is employed for carrier allocation where the system chooses a carrier from all available carriers by carrier sensing, improving the system performance. In this thesis, a *p*-persistent CSMA/CD is utilized in an attempt to reach higher throughput.

3.2.2 A single-band OFDM scheme

The physical layer structure of single-band OFDM scheme is depicted in Fig. 3.1 which is proposed in [14].

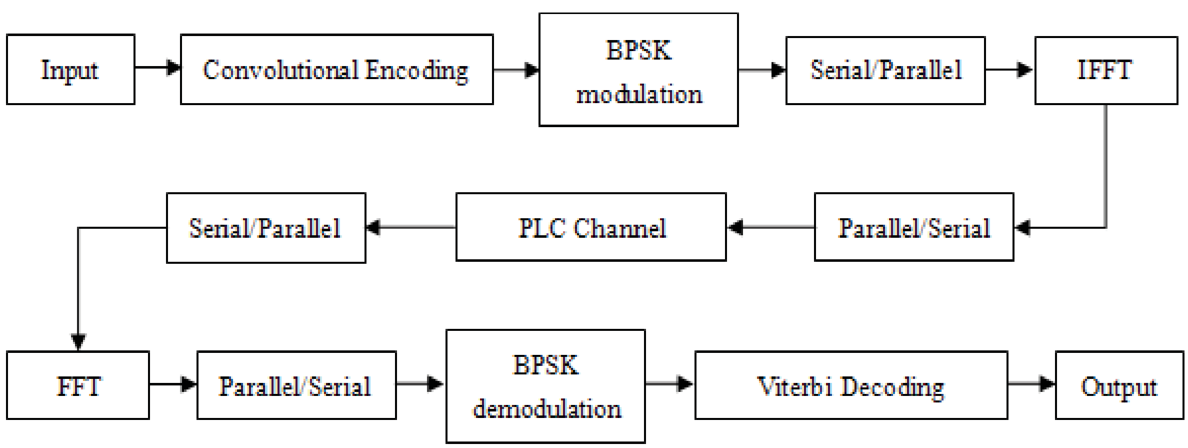

Fig. 3.1 Physical layer structure of single-band OFDM scheme

Transmitter Side:

Input signals go through the convolutional encoder and BPSK (Binary Phase Shift Keying) modulation successively. After they pass through the S/P converter, the encoded serial signals are converted to parallel signals. After IFFT (Inverse Fast Fourier Transform), the parallel signals are converted back to serial signals, and are then propagated over the PLC channel.

Receiver Side:

The procedure for this part is basically an reverse process to the transmitting end. Propagated signals from PLC channel are fed into S/P converter. Signals are then passed through FFT, and are converted back to serial signals. Finally, signals are demodulated and decoded for output. It adopts Viterbi decoding technique due to its efficiency in an environment of burst error.

Since this system transmits one OFDM symbol at one time, which means that the PLC channel is completely occupied for a single signal transmission, we call this system “single-band OFDM system” to differentiate with our proposed system in next chapter.

3.3 Limitations of single-band OFDM system

As we discussed in Chapter 2, the channel environment is very severe with multiple types of noises and fadings (we will elaborate on them in next chapter). Furthermore, the impact of noise and fading is various for different frequency spectrum in the frequency domain.

In the simulation of the p-persistent single-band OFDM PLC network, although the noise characteristics of PLC channel are implemented, however, the single-band scheme refrains the system from taking care of the characteristic of certain ranges of the total bandwidth. Different frequency band are influenced at different time due to the existence of burst noise, so it requires a scheme to divide the total bandwidth into multiple smaller subbands. In view of this, we hereby propose a multi-band OFDM PLC network to meet this requirement.

3.4 Summary

In this chapter, an OFDM-based PLC system was presented. This system applies a single-band OFDM mechanism, which is limited in the full utilization of channel bandwidth and does not fully consider the characteristics of the PLC channel. Consequently, a multi-band OFDM system is proposed in the next chapter.

Chapter 4

PROPOSED SYSTEM AND SCHEMES

4.1 Introduction

Most of the current researches on OFDM systems, including the system we introduced previous chapter, consider only a single-band OFDM system. The major novelty of in this thesis is to apply a multi-band OFDM system. Unlike single-band OFDM, which transmits only one OFDM symbol with the whole spectrum band; in the proposed scheme, two or more OFDM symbols can be transmitted with each occupying *1/n* of the same bandwidth. Here *n* is the number of sub-bands in a multi-band OFDM system.

4.2 Physical Layer Design

4.2.1 System Structure

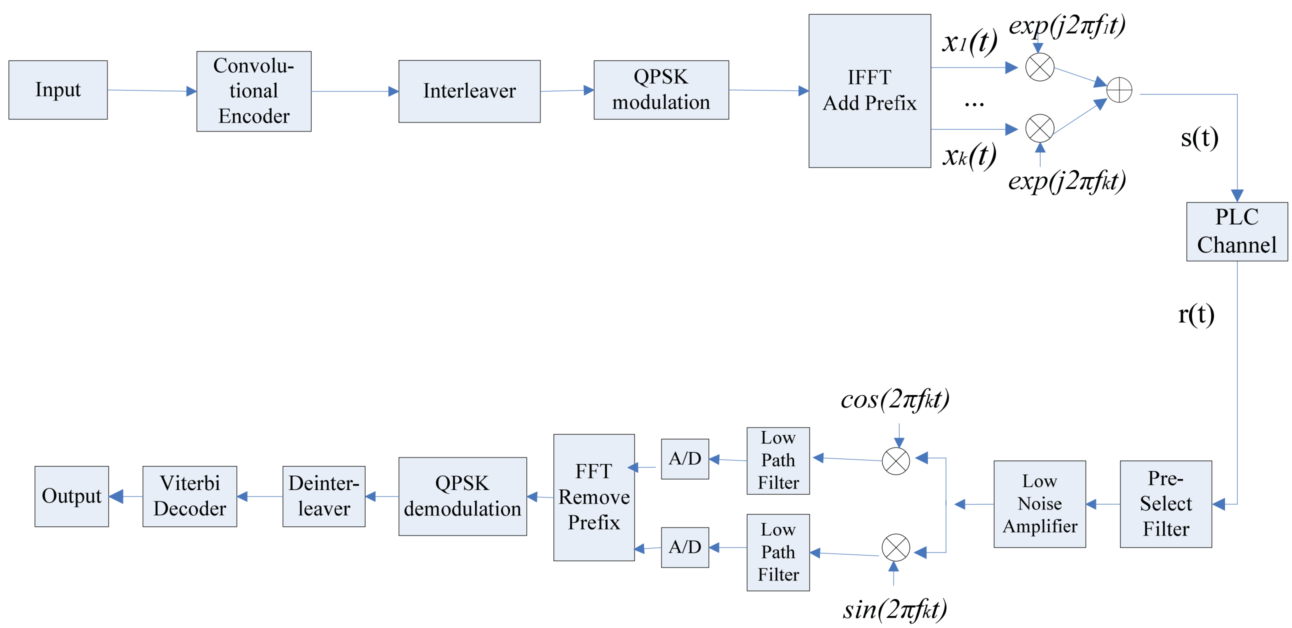

Fig. 4.1 Structure of physical layer

Fig. 4.1 depicts the structure at the physical layer. Here, the incoming data bit stream is first encoded with the convolutional code. Next, the bit stream is interleaved, and then modulated with QPSK. Finally, the data bit stream is OFDM-modulated with IFFT. The modulated signals are then up-converted to a specific sub-band by multiplying it with $exp(j2\pi f_k t)$, as in the following equation:

$$s(t) = \sum_{k=1}^{n} \mathrm{Re}\{(x_k(t) - kT_{SYM})\exp(j2\pi f_k t)\} \tag{4.1}$$

where k is the kth sub-band, $x_k(t)$ is the modulated OFDM signal for the kth sub-band, T_{SYM} is the OFDM Symbol duration, and f_k stands for the center frequency of the kth sub-band. f_k is chosen by our proposed dynamic noise detection scheme according to channel noise model in [6]. We will elaborate on this scheme in later. The sum of n sub-band signals is finally transmitted as the RF signal $s(t)$ into PLC channel.

At the receiving side, the received RF signal is first passed through a bandpass filter to segregate the specific band. Then, it is down-converted to baseband and demodulated with QPSK and FFT. Finally, the received signal is deinterleaved and decoded with Viterbi decoding technique.

The main difference between our proposal and conventional physical structure, as in [8], is that the former fully take into account the characteristic of PLC channel environment of noise and fading, which the latter is not capable of.

4.2.2 Encoding Technique

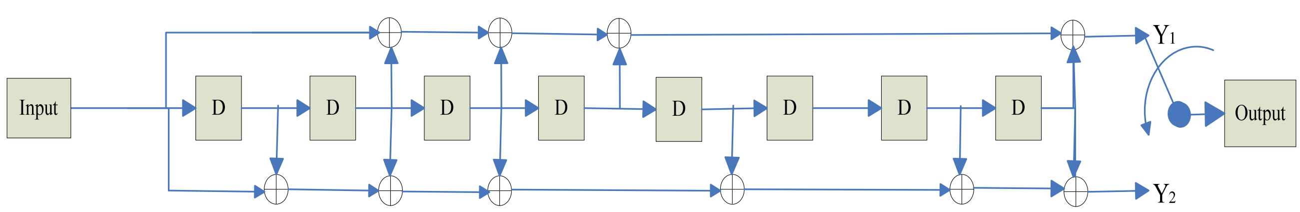

Fig. 4.2 Convolutional encoder

The structure of convolutional encoder is shown in Fig. 4.2. The code rate is *1/2*, for every bit of input, the coder generates totally *2* bits of data, namely, Y_1 and Y_2. The convolutional encoder is composed of eight shift registers. Each register can store one bit that has previously arrived and shift this bit to next register when a new bit arrives. Y_1 and Y_2 are the exclusive OR of the input bit and bits stored in certain registers.

In our design, the generator polynomials in octal numbers are $[561]_8$ for output Y_1 and $[753]_8$ for output Y_2. Eight bits are attached to the end of input data, so that all the registers can be reset to zero after encoding.

4.2.3 Decoding Techniques

We adopt Viterbi Decoder as the decoding technique. The essence of Viterbi decoding is to compare received signal sequence with all possible transmitting signal sequence, and select the sequence that has the minimum Hamming distance as the transmitting sequence [20][25].

In our simulation, we use two modules to implement the decoding:

(1) Generation of Trellis diagram

This module analyzes the regularity of Trellis diagram. For an eight-register decoder, there are 256 probable states all together. If the input bit is decided to be 0, then the next state will be located from 128 to 255; If the If the input bit is decided to be 1, then the next state will be located from 0 to 127. If the current state $i<128$, then the previous state is $2i$ or $2i+1$, and the input bit is estimated to be 1; If the current state $i>=128$, then the previous state is $2i-256$ or $2i-255$, and the input bit is estimated to be 0. Therefore, a 256-state Trellis diagram can be rapidly generated.

(2) Path search

An array is applied to record the distance between previous optimum state and the current state. After finding the shortest path, the input bit can be inferred from the change of each state. According to the Trellis diagram, if the current state i is bigger than the next state j, the input bit is 1, else the input bit is 0.

There are two types of decision: hard-decision and soft-decision [19]. Soft-decision decodes the analogue signals right after the demodulation, while hard-decision quantifies the signal to single bit. Our simulation assumes an ideal soft-decision decoding, in which the signals received from PLC channel are sent directly to decoder without quantification.

4.3 Channel Model and Noise

The prerequisite of exploring the performance of PLC system is to understand the characteristics of PLC channel, including the impedance, attenuation, noise and so on, then establish the coding and modulation scheme accordingly to achieve the best transmission. The initial and major function of powerline is transmitting electrical power instead of transmitting data signals; therefore, the channel characteristics are not ideal for data transmission. In addition, various loads on the low-voltage grid give rise to the time-variant fading and noise, which poses a difficult problem for channel modeling [22]. In the following part, we will elaborate on a feasible PLC channel that we adopt in our systems.

4.3.1. Channel Transfer Function

The theoretical channel model is based on a document approved by OPERA [5]. We adopt an indoor multi-path channel modeled by the following transfer function

$$H(f)=\sum_{i=1}^{n} g_i e^{-(a_0+a_1 f^k)d_i - j2\pi f\frac{d_i}{v_p}}, \tag{4.2}$$

where f is channel frequency, n is the number of paths, g_i is the weight of the ith path, a_0 and a_1 are the attenuation parameters, k is the attenuation factor, d_i is the length of the ith path, and v_p is the propagation speed.

4.3.2 Channel Noise Modeling

Interference in a power line network can be caused by a number of factors, such as lightning, compensation capacitors, and auroral discharge, etc. Since these noises are filtered by low-voltage transformers, the main interference source consists in home electrical appliances. Different appliances produce a variety of noises when they are working and being turned on/off.

In this thesis, we follow the five different types of noise which additively and independently overlay each other in [6][23]. The noises are colored background noise, narrow band noise, periodic impulsive noise, aperiodic impulsive noise, and burst noise.

(1) Colored Background Noise

This kind of noise is generated by motors in home appliances, such as washing machine and vacuum cleaner. The characteristic of this noise is the expansive span across the frequency spectrums and low power spectrum density. Normally this noise is considered as a White Gaussian Noise.

We model the colored background noise with the following equation:

$$S(f) = S(\infty) + \left[S(0) - S(\infty)\right]e^{-f/f_0}, \qquad (4.3)$$

where $S(f)$ is power density for frequency f, $S(\infty)$ = -136 dB (V^2/Hz), $S(0)$ = -38 dB (V^2/Hz) and f_0 = 0.7 MHz. In our simulation, we generate the noise by filtering a white Gaussian noise process.

(2) Narrow Band Noise

This kind of noise is generated when medium and short wave radio is being coupled to PLC channel. The amplitude of narrow band noise can be larger than that of OFDM signals.

Narrow band noise is the summation of several sinusoidal waves：

$$n_{narrow}(t) = \sum_{i}^{4} A_i(t)\sin(2\pi f_i t + \varphi_i), \qquad (4.4)$$

where $A_i(t)$ is the amplitude of the ith sinusoidal wave; f_i is the carrier frequency; φ_i is the phase, which is a evenly distributed random number in the range of [0, 2π].

We use the following parameters:

$$A_1 = -112 \text{ dB}, \quad f_1 = 4 \text{ MHz}$$

$$A_2 = -113 \text{ dB}, \quad f_2 = 6 \text{ MHz}$$

$$A_3 = -110 \text{ dB}, \quad f_3 = 10 \text{ MHz}$$

$$A_4 = -105 \text{ dB}, \quad f_4 = 12 \text{ MHz}$$

(3) Periodic Impulsive Noise

Periodic impulsive noise includes net-synchronous periodic impulsive noise and net-asynchronous periodic impulsive noise. The latter is generated by switching power supplies, whose spectrum is composed of discrete spectral lines. Since the duration time and amplitude of net-asynchronous periodic impulsive noise are both relatively small compared with other noises, it is normally ignored in noise modeling. In our simulations, we override the noise with colored background noise.

Net-synchronous periodic impulsive noise is generated by Silicon Controlled Rectifier (SCR), which are currently widely used in dimmable light, electrical fan, and copying machine. SCR devices produce two impulse voltage of large amplitude per power frequency period, and have been playing an important role in home and office.

(4) Burst Noise

Burst impulses are generated by turning on/off operations of different devices. Each impulse can affect a broad range of bandwidth, and the power spectral density can be 50 dB higher than background noise. Burst noise occurs randomly, sometimes a group of impulses occurs successively, which imposes a severe influence to the PLC channel.

The burst noise can be represented by a two-level description. In the macro level view, the noises in PLC channel are composed of a bunch of burst groups throughout the time axis. In the micro level view, each burst group can be further decomposed into numerous impulses, as show in Fig. 4.3.

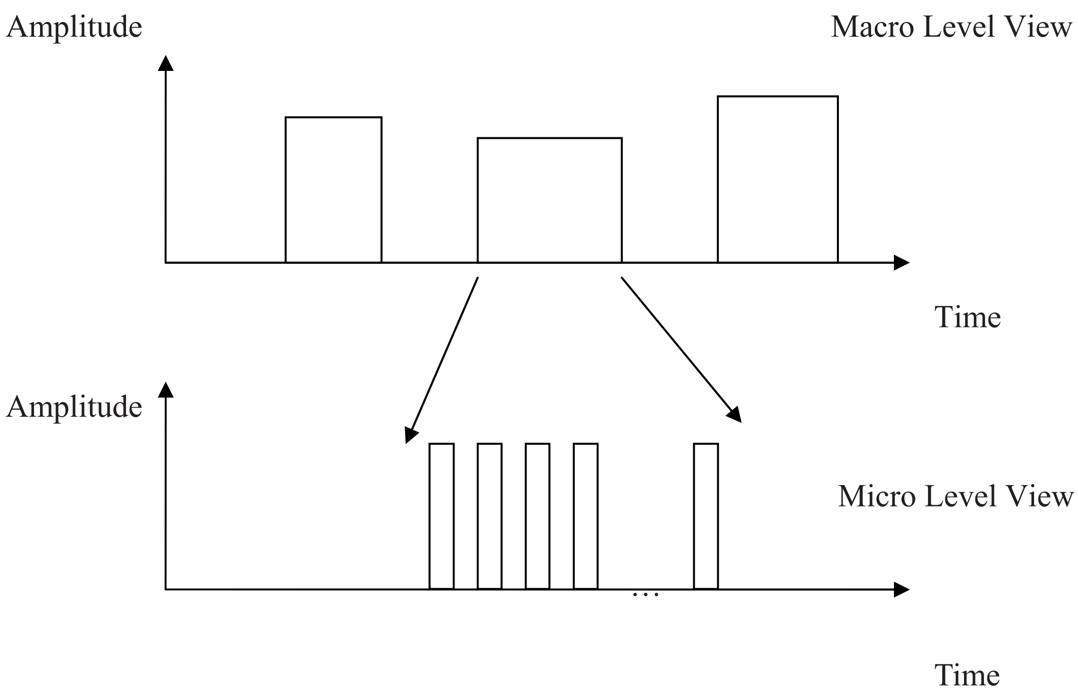

Fig 4.3 Two-level view of burst noise

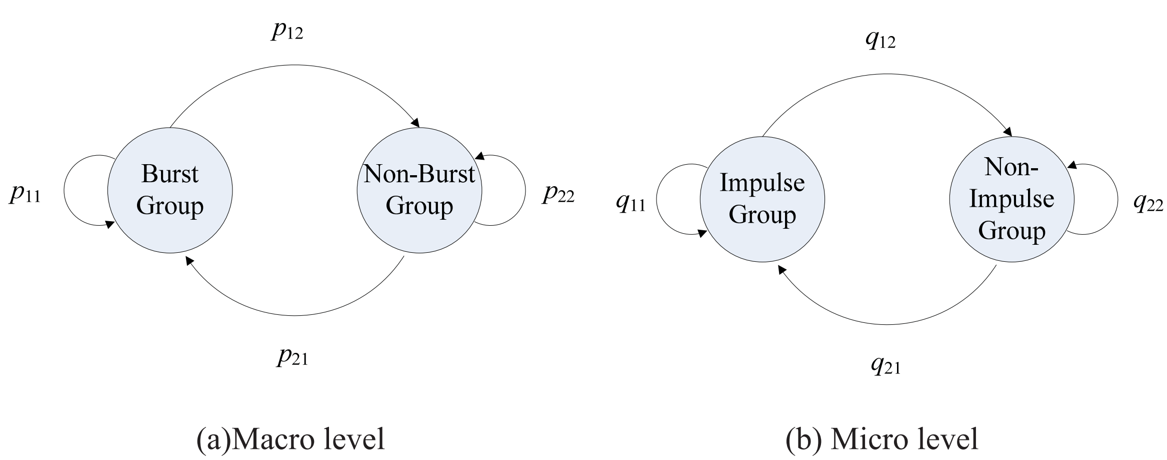

Fig. 4.4 The state transition diagram for burst noise

The duration of each burst group is determined by a Markov chain. A Markov chain consists of a number of states, among which the next state depends only on the current state and has nothing to do with previous states. In our model, the state denotes either burst group or non-burst group in the macro level, and either burst impulse or non-burst impulse in the micro level. In Fig. 4.4, p_{ij} indicates the transition probability from state i to state j. Two states exist in our modeling: burst and non-burst. In the marco level view, state i may switch to the other state j with a transition probability of p_{ij} or stay at the same state with a transition probability of p_{ii}. The case of micro level view is similar to that of macro level. The parameters of transitional probabilities are listed in the following Table 4.1(a) and Table 4.1(b).

Table 4.1(a) Transition Probabilities for Macro Level

Transition Probabilities p_{ij}	j = 1	j = 2
i = 1	0.999	0.001
i = 2	0.8	0.2

Table 4.1(b) Transition Probabilities for Micro Level

Transition Probabilities q_{ij}	j = 1	j = 2
i = 1	0.9571	0.0429
i = 2	0.9	0.1

4.4 DNDMS Scheme

The modeling of each noise is based on our previous work. Among all five noises, the power spectrum of burst noise is significantly larger, usually 50 dB higher than the background noise, thus it has the most prominent influence on the PLC channel and plays a major role in the generation of bit errors. However, the interference of burst noise could be countered by a dynamic noise detection and multi-band switch (DNDMS) scheme proposed in this thesis as follows.

DNDMS scheme is proposed by considering the frequency domain characteristics of burst noise. The arriving time of each group of burst error is determined by transition probabilities in a two-level Markov chain in [6]. We analyze the spectrum of incoming signals in the PLC channel in the frequency domain. It is easy to observe the distribution of each frequency component for two cases: spectrum with burst error and without burst error. For the former case (Fig. 4.5), the power is centralized in the lower frequency part, while for the latter case (Fig. 4.6), it is scattered all over the band.

The dynamic noise detection is implemented by monitoring the frequency spectrum of PLC channel in real time. The distribution of frequency component can be obtained by measuring the Spectrum Gravity Center (SGC) of all frequency components with the following equation:

$$\mathrm{SGC} = \frac{1}{f_{\max}} \frac{\sum A_i f_i}{\sum A_i}, \tag{4.4}$$

where, A_i denotes the amplitude of the ith frequency component, f_i is the correspondent frequency, and f_{max} is the frequency of the maximum amplitude all over the band. The sum is for the whole bandwidth. If *SGC* is close to 1, it indicates that the frequency components are centralized around the f_{max}, which is the case when burst noise arrives (Fig. 4.7). To enable the real-time communication of detection signals, an extra control channel is set up to transfer the monitor signal of burst noise. At the moment when *SGC* turns to 1, that is when a group of burst noise arrives, the transmitter receives a switch signal from the control channel. After that it immediately switches to a higher band. Since the higher frequency components are less influenced by burst noise, thus this method would lead to a lower bit error rate of at the receiver end.

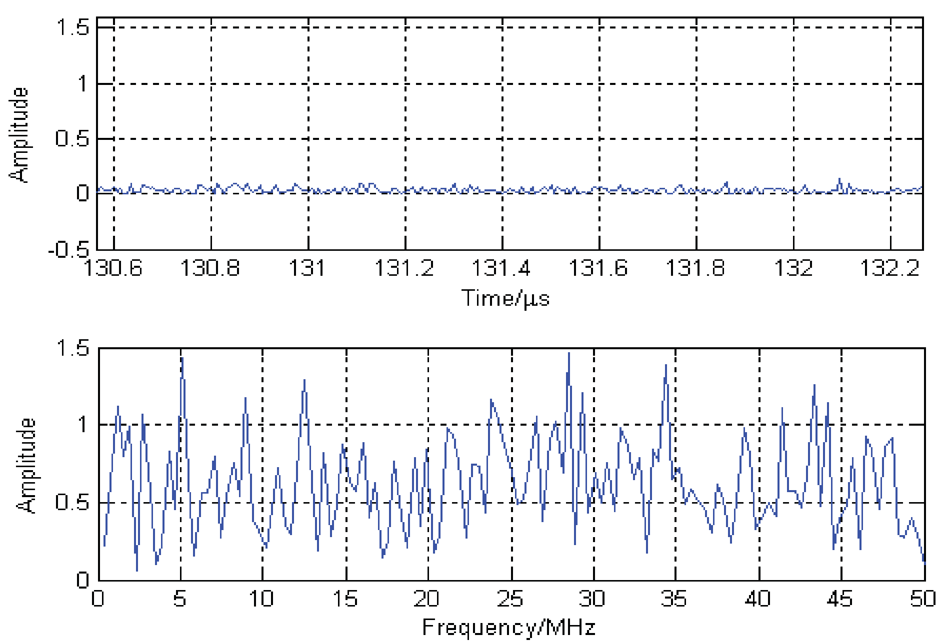

Fig. 4.5 Spectrum without burst noise

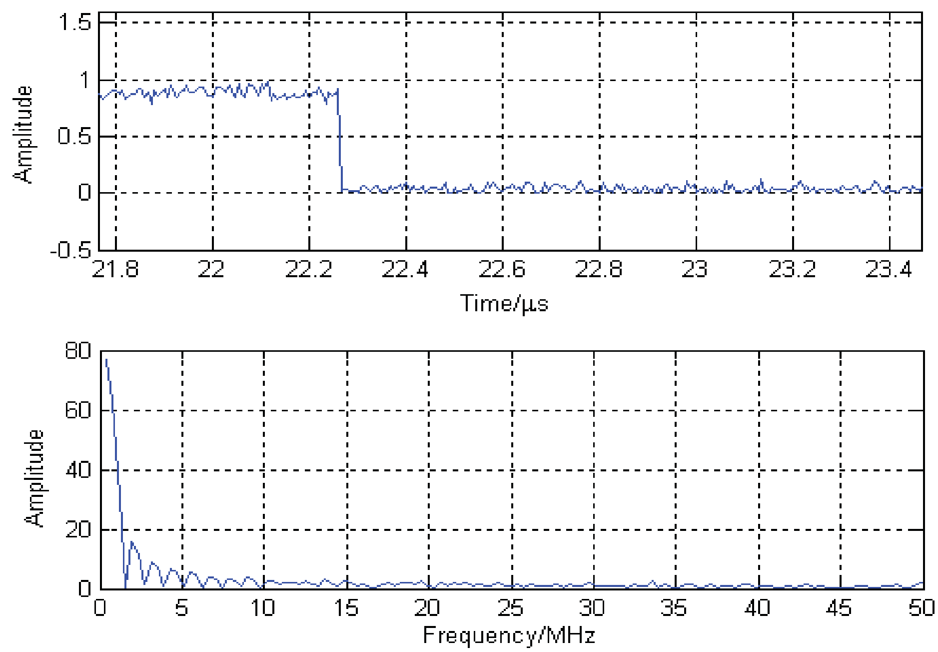

Fig. 4.6 Spectrum with burst noise

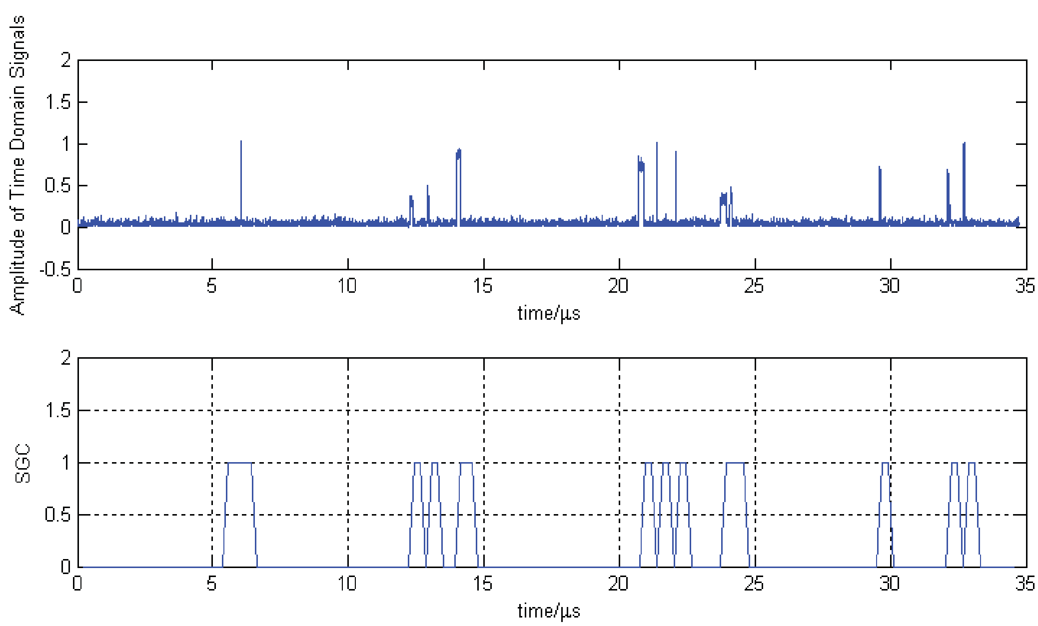

Fig. 4.7 Dynamic detection with SGC

4.5 Sliding DFT Algorithm

The DNDMS Scheme requires a high-speed calculation of spectrum in the frequency domain. Traditionally, we may adopt FFT to deal with this process. However, take into account the implementation of the DNDMS Scheme, we may find that as the sliding window moves with a step size of merely a small portion of the total window size. This indicates that the Digital Signal Process Module in the system once again deals with data that have been processed during previous sliding windows. The efficiency is then affected to some extent.

The sliding DFT (SDFT) is a high-performance algorithm, which requires simple computation of the last sliding window of input samples to derive updated output DFT continuously in a real-time oriented system without repetition of DFT, thus outperforming FFT [21].

The Sliding DFT is calculated by the following equation.

$$X_{i+1}(k) = [X_i(k) + x(n+N) - x(n)]e^{j2\pi k/N} \tag{4.5}$$

Evidently, N-point DFT for the current moment is attained by iterating the N-point DFT at previous moment. A sequence $X_i(k)$ can be attained (k=0,1,…,N-1) by doing the DFT of a time-domain sequence $x(n), x(n+1), \ldots, x(n+N-1)$. As the sliding window moves by one point, the new DFT $X_{i+1}(k)$ can be calculated by adding the previous DFT $X_i(k)$ by the lately arrived point $x(n+N-1)$ and subtracting the earliest point x(n). Therefore, SDFT requires only one complex multiply and two complex add. The computational complexity is $O(N^2)$ for DFT, $O(N\log_2 N)$ for FFT, and O(N) for SDFT [21].

For multi-sample SDFT, in which the sliding window slides p points each time, the equation is given by as follows. *Xi+p(k)* stands for a N-point DFT that start from the position *i+p*, where p is the interval between two sliding windows, $p=2^L$.

$$X_{i+p}(k)=\left\{X_i(k)+\sum_{n=0}^{N-1}\left[x(n+N)-x(n)\right]e^{-j\frac{2\pi}{N}nk}\right\}e^{j\frac{2\pi}{N}pk} \quad (4.6)$$

Generally speaking, the difference between SDFT and traditional FFT is that when single or multiple sample input are arriving, SDFT uses the previous sliding window to attain the present sliding window, while FFT has to recalculation the frequency spectrum of the whole sliding window. Therefore, SDFT greatly improves the computational efficiency. The computational complexities are list as follows in Table 4.2:

Table 4.2 Comparison of Computation Complexity of Different Algorithms

	Initial window		Next window	
	Complex multiply	Complex add	Complex multiply	Complex add
DFT	N^2	$N(N-1)$	N^2	$N(N-1)$
FFT	$\frac{N}{2}\log_2 N$	$N\log_2 N$	$\frac{N}{2}\log_2 N$	$N\log_2 N$
Single-sample SDFT	$\frac{N}{2}\log_2 N$	$N\log_2 N$	N	$N+1$
Multiple-sample(*p*-sample) SDFT	$\frac{N}{2}\log_2 N$	$N\log_2 N$	$\frac{N}{2}\log_2 4p$	$p+N\log_2 2p$

4.6 MAC Layer Protocol

A p-persistent slotted CSMA/CD protocol is employed in the MAC layer due to its superiority in throughput compared with other contention-based MAC protocols [30][31]. In this protocol, the transmitting node senses the medium when it has a packet to send. If the medium is idle, the node transmits the packet instantly with a probability of p or delay with a probability of 1-p until the next available slot. If the medium is busy, the terminal waits until the medium becomes idle. The transmission of a packet is aborted immediately rather than being fully transmitted when a collision is detected. The node waits for a random period before making any new attempt to transmit the packet. The CSMA/CD protocol considers the unique multipath propagation of PLC channel, which is modeled by Fig. 4.8 and Table 4.3 [5]. In Fig. 4.8, each letter stands for a node in PLC network. The distance between two nodes follows the d_i in Eq. 4.1.

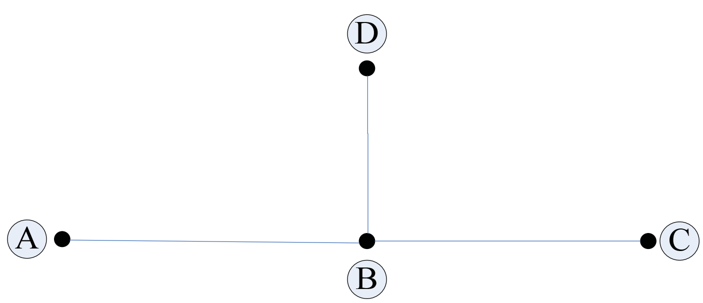

Fig. 4.8 Multi-path propagation along a line with one branch

Table 4.3 Propagation paths

Path No.	**Way of the Signal Path**
1	A→B→C
2	A→B→D→B→C
…	…
N	A→B(→D→B)$^{N-1}$→C

The flow chart of *p*-persistent slotted CSMA/CD is shown in Fig. 4.9.

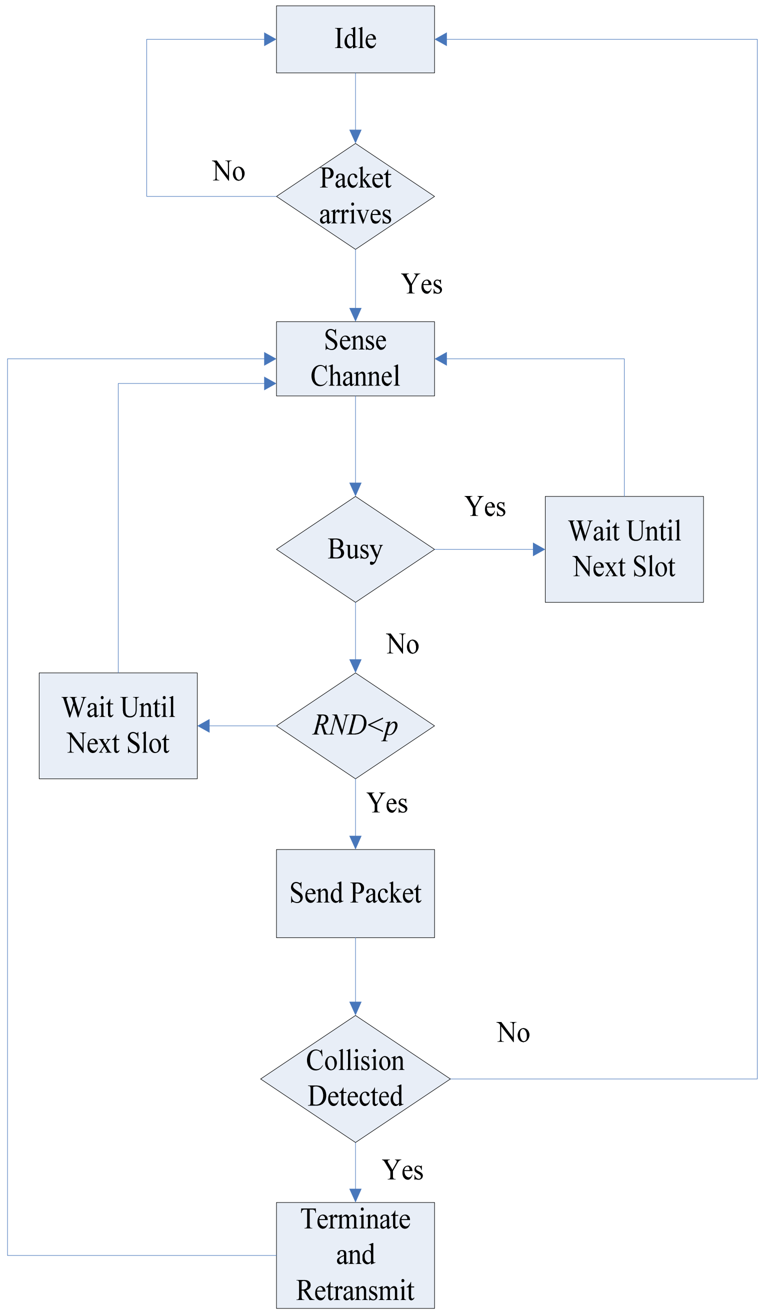

Fig. 4.9 Flow chart of *p*-persistent slotted CSMA/CD

4.7 Summary

In this chapter, we have introduced a novel multi-band OFDM system for PLC network. In our proposed system, the bandwidth is divided into multiple sub-band, enabling multiple OFDM symbols to transmit simultaneously. Taking account of the unique characteristics of PLC channel noise, we further propose a DNDMS to monitor the frequency spectrum of channel noise and switch the sub-band to in real-time to achieve better transmission accuracy. The simulation results will be shown in the next chapter.

Chapter 5

PERFORMANCE EVALUATION

5.1 Introduction

In this chapter, we will conduct simulations on the proposed PLC multi-band OFDM system. The simulations are firstly examined on the Physical Layer to compare the BER for conventional scheme and the proposed scheme. Then, the MAC layer protocols are considered to examine the system throughput.

5.2 System Setting and parameters

The simulation in this thesis is implemented in the environment of Microsoft Visual C++ 6.0. The main parameters in this simulation are partially based on [14], which are listed as follows in Table 5.1:

Table 5.1 Parameters in simulation

Physical Layer	Coding rate of convolutional encoder	1/2
	generator polynomials (octal)	Y_1: $[561]_8$ Y_2: $[753]_8$
	Packet length	1024 bits
	Number of OFDM sub-carriers	512
	Dimension of interleaver	512*1024
Channel Noise	Colored background noise	A_∞ = -136 dB A_0 = 38 dB β = 0.7 MHz
	Narrow-band noise	A_1 = -112 dB, f_1 = 4 MHz A_2 = -113 dB, f_2 = 6 MHz A_3 = -110 dB, f_3 = 10 MHz A_4 = -105 dB, f_4 = 12 MHz
	Burst noise	See Table 4.1(a)(b)
MAC Layer	Number of nodes	20
	Distance between neighboring nodes	Uniform distribution in the range of [0,5]
	Packet arrival	Follow Poisson Distribution

5.3 Physical Layer Simulation

As in Fig. 5.1, BERs for OFDM system with different number of bands are illustrated. For the system that has more than one band, we select the band through which the received signal that has the lowest BER. The results show that compared with conventional single-band OFDM, two-sub-band OFDM has the best improvements of BER, while three-sub-band OFDM achieves higher BER than two-sub-band OFDM, and even higher for four-sub-band OFDM. The difference is caused by the fading in the multipath PLC channel. The noise spectrum has lower power components in high frequency, where PLC channel has greater fading. The selection of number of bands is a trade-off between noise and channel fading. Here we have the two-sub-band OFDM scheme as the best choice. Then, DNDMS is considered in simulation. In Fig. 5.2, the BER of DNDMS scheme is greatly decreased.

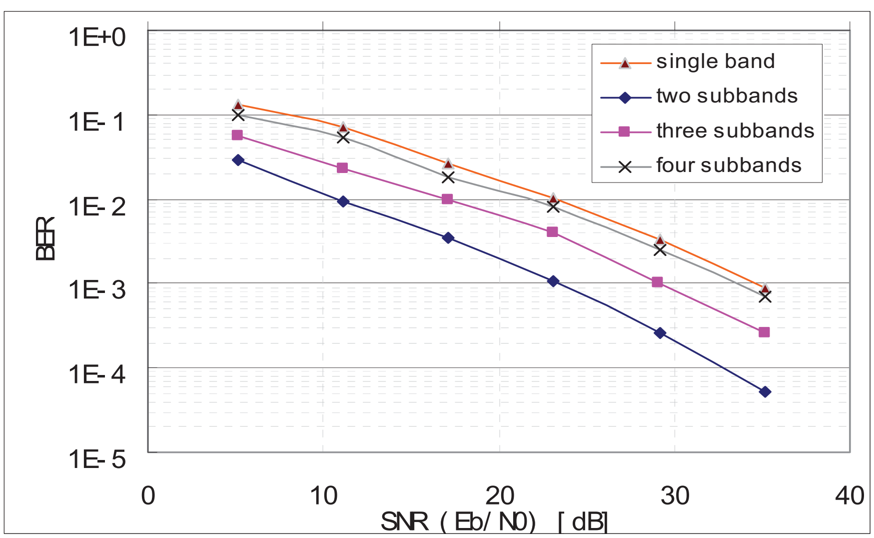

Fig. 5.1 System performance of different bands

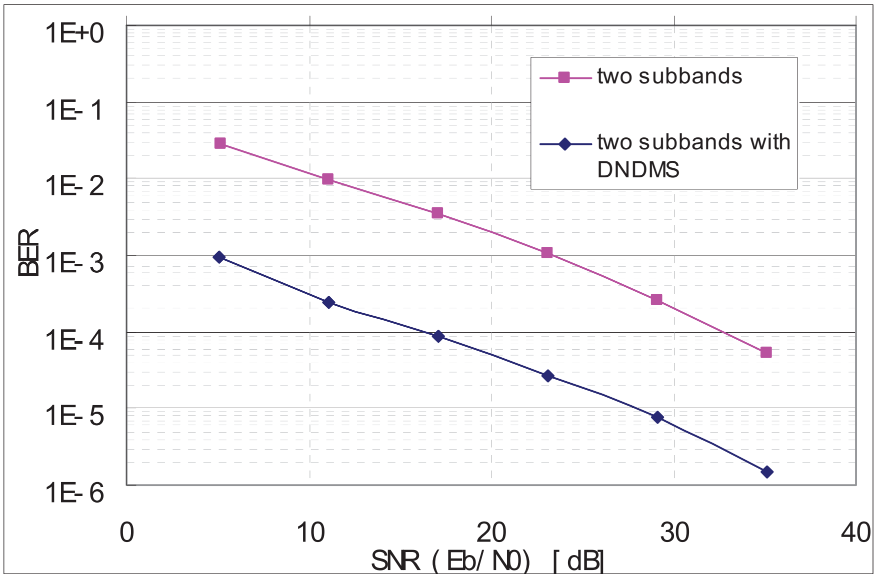

Fig. 5.2 System performance of DNDMS

5.4 System Throughput

The performance of our overall system with different probability of p is shown in Fig. 5.3. The simulation is implemented with a SNR of 35 dB and a total number of nodes $M=20$.

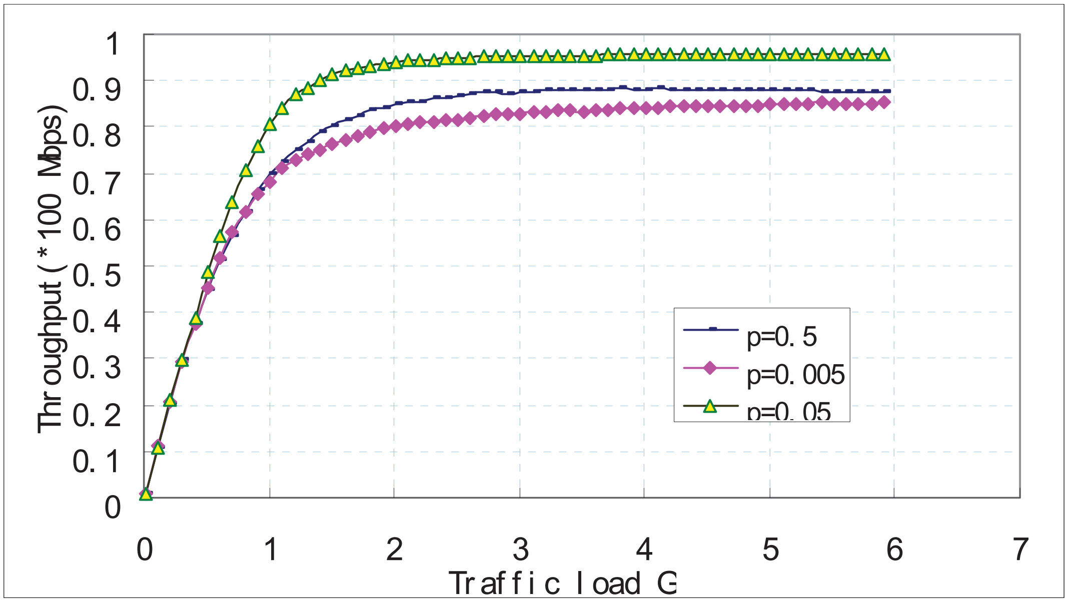

Fig. 5.3 Throughput with varying *p*

In Fig. 5.3, the throughput with varying *p* is evaluated. Three different probabilities of *p* for 0.005, 0.05, and 0.5 are compared, respectively. The best performance (96 Mbps) is obtained when *p* = 0.05, which is 1/M. The results well fit the mechanism of *p*-persistent CSMA/CD. When *p* is too large, nodes that have collided packets will retransmit their packets within a relatively short range of time slots, then these nodes will have high probability of repeating collision. On the other hand, when *p* is too small, every node will wait for a much longer time to retransmit, which decreases the overall throughput.

5.5 Summary

In this chapter, extensive simulations were conducted for the proposed PLC system. The simulation results show that, compared with previous single-band OFDM system, the multi-band

OFDM system conspicuously reduces the BER in the physical layer. Furthermore, the DNDS works effectively to select the sub-band that has the minimum influence to the channel transmission. The simulations on overall system throughput confirm that our proposed system can achieve a high transmission rate.

Chapter 6

CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

The PLC network is known as a network of high transmission speed and reliability, and is convenient and economical in the “Last Mile” access. A PLC network is normally based on OFDM modulation technique, which converts serial high-speed data signals into parallel low-speed data streams, and transmit them with a set of orthogonal sub-carrier waves. Consequently, this system is strong in resisting frequency selective fading, multipath fading, and all kinds of channel noise.

This thesis is extended from conventional research on OFDM-based PLC system which are focused on single-band utilization of PLC channel. After in-depth analysis and comparison of existing systems and schemes, we have presented a novel multi-band OFDM system. Then the severe environment of PLC channel is described and thus an indoor PLC channel model proposed by OPERA is employed. Extensive simulations are carried out on the performance of different number of sub-bands. The multi-band OFDM system achieves optimal BER in the scenario of two sub-bands. Our proposed Dynamic Noise Detection and Multi-band Switch scheme further reduces the BER of two-sub-band system. The high system throughput indicates that this research can provide an efficient option for PLC network.

6.2 Future Work

For multi-band OFDM system, different sub-band has different BER. Taking account of requirements of multi-media streams, such as video, audio and Internet data, we can apply the multi-band scheme to allocate an appropriate sub-band for each medium. Our future work will focus on proposing a solution to resource management of multi-media transmission.

On the other hand, the MAC layer protocol can be further modified by considering ARQ (Automatic Repeat Request). Since this protocol can better address the issue of the order of received data packets, better system reliability and throughput can be expected.

The final target of our research is to build a hardware test-bed for the proposed system.

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