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공학박사 학위논문

Efficient Protocol Design for Power Line Communications

전력선 통신을 위한 효율적인 프로토콜 설계

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Abstract

Power line communications (PLC) use power line as a communication media. PLC has an advantage over the other communication systems because a power line infrastructure exists everywhere. The recent momentum of replacing the aging power grid through combining the energy technology (ET) with the information and communication technology (ICT), which is called 'smart grid', is bringing attention to the use of PLC as an appropriate networking technology within the grid. PLC has two major directions of development, i.e. access network (AN) and in-home (IH). PLC-AN targets both high and low data rate communications for the Internet access to homes or for remote metering and load control applications in regional areas. On the other hand, the main objective of the PLC-IH is to provide a backbone network for home network system. It requires high bandwidth to support various home network functionalities. Since the characteristic of power line channel is very different from that of wireless channel, power line channel characteristics aware MAC and network layer protocols improve system performance.

In this dissertation, we design three different protocols that aim improving PLC performance. Firstly, we design a routing algorithm for PLC-AN in the smart gird. Since a transmission signal of narrow-band PLC penetrates electronic devices, a use of opportunistic routing (OR) for PLC-AN, which is constructed with medium and low voltage distribution networks, is possible. In this problem, we investigate the feasibility of OR in PLC-AN and propose a customized OR for it, named PLC-OR, which uses static geographical information. For doing this, we formulate a bit-meter per second maximization problem and solves it in a distributed manner. Through simulations, we confirm that our proposed PLC-OR successfully reduces packet transmission time compared to the traditional sequential routing while achieving the same level of reliability in packet delivery.

Secondly, we propose a carrier sense multiple access with collision avoidance (CSMA/CA) protocol for orthogonal frequency-division multiple access (OFDMA) based PLC. Using the relatively static and cyclostationary characteristic of power line channel, OFDMA in PLC can achieve multi-user diversity gain even in random access scheme. We formulate a network wide utility maximization problem in our proposed OFDMA CSMA/CA framework. The problem is solved by two phases. At first, the whole bandwidth is divided into several subchannels, and then the subchannels are allocated to each node. We propose optimal and heuristic algorithms in each problem. Through extensive simulations, our proposed algorithm improves the system utility compared to the single channel CSMA/CA.

Finally, we design a new PLC medium access control (MAC) protocol considering two different types of power line noise models, i.e., impulsive noise [generated by on-off switching of electronic devices] and background noise. When a transmission error occurs, the transmitter in our proposal adjusts its transmission rate according to the receiver's feedback and determines the contention window (CW) size appropriately according to the current loading. We verify that our proposed MAC scheme improves network throughput under various scenarios compared to conventional PLC MAC through extensive simulations.

Keywords: power line communications, smart grid, optimization, opportunistic routing, OFDMA, CSMA/CA, MAC, rate adaptation, contention window.

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Chapter 1

Introduction

Power line communications (PLC) use power line as a communication media. While PLC originated from very humble beginnings for exchanging a few bits of control signals, one state-of-the-art PLC standard is expected to achieve throughput performance of more than 1 Gbps. PLC has two major directions of development, i.e. access network (AN) and in-home (IH). The main role of PLC-AN, which is constructed with medium voltage (MV) and low voltage (LV) distribution networks, is to exchange control signals between substations and end users or to provide the Internet access to homes. So, the system normally goes with narrowband PLC solutions which operate in the band of 3-500 kHz. On the other hand, the main objective of the PLC-IH is to provide a backbone network for home network system. It requires high bandwidth to support various home network functionalities and uses broadband such as 2-30 MHz and 30-86 MHz

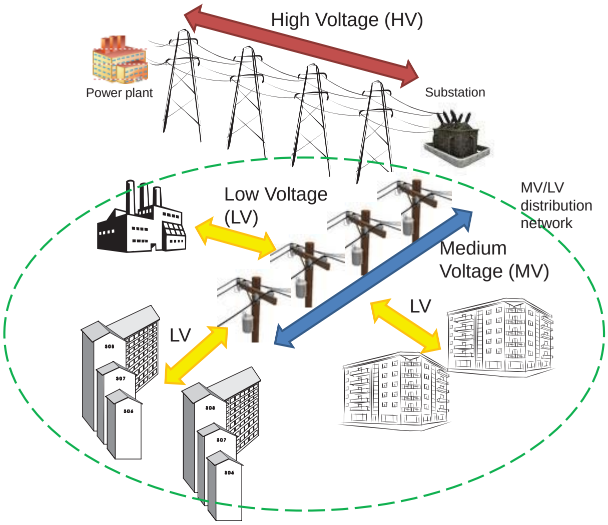

Figure 1.1: HV, MV and LV in a power network.

additional bandwidth. One of the newest broadband PLC systems targeting PLC-IH is HomePlug AV2 (HPAV2) released by the HomePlug Power Line Alliance, and it enables gigabit-class speeds for multiple HDTV streaming and online gaming.

Power systems consist of four parts in general: generation, transmission, distribution and consumption. The power is generated and transported in high voltage (HV). Then, it is distributed over regional areas in MV and LV, and consumed in LV as shown in Fig. 1.1. Among this power system, PLC-AN and PLC-IH generally deal with the MV/LV distribution network and the LV home network, respectively.

The recent momentum of replacing the aging power grid through combining the energy technology (ET) with the information and communication technology (ICT), which is called ‘smart grid’, is bringing attention to the use of PLC as an appropriate networking technology within the grid. The smart grid requires advanced information, control, and communication technologies to support such intelligent features as electronic control, monitoring, self-healing, diagnoses, and an advanced metering infrastructure (AMI). The success of the smart grid heavily depends on fast and reliable data transmission since some smart grid applications should be performed in real time. There are ongoing debates on the actual roles of PLC for the smart grid, i.e. whether PLC becomes the alternative of already-in-market wireless technology or not. However, there is no doubt that the smart grid will exploit multiple communication technologies to guarantee reliability, and that PLC has an advantage over the other communication systems because a power line infrastructure exists everywhere. This advantage enables distributed, efficient and economical power management through PLC.

To apply some advanced wireless techniques to PLC, understanding the unique characteristics of power line channel is important. The power line is a wired communication medium, but its channel characteristics are very much different from the conventional wired media such as telephone and Ethernet lines since it is not designed for communications. Some characteristics of the power line channel are similar with those of the wireless channel, but their detail styles of the characteristics are different. For instance, both power line and wireless channels are fading channel and have several frequency notches. The frequency notch in the power line channel, however, does not fluctuate very much because of static topology while that in the wireless channel changes frequently due to the dynamic environment.

Another important characteristic of power line channel is that its channel response is a cyclostationary process. The channel response and noise in PLC look like time varying, but they show periodic behaviors. It is because electrical devices installed in the power line, which are major noise sources in PLC, operate with the AC line cycle. Therefore, the channel and noise characteristics change along with this cycle. In other words, power line channel is predictable and its pattern slowly changes compared to wireless channel. This is called the cyclostationary nature of the power line channel.

Also, power line channel has a unique noise, i.e. impulsive noise. The impulsive noise in the power line channel is generated by on-off switching of electronic devices. The duration of each impulsive noise is very short, i.e., less than 2 msec, and its power spectral density (PSD) is about 50 dB higher than that of the background noise. Thus, if the impulsive noise is generated during a data transmission, the transmitted signal will be severely damaged and fall into a burst error.

In this dissertation, we design three different protocols that aim improving PLC performance. Since the characteristic of power line channel is very different from that of wireless channel, power line channel characteristics aware MAC and network layer protocols improve system performance. The result of extensive simulations shows that our proposed protocols can enhance PLC performance.

1.1 Outline

This dissertation is organized as follows.

In Chapter 2, we design a routing algorithm for PLC-AN in the smart gird. Since a transmission signal of narrowband PLC penetrates electronic devices, a use of opportunistic routing (OR) for PLC-AN, which is constructed with medium and low voltage distribution networks, is possible. In this problem, we investigate the feasibility of OR in PLC-AN and propose a customized OR for it, named PLC-OR, which uses static geographical information. For doing this, we formulate a bit-meter per second maximization problem and solves it in a distributed manner. Through simulations, we confirm that our proposed PLC-OR successfully reduces packet transmission time compared to the traditional sequential routing while achieving the same level of reliability in packet delivery.

In Chapter 3, we propose a carrier sense multiple access with collision avoidance (CSMA/CA) protocol for orthogonal frequency-division multiple access (OFDMA) based PLC. Using the relatively static and cyclostationary characteristic of power line channel, OFDMA in PLC can achieve multi-user diversity gain even in random access scheme. We formulate a network wide utility maximization problem in our proposed OFDMA CSMA/CA framework. The problem is solved by two phases. At first, the whole bandwidth is divided into several subchannels, and then the subchannels are allocated to each node. We propose optimal and heuristic algorithms in each problem. Through extensive simulations, our proposed algorithm improves the system utility compared to the single channel CSMA/CA.

In Chapter 4, we design a new PLC medium access control (MAC) protocol considering two different types of power line noise models, i.e., impulsive noise [generated by on-off switching of electronic devices] and background noise. When a transmission error occurs, the transmitter in our proposal adjusts its transmission rate according to the receiver's feedback and determines the contention window (CW) size appropriately according to the current loading. We verify that our proposed MAC scheme improves network throughput under various scenarios compared to conventional PLC MAC through extensive simulations.

We conclude the dissertation in Chapter 5.

Chapter 2

Opportunistic Routing for Smart Grid with Power Line Communication Access Networks

2.1 Introduction

The recent momentum of replacing the aging power grid through combining the energy technology (ET) with the information and communication technology (ICT), which is called 'smart grid', is bringing attention to the use of power line communications (PLC) as an appropriate networking technology within the grid. The smart grid requires advanced information, control, and communication technologies to support such intelligent features as electronic control, monitoring, self-healing, diagnoses, and an advanced metering infrastructure (AMI). The success of the smart grid heavily depends on fast and reliable data transmission since some smart grid applications should be performed in real time [1]. There are ongoing debates on the actual roles of PLC for the smart grid, i.e. whether PLC becomes the alternative of already-in-market wireless technology or not. However, there is no doubt that the smart grid will exploit multiple communication technologies to guarantee reliability, and that PLC has an advantage over the other communication systems because a power line infrastructure exists everywhere.

PLC standards are designed to meet in-home (IH) multimedia or access network (AN) requirements [2, 3]. They are targeting both high and low data rate communications for the Internet access to homes or for remote metering and load control applications in regional areas. In this paper, we focus on an AN which covers medium voltage (MV)/low voltage (LV) distribution networks. As a candidate networking technology in the AN, PLC is attracting attention since it can support communication between power producing and consuming entities. This enables distributed, efficient and economical power management through PLC.

PLC-AN requires a routing functionality because an MV/LV distribution network covers a wide area and several intermediate nodes are involved[1]. Since the characteristics of power line channels are different from those of wireless and conventional wired channels, routing greatly affects network performance. Thus, it is necessary to design a PLC customized routing protocol which exploits power line characteristics.

Opportunistic Routing (OR) has emerged as a promising way of improving network performance by exploiting the broadcasting nature of wireless medium in ad-hoc and sensor networks. Traditional routing delivers a frame with predetermined intermediate nodes before the transmission starts, and the dedicated next node is appointed to forward it. In OR, forwarder nodes are decided in advance since multiple intermediate nodes stochastically overhear the transmission from a sender. Then, a node with closest to the destination rebroadcasts the frame. This forwarding process continues until the frame reaches the destination. It has been shown that OR improves network performance compared to traditional sequential routing schemes, in terms of end-to-end throughput, reliability, and the number of transmissions [4].

Recently, researches on the routing functionality in PLC-AN have been done [5, 6, 7]. In [5], flooding is shown to be an efficient routing scheme in PLC-AN when all nodes need to receive identical information from the network. However, neither all automation networks nor smart grid applications have the same requirements. Applications

[1] It is different from PLC IH where most of power devices are in one hop distance to each other.

such as AMI, system breakdown sensing, and recharging systems for electric vehicles require point-to-point communications. Another researches on PLC-AN routing [6, 7] have introduced geographic routing, which requires location information of each power device. Biagi et al. have briefly applied wireless routing schemes to the PLC-AN in [6] and extended those in [7]. However, they have not considered the case of multiple receivers.

In this paper, we argue the feasibility of OR in the PLC-AN and propose a PLC-AN customized OR, named PLC-OR. OR can be a good candidate in PLC-AN because of the penetration characteristic of electric devices in power line. Our proposed PLC-OR uses topological information to build a routing table, and it chooses a single route to the destination. Because of its use of single path for routing, PLC-OR does not suffer from duplicated reception at the final destination. Our PLC-OR also uses ACK based distribution coordination. We formulate a bit-meter per second maximization problem to select transmission rate, tone mapping pattern, and forwarder set. Then, we propose a distributed algorithm which finds its optimal solution.

The rest of this paper is organized as follows. We first briefly overview narrowband PLC standards and OR in Section 2.2. Then, our system model is described in Section 2.3. We design a PLC-OR scheme in Section 2.4. After evaluating our proposed schemes in Section 2.5, we conclude our paper in Section 2.6.

2.2 Background

2.2.1 PLC Standards

There are two approaches in PLC. The first one is a narrowband solution that operates below 500 kHz band at rates of up to hundreds of kbps, and the second one is a broadband solution running at the band of 2-30 MHz with rates of up to a couple of hundred Mbps. All the state-of-the-art PLC standards have employed newest techniques for wireless systems such as orthogonal frequency division multiplexing (OFDM) and adaptive modulation and coding (AMC).

In PLC-AN, the narrowband solution is more appealing due to several reasons. First, it offers a longer transmission range as channel attenuation increases with the frequency [8]. It does not have significant emission issues differently from the broadband solution [9]. The narrowband signal can penetrate electrical devices, such as capacity banks and transformers, while the broadband signal cannot [3].

Second, many of smart grid applications do not require data rates of hundreds of Mbps [9]. Automated metering infrastructure (AMI), sensing/monitoring/controlling power devices, system malfunction recognition, and recharging control systems for electric vehicles are appropriate applications to the narrowband solution due to their moderate data rate requirements.

Finally, considering the OFDM technology in up-to-date PLC, the broadband solution requires higher complexity than the narrowband solution as it supports a higher number of subcarriers [2, 3]. Therefore, the narrowband solution achieves a low-cost and wide-coverage network over MV and LV power grids. In this paper, we consider the narrowband solution for PLC-OR design.

Recently, several narrowband PLC standards aiming at smart grid applications have been issued. They are G3-PLC , PRIME, ITU-T G.hnem, and IEEE 1901.2. These standards enhance the throughput performance with wide band, OFDM, and AMC. In addition, to exploit PLC channel characteristics, adaptive tone mapping has been defined. It enables a transmitter to exclude some channels experiencing heavy interference from allocation, and to use higher modulation and coding (MCS) level.

Because of the multihop characteristic in PLC-AN, routing is essential for packet delivery. To the best of our knowledge, there is no previous investigation on the routing issue about new narrowband PLC that supports multiple transmission rates and adaptive tone mapping.

2.2.2 Opportunistic Routing

OR basically exploits the broadcasting nature of wireless medium where a transmission can be overheard by several neighbors. One of those who have overheard the transmission rebroadcasts the received frame toward the destination node, and this rebroadcasting continues until the frame reaches the destination. Since the forwarding continues as long as at least one neighbor receives the frame correctly, OR improves the reliability of a network. Furthermore, since there is a chance for a transmission to travel through multiple hops at a time, OR contributes to reducing the total number of transmissions.

The key design issues to achieve these goals are: forwarder set selection, prioritization, and duplicated transmission avoidance/suppression [4]. The forwarder set selection is to determine candidates of relaying neighbors. It should be done carefully toward the direction of the destination, i.e., having the routing progress. The prioritization is to give priority to selected candidates so that one with the most routing progress in the set is selected as an actual relay. If the most progressive one fails to relay the frame, the second most one should be selected and so on. Finally, relaying should be performed in a way of reducing duplicated transmissions that degrade network performance due to the waste in network resource use.

Fig. 2.1 shows the difference between traditional sequential routing and OR. In the traditional routing, a frame travels through a predetermined route, passing through each node on the path in a sequential way. In OR, however, for each transmission, a forwarding set is selected first (dotted rounded square), and the node priority within the set is given in some way (upper square). According to the transmission result, i.e. success or failure, an actual relay will be chosen to forward the frame to the next forwarding set. In this example, OR requires three transmissions while the traditional routing

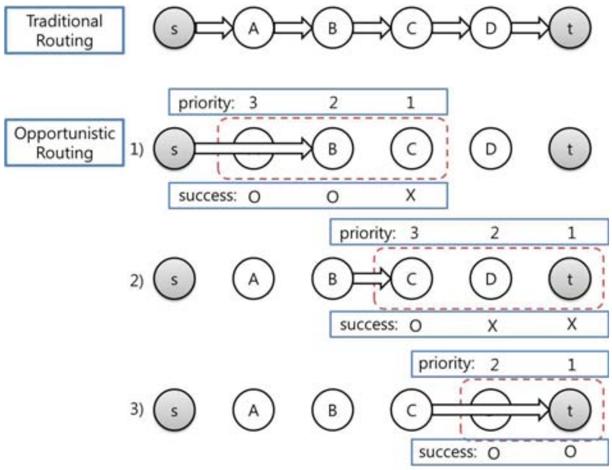

Figure 2.1: An illustration of OR in a linear topology.

five transmissions for delivery. In general, OR requires a less number of transmissions or retransmissions. This is because relaying can be done by some other neighbors in OR when a specific neighbor fails to receive a sender's transmission. However, forwarder set selection, prioritization and duplicated transmission avoidance/suppression requires some processing. So, there exists a tradeoff between progressing gain and processing delay in OR protocol design.

2.3 System Model

2.3.1 Narrowband channel model

In this subsection, we describe noise models and empirical channel measurement results of channel characteristics for narrowband PLC systems over the LV and MV power grid.

Since the bandwidth of narrowband PLC is only several kHz and OFDM technique divides the whole channel into several subchannels[2], a subchannel can be modeled as frequency flat while the whole bandwidth as frequency selective. If there is a narrowband noise source, the signal-to-noise ratio (SNR) of each subchannel can be very different. Since a power line acts as an antenna from a wireless system point of view, if there exist narrowband noises from wireless radio sources such as radio broadcasting/navigation and amateur radio, the band is severely interfered. This is called an interference from wireless to PLC or tone jammer. Also, if an electrical device generates noise periodically, called narrowband disturber, the band is also severely affected [10]. To get over these narrowband interferences, narrowband PLC standards have proposed to use adaptive tone mapping.

The empirical channel measurement results for narrowband PLC systems over the LV and MV grids are summarized as follows [8, 10, 11, 12]:

- The channel has not only frequency selective dependency but also position dependency on the LV and MV grid topology owing to impedance mismatches at the various branch points, transformers and open circuits [11].

- The channel attenuation increases with the distance in LV and MV lines. The mean channel attenuation in LV lines [8] is given

[2]In this paper, we use the terms tone and subchannel interchangeably.

by

$$\mu_{LV}(f, D) = (0.0034D + 1.0893)f + 0.1295D + 17.3481,$$

where f is the frequency in MHz and D is the distance in meters. Also, the mean channel attenuation in MV lines [8] is

$$\mu_{MV}(f, D) = 1.77f + 0.01D + 32.9.$$

- A capacitor bank attenuates signals more at higher frequencies. Each capacitor bank incurs about 10 dB attenuation in the narrowband signals between 10 kHz and 95 kHz [11].
- An MV/LV transformer shows a frequency selective characteristic in low frequency bands. It gives about 50 dB attenuation in the narrowband signals [12].
- PLC noise has a frequency selective characteristic and its energy profile varies significantly. The noise in MV lines is stronger than that in LV lines by around 10 dB in the 30-90 kHz band [9].

We consider three channel models for MV and LV access networks according to the channel measurement results: i) MV channel model without capacitor banks, ii) MV channel model with capacitor banks, and iii) LV channel model. The signal-to-noise ratio (SNR) can be calculated as

$$\mathrm{SNR_{dB}}(f, D) = P_r - \mu(f, D) - N(f),$$

where P_r is the transmit power spectral density and $N(\cdot)$ is the noise power spectral density. We set that $P_r = -60$ dBV^2 and $f = 0.05$ MHz for the narrowband PLC systems [6]. For the channel model ii), the SNR is lowered by 10 dB in each capacitor bank.

2.3.2 Network Model

We consider an electrical grid, represented as a communication network graph $\mathcal{G} = \{\mathcal{V}, \mathcal{E}\}$, where $\mathcal{V}$ and $\mathcal{E}$ are the sets of vertices (nodes) and edges. The set of edges is defined $\mathcal{E} = \{(i, j)|p_{ij} < 1 - \epsilon\}$ where p_{ij} is a frame error rate (FER) and ϵ is a small positive real number. When there is a destination D, the distance improvement gain G_{ij} from node i to j is defined as $G_{ij} = d(i, D) - d(j, D)$ where $d(\cdot, \cdot)$ is the distance between the two nodes along the power line[3]. $\mathcal{N}_i$ is a neighbor candidate set of node i, that is $\mathcal{N}_i = \{j|(i, j) \in \mathcal{E} \text{ and } G_{ij} > 0\}$. A ordered set $\mathcal{F}_i$ is a forwarder set of node i which is a subset of $\mathcal{N}_i$. M_i is a tone mapping pattern of node i, that is, $M_i = \{M_{i1}, M_{i1}, \cdots, M_{iM}\}$, where M_{il} is a tone mapping index of node i and subchannel l, and M is the number of subchannels. When $M_{il} = 1$, the subchannel l is used, while it is not otherwise. The number of used tones at node i

[3]This function always returns positive value and $d(a, b) = d(b, a)$.

is $M^i = \sum_{l=1}^{M} M_{ij}$.

We assume that PLC-AN channel is frequency selective while each subchannel is frequency flat. According to the recent specification of narrowband PLC [3, 13], one frame is 2D interleaved into time and frequency. Assuming a perfect interleaving scheme, we obtain the FER as

$$p = 1 - \prod_{l=1}^{M} M_{il}(1 - p_b^l)^{L/M^i}, \qquad (2.1)$$

where L is the frame length in bits and p_b^l is the BER of subchannel l.

2.4 Design of PLC-OR

In this section, we design a simple and practical OR protocol in PLC-AN, named PLC-OR under the most recent narrowband PLC standard of G3-PLC [3]. It can be easily extended to any other narrowband PLC standards since it only uses basic functions of G3-PLC.

2.4.1 Motivation

Although OR is attracting much attention owing to its improvement in network routing performance, it still has some obstacles to be tackled in general. OR gives performance enhancement in static topological environments such as sensor and mesh networks. In a network with mobility, such as mobile ad-hoc network (MANET), OR's performance gain can be marginal due to frequent changes of the topology. OR may not be applicable when the physical channel condition varies rapidly even in static topology environments. It is because the decision on forwarder set selection and prioritization should be performed with channel changes, which causes network-wide signaling overhead. Furthermore, isometric antennas and the broadcasting nature of the wireless channel incur duplicated frame delivery to the final destination since some intermediate relaying nodes are not in the communication range of each other [4].

In PLC-AN, however, the problems mentioned above can be relatively easily resolved due to the following reasons. First, the topological structure in PLC-AN is completely static. Second, the average channel condition in PLC is relatively static compared to the wireless channel. Most fortunately, even though the channel response varies, relative channel conditions between sequentially connected nodes do not change. For example, the channel response between (s, A) is always better than that between (s, B) in Fig. 2. Therefore, the forwarder set and priority among them are unchanged unless intermediate nodes fail. Lastly, in the case that a forwarder set is selected along a physically connected line, which is excluded from other power lines, duplicated transmissions due to multi routes do not happen since all forwarders are in the communication range of each other.

2.4.2 Default path selection

We assume that each node knows its own location information a priori [6]. To prevent duplicated frame delivery, PLC-OR does not allow multipath routing, i.e., all the nodes in a forwarder set lie along the same route. Therefore, network coding which generally goes with OR is not required. This single path routing scheme guarantees that the sender and all the forwarder nodes are in the same transmission domain. To this end, Dijkstra's algorithm is used to select the route between a source and a destination. The weight between the two nodes is the actual distance in meters so that the algorithm returns the shortest path between the source and the destination.

We also define a 'Hello' message which is periodically transmitted. The 'Hello' message is used for each node to maintain its neighbor list and update the FER. Although PLC channel has no moving elements, the channel response changes slowly. It is because the load change in each branch results in impedance change [14]. The overhead for 'Hello' message is about 15 msec [3] which is 0.15 % when the message is broadcasted every 10 seconds.

With geographical information and the minimum distance default path selection algorithm, all the intermediate nodes in the route select the same route in real time. When a forwarder correctly receives a frame and becomes a new sender, it understands the destination. The new sender looks for the shortest route to the destination using Dijkstra's algorithm. Since the new sender is on the previous short-

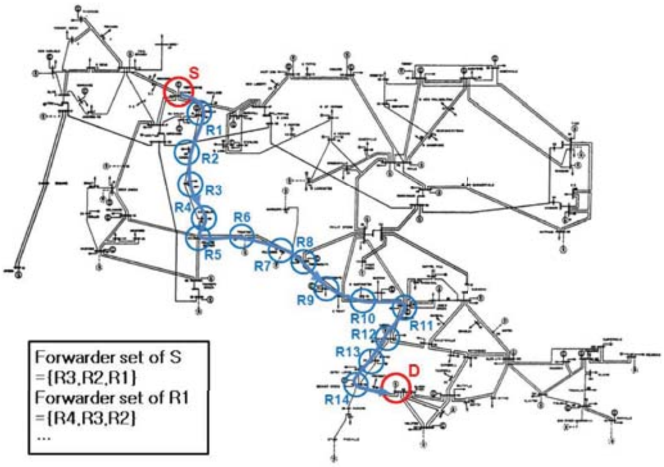

Figure 2.2: An example of a path in a topology of 118-node. Between the source and the destination, there are 14 relay nodes.

est route, the new shortest route to the destination should be the same. Only the destination address is needed to find the same route. Therefore, each node does not need a routing table.

Fig. 2.2 shows a specific path from a source to a destination in a topology constructed with 118 nodes. This figure comes from the New England power system [15]. In our proposed OR, only one minimum distance path is selected for the forwarder nodes, although there exist other paths from source S to destination D. There are 14 intermediate relay nodes placed along the path from S to D in this example.

2.4.3 ACK-based coordination scheme

Our proposed PLC-OR uses fast slotted acknowledgment (FSA) [16] for priority realization which is an ACK based distributed coordination technique. Relaying priority is realized by discriminated ACK timing in the MAC layer.

For channel access, G3-PLC uses the same carrier sensing medium access/collision avoidance (CSMA/CA) scheme as in IEEE 802.15.4. In G3-PLC, a sender gets a right to access the channel through contention by choosing a random backoff number. After the sender finishes its transmission, the intended receiver waits for the response interframe space (RIFS) interval and replies back to the sender with the ACK message. Then, after the contention interframe space (CIFS) interval, a new contention starts.

In our proposed PLC-OR, the ACK transmission period of each forwarder node is reserved. The highest priority node gets the chance to transmit ACK immediately after RIFS, and the other nodes get the opportunities when the highest priority node fails to decode the frame. If a node senses the channel idle and successfully decodes the frame, it becomes an actual relay. It notifies to the sender and the other possible relay nodes confirm this information through ACK message during the granted ACK period. After sensing a higher priority node's ACK transmission, all the other lower priority nodes stop their ACK transmissions. Note that in the G3-PLC standard, virtual carrier sensing (VCS) technique is adopted, so the ACK-based coordination

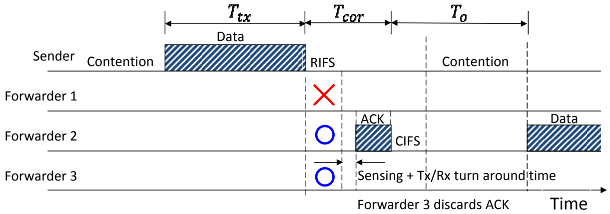

Figure 2.3: An example of PLC-OR ACK transmission. T_{tx}, T_{co}, and T_{po} are actual transmission time, coordination delay of PLC-OR, and CSMA/CA protocol overhead time, respectively.

scheme can be easily applied by setting the VCS period with some coordination time to a proper value. Since the VCS has a time limit, we define the maximum size of forwarder set as K_{max}.

Fig. 2.3 presents a specific example of PLC-OR's coordination. In this example, the node with the first priority failed to receive the data frame successfully while the second and third ones succeeded. In the first ACK period, the highest priority node (Forwarder 1) does not transmit the ACK. Sensing that there is no ACK, the next priority node (Forwarder 2) knows that it is chosen as a relay, and sends ACK. The third node (Forwarder 3) senses the medium busy so that it discards its ACK transmission. From receiving the ACK, the sender realizes that its transmission was successful and the relaying process is running as desired. The chosen relay (Forwarder 2) is then becomes a new sender and the same process will continue until the frame reaches the final destination.

A successful transmission at the jth forwarder node requires $T_j = T_{tx} + T_{co} + T_{po}$, where T_{tx}, T_{co}, and T_{po} are actual transmission time, coordination delay of PLC-OR, and CSMA/CA protocol overhead time, respectively. The coordination delay is given as $T_{co} = T_{RIFS} + (j-1)T_s + T_{ACK}$, where T_{RIFS} and T_s are RIFS time and sensing time, respectively. Similarly, the protocol overhead time is $T_{po} = T_{CIFS} + P\sigma$, where T_{CIFS} and σ are CIFS time and idle slot time, respectively. P is a random variable that describes a number of idle slots before starting a transmission.

Each transmission in PLC-OR requires more time than that in a traditional scheme due to the coordination overhead. The time required in the traditional scheme for each transmission is $T_{tx}+T_{RIFS}+T_{ACK}+T_{po}$, while that in PLC-OR needs $(n-1)T_s$ more. With the actual parameters in G3-PLC, the traditional scheme and PLC-OR scheme have 97.82 msec and 100.6 msec on average, respectively, assuming that $K_{max} = 3$. Therefore, PLC-OR wastes about 3% time more for each transmission. However, since the number of transmissions for a frame to get to the final destination in PLC-OR is much smaller than that in the traditional scheme, the total transmission time significantly decreases.

2.4.4 Rate, tone mapping pattern, and forwarder set selection

After constructing the default path by Dijkstra's algorithm, each node i selects transmission rate R_i, tone mapping pattern M_i, and forwarder set $\mathcal{F}_i$. We formulate it as a bit·meter/sec maximization problem as in [17]. That is, each node i tries to maximize

$$(\mathbf{P}) \quad \max \frac{L \sum_{j=1}^{|\mathcal{F}_i|} G_{ij}(1-p_{ij}) \prod_{k=1}^{j-1} p_{ik}}{T_{out} \prod_{j=1}^{|\mathcal{F}_i|} p_{ij} + \sum_{j=1}^{|\mathcal{F}_i|} T_j(1-p_{ij}) \prod_{k=1}^{j-1} p_{ik}} \quad (b \cdot m/sec) \qquad (2.2)$$

where L is the frame length in bits, T_{out} and T_j are medium holding times when all the forward nodes failed to decode the frame and when the jth priority forwarder node successfully received the frame, respectively. In this form, $\mathcal{F}_i$ is the only control variable, but p and T change with R_i and M_i change. Therefore, the control variables in $(\mathbf{P})$ are transmission rate R_i, tone mapping pattern M_i, and forwarder set $\mathcal{F}_i$.

The three control variables are discrete variables so that this is a discrete and combinatorial optimization problem. The total number of possible combinations in $(\mathbf{P})$ is $J \cdot 2^M \cdot {}_N\mathrm{P}_K$ where J and M is the number of MCS levels and subchannels, respectively. N and K are the sizes of $\mathcal{N}_i$ and $\mathcal{F}_i$, respectively. Since $\mathcal{F}_i$ is an ordered set, the number of possible combination patterns is not ${}_N\mathrm{C}_K$ but ${}_N\mathrm{P}_K$. To reduce the search space, we use a branch and bound algorithm.

The numerator of the problem $(\mathbf{P})$ is the expected packet advancement (EPA) proposed in [18]. As shown in their work, the EPA show two nice lemmas which are priority rule and containing property.

Lemma 1. *Replay Priority Rule (RPR) - Given the elements of $\mathcal{F}_i$, M_i, and R_i, the optimal forwarder set $\mathcal{F}_i^*$ is achieved if and only if a* *closer node to the destination gets a higher priority.*

Lemma 2. *Forwarder Set Containing Property (FSCP) - Let $\mathcal{F}_i^*(k)$ be the optimal forwarder set with k forwarders. When $\mathcal{N}_i$ is given, $\mathcal{F}_i^*(k-1) \subset \mathcal{F}_i^*(k)$, for all $1 \leq k \leq |\mathcal{N}_i|$.*

Owing to the use of RPR and FSCP, it becomes easier to select the forwarder set for (**P**). The following lemma also leads our proposed algorithm to find the optimal tone mapping pattern. Let $M_i^*(n)$ be the optimal tone mapping pattern when n subchannels are on. The term 'optimal' means that this tone mapping pattern gives the lowest FER in (2.1).

Lemma 3. *Tone Mapping Containing Property (TMCP) - Given a transmitter and receiver pair, $M_{ij}^*(n-1) = 0$ if $M_{ij}^*(n) = 0$.*

Proof. We prove that $M_i^*(n)$ is simply achieved by removing the lowest $M-n$ SNR subchannels. This is proven by contradiction. Assume that there is a non-masked subchannel j which has a higher BER than a masked subchannel i. That is, $p_b^j > p_b^i$. According to (2.1), if we change the masked subchannel from i to j, the changed FER becomes lower than before. This is a contradiction. □

According to TMCP, to get $M_i^*(n-1)$, we need to use the same tone mapping pattern of $M_i^*(n)$, and then removing one more tone results in an optimal pattern. With these three lemmas, we propose a searching algorithm to find the optimal values R_i^*, M_i^*, and $\mathcal{F}_i^*$. Our proposed algorithm finds these within the iterations of $J \cdot M \cdot NK$.

Algorithm 1: Tx rate, tone mapping pattern, and forwarder set selection at node i

```
// Initialize ;
Forwarder Set F_i^* ;
Tone mapping M_{ij}^* ;
Rate R_i^*;
for Each tx rate R_i do
    for Tone mapping pattern M_i inquiry do
        F_i = ∅ ;
        Initialize 𝒩_i ;
        O_{max} = 0 ;
        repeat
            for Each node n ∈ 𝒩_i do
                F_i = F_i ∪ {n};
                O_{cur} = CalcCost(F);
                if O_{cur} > O_{max} then
                    O_{max} = O_{cur};
                    n^* = n
                end
                F_i = F_i − {n};
            end
            F = F ∪ {n^*};
            𝒩_i = 𝒩_i − {n^*}
        until |F_i| < K_{max} and 𝒩_i ≠ ∅;
    end
    Choose maximum M_i and F_i
end
Choose maximum R_i^*, M_i^*, and F_i^*;
Return R_i^*, M_i^*, and F_i^*
```

Algorithm 1 is a pseudo code to obtain R_i^*, M_i^*, and $\mathcal{F}_i^*$. The repeat procedures (lines 9-21) find $\mathcal{F}_i^*$, given R_i and M_i. Owing to the use of RPR, the priority among candidate nodes in $\mathcal{F}_i^*$ shows the descending order in distance. Lines 10-18 select a best improvement node in $\mathcal{N}_i$ and put it into $\mathcal{F}_i$. This procedure repeats the maximum of K_{max} times or until there is no more neighbor candidate node. From FSCP, the result is $\mathcal{F}_i^*$, given R_i and M_i. For doing this, the maximum number of iterations is NK. The previous 'for loop' of line 5 returns M_i^*. It starts from all tones on, and then removes one by one in an ascending order of SNR. From TMCP, this approach guarantees to obtain the optimal tone mapping with at most M iterations. The first 'for loop' of line 4 tries all the possible rates, i.e. J times. At line 25, the algorithm chooses $\mathcal{F}_i^*$, R_i^* and M_i^* that maximizes the objective function.

2.5 Evaluations

In this section, we investigate the performance improvement of PLC-OR in terms of transmission time and reliability through simulations. The results are compared with those of shortest path routing (SPR) that is an optimal one among the traditional sequential routings[4], simple OR, OR with adaptive tone mapping (OR-TM), and OR with multi-rate support (OR-MR). SPR uses both adaptive rate and tone mapping methods. OR, OR-TM, and OR-MR use the expected num-

[4]We use SPR1 in [6] which does not consider energy consumption.

ber of transmissions (ETX) [19] as the prioritization and the forwarder set selection metric. OR and OR-TM do not change their MCS levels[5]. OR and OR-MR do not use adaptive tone mapping, but simply use the whole bandwidth regardless of the narrowband interference. Note that OR is regarded as a simple application of wireless OR to PLC-AN or beacon based routing (BBR) [7].

2.5.1 Settings

In G3-PLC specification, the maximum number of data symbols in one transmission is 252, and the channel sensing time is two symbols. Then, four symbols are needed to prioritize three forwarder nodes. We set $K_{max} = 3$ and the maximum number of data symbols as 248[6] The power line channel models in our simulation are described in Section 2.3.1. We consider three density models: high, medium, and low density. The distances between the two neighboring nodes in the three models follow the normal distributions with mean and variance of (1 km, 0.5 km), (1.5 km, 0.75 km), and (2 km, 1 km), respectively. The maximum distance between the two neighbor nodes in high, medium, and low density modes are 2 km, 3 km, and 4 km, respectively. When there exists a narrowband interference, it is assumed that the SNR of the corresponding subchannel is lowered by 10 dB [10].

[5]They use DBPSK with 1/2 convolutional coding which is the basic modulation and coding scheme.

[6]Higher K_{max} results in a less number of required data symbols.

We first measure the transmission time with the number of nodes in a simple chain topology. Then, we extend the simulation case to IEEE-300 system constructed by the measured data in New England [15], which is suited for observing the effect of OR on an actual PLC-AN environment. In the IEEE-300 system, one node is selected as source, and a destination is randomly chosen among the other 299 nodes. The default path to each destination is selected by Dijkstra's algorithm. The closest and furthest distance nodes are one and 14 hops away, respectively, and the average distance is 8.35 hops. Since the IEEE-300 system is MV power network, we assume that there is an LV distribution network after the destination node in the IEEE-300 system. There are consecutively connected 10 buildings through the LV power line, and the distance between two neighboring buildings follows normal distribution with mean 100 m and variance 100 m [14]. The final destination of the packet is one randomly chosen building among the 10 buildings in the LV line. We also assume that the narrowband interference exists in the grid network with the probability of 0.2.

2.5.2 Performance results

Figs. 2.4 and 2.5 show the transmission time in seconds to reach the destination for the three density models without and with the narrowband interference, respectively. We use MV channel model in this simulation. OR and OR-TM are the same scheme when there is no

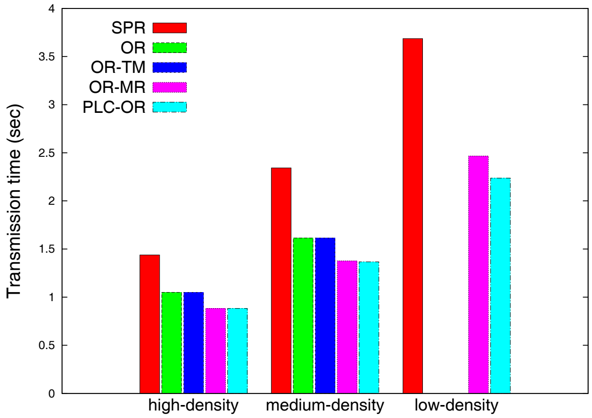

Figure 2.4: Average transmission time without the narrowband interference in a chain topology for three density models.

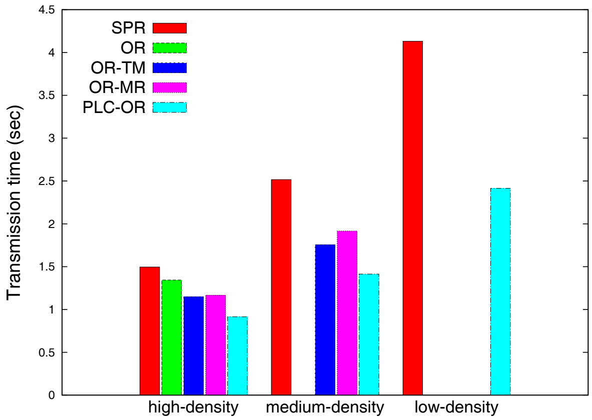

Figure 2.5: Average transmission time with the narrowband interference in a chain topology.

narrowband interference. Since one of the main control variables in PLC-OR is transmission rate when there is no narrowband interference, PLC-OR and OR-MR show similar performance in the cases of high and medium density models. However, in the low density model, our proposed PLC-OR shows the best performance since it adaptively changes the transmission rate and the forwarder set. Sometimes, single rate ORs (OR and OR-TM) fail to deliver packets to the destination in the low density model. That is, multi-rate capability improves routing reliability.

With the narrowband interference, OR-TM has some gain over OR, and plain OR is not reachable in the medium and low density models. The performance gains of OR, OR-TM, OR-MR, and PLC-OR over SPR in the high density model with the narrowband interference are about 13 %, 23 %, 22 %, and 39 % respectively. OR-TM shows a slightly better performance when there is a narrowband interference. OR, OR-TM, and OR-MR suffer from the reliability problem while our proposed PLC-OR does not. That is, our proposed PLC-OR significantly reduces the total transmission time while achieving the same level of reliability as SPR.

To get a result of IEEE-300 model, simulations are performed 10,000 times and the results are averaged in Fig. 2.6. The general tendency is the same as that in the chain topology. In some cases, OR failed to deliver packets. OR-TM and OR-MR show about 20 % gain over SPR, and PLC-OR performs best and shows about 40 %

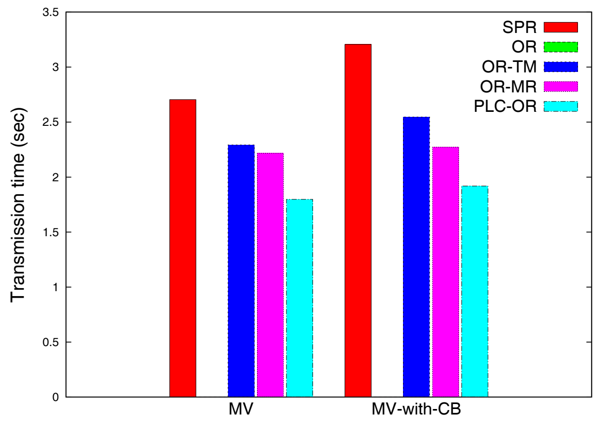

Figure 2.6: Average transmission time in the IEEE-300 system.

gain. In the graph of 'MV-with-CB', the capacitor bank is installed if a distance between the two neighbor nodes is longer than 1 km. Overall transmission time increases since each capacitor bank degrades the SNR by 10 dB.

2.6 Conclusion

With the recent proliferation of interest in the smart grid, power line communications (PLC) are attracting attention again as an appropriate networking technology for an access network (AN) covering a regional area of power systems. A narrowband solution in PLC is appealing to the medium and low voltage distribution networks that demands applications of moderate data rates. Meanwhile opportunistic routing (OR) is a new routing paradigm that makes use of the broadcasting nature of the wireless channel. In this paper, we argued that, with the narrowband solution, OR can improve in routing performance by exploiting the penetrating characteristic of power line channels in PLC-AN. Then, we design a PLC customized OR, named PLC-OR, which basically use single path route selection and simple ACK-based coordination. It includes an algorithm to decide transmission rate, tone mapping, and forwarder set selection. Through simulations, it is shown that our proposed PLC-OR lowers the transmission time. The end-to-end delay is reduced by about 40% compared to the traditional sequential routing. A simple application of wireless OR to a PLC network has some gain over the traditional routing, but experiences delivery failure in some cases.

Chapter 3

Opportunistic OFDMA CSMA/CA Protocol for Power Line Communication

3.1 Introduction

Power line communications (PLC) have two major directions of development, i.e. access network (AN) and in-home (IH). PLC AN targets exchanging control signals between substations. So, the system normally goes with narrowband PLC which operates in the band 3-500 kHz. On the other hand, The main objective of the PLC IH is to provide a backbone network for home network system. It requires high bandwidth to support various home network functionalities and uses broadband such as 2-30 MHz and 30-86 MHz additional bandwidth. One of the newest broadband PLC systems targeting PLC IH is HomePlug AV2 (HPAV2) released by the HomePlug Power Line Alliance [20], and it enables gigabit-class speeds for multiple HDTV streaming and online gaming. To enhance throughput performance of HPAV2, it brings state-of-the-art techniques from wireless system such as orthogonal frequency-division multiplexing (OFDM) and multiple-input and multiple-output (MIMO) with beamforming.

To apply new wireless techniques to PLC, understanding the unique characteristics of power line channel is important. The power line is a wired communication medium, but its channel characteristics are very much different from the conventional wired media such as telephone and Ethernet lines since it is not designed for communications. Some characteristics of the power line channel are similar with those of the wireless channel, but their detail style of the characteristics are different. For instance, both power line and wireless channels are fading channel and have several frequency notches. The frequency notch in the power line channel, however, does not fluctuate very much because of static topology while that in the wireless channel changes frequently due to the dynamic environment. Another important characteristic of power line channel is that its channel response is a cyclostationary process [21]. The channel response and noise in PLC look like time varying, but it shows periodic behaviors. It is because electrical devices installed in the power line, which are major noise sources in PLC, operate with the AC line cycle. Therefore, the channel and noise characteristics change along with this cycle. In other words, power line channel is predictable and its pattern slowly changes compared to wireless channel. This is called the cyclostationary nature of the power line channel.

Recently, a new carrier sense multiple access with collision avoidance (CSMA/CA) protocol using orthogonal frequency-division multiple access (OFDMA) was discussed in wireless communications [22]. The main benefit of using OFDMA comes from that each node can get the whole channel status through one fast Fourier transform (FFT). In the OFDMA CSMA/CA protocol, the whole bandwidth is divided into several subchannels and more than one links can simultaneously active resulting in reduced collision probability.

Owing to the predictable characteristic of power line channel, PLC system gets higher performance by exploiting multi-user diversity with a proper design of OFDMA CSMA/CA for PLC as well as low collision probability. To this end, we propose an OFDMA based CSMA/CA protocol for PLC systems. Our proposal divides the whole bandwidth into several subchannels and allocates each node with its favorable subchannel. We formulate a sum of node utility maximization problem. The problem is divided into two sub problems. First problem decides the number of subchannels and second problem allocates each node to a certain subchannel. Both optimal and heuristic solutions are proposed and their performances are compared through simulations. Because of low collision probability and multi-user diversity gain, our proposed OFDMA CSMA/CA for PLC outperforms the conventional single channel CSMA/CA.

The rest of the paper is organized as follows. We first review the related work for power line channel and multiple access schemes to OFDMA in Section 3.2. Then, we propose OFDMA CSMA/CA for PLC in Section 3.3.2. This section also include the system model and optimization problem formulation. The problem is solved into two subproblems, and each problem solving algorithms are presented in Sections 3.4 and 3.5. After evaluating the proposed protocol in Section 3.6, we conclude our paper in Section 3.7.

3.2 Related Work

3.2.1 Power line channel

The power line channel has its genuine characteristics. Firstly, it has a frequency selective channel response. Because of many branches and taps in the power network, the transmitting signal splits so that the receiver receives multiple signals with time difference. It makes the power line channel frequency selective. Since each transmitter and receiver pair has different impedance and number of taps, each channel has unique parameters, such as frequency dependant response and root-mean-square (RMS) delay spread. In [23], the authors have analyzed the frequency selective characteristic of the power line channel.

Secondly, the channel response periodically varies according to the AC line cycle. Canete et al. [21] have shown that the power line channel can be modeled as a linear periodically time-varying system since the impedance of electrical devices is time-variant. Because electrical devices in the power line generate cyclostationary noises that are synchronized with the AC line cycle, the channel response changes periodically. In time domain, Umehara et al. [24] have shown that the power line channel periodically switches between two different channel responses, i.e., $H_{Low}(f)$ and $H_{High}(f)$. Due to switching in regulators used in electrical appliances, the channel response $H(t, f)$ depends on the power supply voltage, which can be expressed as

$$H(t,f) = \begin{cases} H_{Low}(f) & |v_{ac,\theta}(t)| \leq V_{thr} \\ H_{High}(f) & |v_{ac,\theta}(t)| \geq V_{thr} + \Delta V \end{cases}, \tag{3.1}$$

where $v_{ac,\theta}(t)$, V_{thr}, and ΔV denote the power supply voltage, the threshold voltage, and the transient duration from $H_{Low}(f)$ to $H_{High}(f)$, respectively. Therefore, in the upper layer point of view, this result implies that the power line channel has regular and periodic properties.

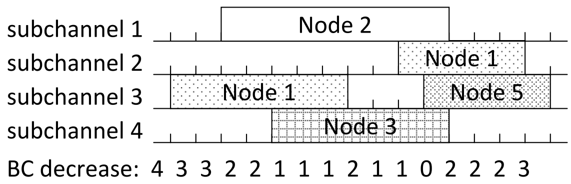

Figure 3.1: Example of the OFDMA CSMA/CA protocol operation. Because of the advantage of OFDMA, more than one node can transmit simultaneously. In this protocol, each node decreases its own BC by the number of idle subchannels rather than one, and transmits a frame through a randomly chosen subchannel among the idle subchannels.

3.2.2 OFDMA CSMA/CA

CSMA/CA protocol efficiently controls the shared medium in a distributed manner. To enhance the throughput efficiency of PLC CSMA/CA, previous investigations have focused on lowering the collision probability [25, 26]. Recently, Kwon et al. [22] presented a new OFDMA CSMA/CA in wireless communications. In OFDMA, a node can get the status of each sub-carrier by the FFT processing of the received OFDMA symbol. Using this, they designed a multichannel MAC named the OFDMA CSMA/CA protocol where each transmitter contends with others through many subchannels, resulting in reduced collision probability.

Fig. 3.1 shows an example of the OFDMA CSMA/CA protocol operation. While each node decreases its backoff counter (BC) by one for each idle slot in the legacy IEEE 802.11 CSMA/CA, it decreases the BC by the number of idle subchannels in the OFDMA CSMA/CA protocol. The number of idle slots per transmission in the OFDMA CSMA/CA protocol is less than that of legacy CSMA/CA, leading to lowered collision probability. Therefore, the throughput performance is enhanced in the OFDMA CSMA/CA protocol.

Moreover, the authors have developed their scheme to opportunistic multi-channel CSMA/CA protocol [27]. In the scheme, multi-user diversity gain was achieved by arranging each node to transmit on its favorable subchannel with an assumption of stationary channel. However, in the wireless system, the stationary assumption is not widely accepted.

Inspired the multi-user diversity from sub-channelizing in the OFDMA system, several investigations [28, 29, 30] have recently done in PLC networks. Oh et al. [28] proposed a cognitive power line communication (CPLC) system which allows the secondary node to reuse the unused frequency bands from the primary node. However, at most two nodes can be simultaneously transmit in the CPLC system. In [29], the authors proposed a cognitive resource allocation scheme that scheduled its favorable subchannel to each node. This work has considered TDMA and centralized environment. A two-dimensional opportunistic CSMA/CA protocol is proposed in [30] to enjoy the multi-user diversity gain. However, their scheme has a severe temporal unfairness problem between good channel nodes and bad channel nodes.

All the previous works investigating OFDMA CSMA/CA do not consider an important side effect of the sub-channelization, that is, increase header overhead. Since each node uses partial bandwidth in OFDMA CSMA/CA, the number of OFDMA symbols for header transmission increases resulting in the decrease of data transmission time. In this paper, we formulate an optimization problem to answer how many subchannels is the best considering the multi-user diversity gain and the increase of header overhead.

3.3 OFDMA PLC for CSMA/CA

3.3.1 Motivation

The main difference between the wireless OFDMA CSMA/CA and our proposed OFDMA CSMA/CA for PLC comes from the genuine characteristics of the power line channel. Wireless OFDMA CSMA/CA system [22] creates a subchannel by spreading it over the whole frequency band to average its randomness as shown in Fig. 3.2. On the other hand, to achieve the multi-user diversity gain, allocating a particular frequency band to a subchannel would be better as shown in Fig. 3.3. In [27], the authors proposed OFDMA CSMA/CA with this channel division. However, due to the short term fading in wireless channel, this channel division scheme is not proper. As the power line channel shows periodic and stable channel response, the latter approach can be used for achieving the multi-user diversity gain.

Another approach to enhance the throughput performance is low-

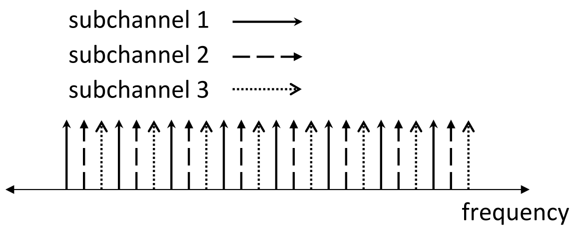

Figure 3.2: Spreading sub-carriers to average the channel randomness.

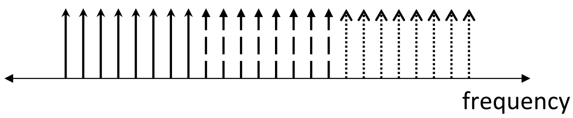

Figure 3.3: Gathering sub-carriers to achieve multi-user diversity.

ering collision probability. Chung et al. [31] presented a detailed analysis for HomePlug CSMA/CA by using the Markov Chain model. The analysis showed that the throughput decrease with number of contending nodes. Our proposed OFDMA CSMA/CA reduces the number of nodes in each subchannel so that the collision probability is lowered.

3.3.2 System Model and Problem Formulation

We consider an in-home power line network with N number of nodes. It is assumed that the system uses the HPAV MAC protocol [32, 33] which is standardized by the HomePlug Powerline Alliance[1]. Each HPAV network has a special node, named central coordinator (CCo), which takes charge of the control of the network. We also assume that the channel responses between nodes are periodic and each node

[1]HPAV and HPAV2 are backward compatible.

knows its channel response gain. The whole frequency band is divided into M subchannels. Differently than the other OFDMA CSMA/CA, each subchannel operates the CSMA/CA protocol independently. For instance, when a node allocates to the subchannel 1, it only uses the subchannel to transmit its data.

Our objective is to maximize the sum of utilities of nodes by adjusting the number of subchannels and allocating each subchannel to each node. The utility function $U(\cdot)$ is defined as a function of throughput. Let $\mathbb{I} = \{I_{i,j}, i = 1, \ldots, N, j = 1, \ldots, M\}$ denote the association indication vector where $I_{i,j}$ is an association indicator. When node i associates with subchannel j, $I_{i,j} = 1$ and 0 otherwise. The problem is formulated as

$$\begin{aligned} (\mathbf{P}) \quad & \max_{M,\mathbb{I}} \quad \sum_{i=1}^{N} U(R_i) \\ \text{subject to} \quad & \sum_{j=1}^{M} I_{i,j} = 1, \ \text{for all } i, \end{aligned}$$

where R_i is the throughput of node i. The throughput of node i is obtained by

$$R_i = \sum_{j=1}^{M} I_{i,j} \cdot r_{i,j} \frac{S(N_j, M)}{N_j}, \tag{3.2}$$

where $r_{i,j}$ is the feasible PHY transmission rate of node i on subchannel j and N_j is the number of nodes in the subchannel j, that is, $N_j = \sum_{i=1}^{N} I_{i,j}$. $S(n, m)$ denotes the saturated throughput of CSMA/CA with n nodes and m subchannels which is the time fraction of the successful data transmission. The reason for dividing N_j in (3.2) is that each node in subchannel j equally shares the duration of the successful data transmission from long-term fairness nature of CSMA/CA protocol and the saturation assumption. Using the result in [31], we have

$$S(n,m) = \frac{P_{tr}(n)P_s(n)T_D(m)}{(1-P_{tr}(n))\sigma + P_{tr}(n)(P_s(n)T_s(m) + (1-P_s(n))T_c)}$$

where $P_{tr}(n)$ and $P_s(n)$ are the probabilities that at least one node transmits and that a node successfully transmits, respectively and they are function of number of nodes. $T_D(m)$, σ, $T_s(m)$, and T_c denote the data transmission time, an idle slot time, the required time for one successful transmission, and the wasted time due to a frame collision, respectively. $T_s(m)$ is a function of number of subchannels. In one successful transmission, $T_s(m) = T_H(m)+T_D(m)+T_{RIFS}+T_{ACK}+T_{CIFS}$ time is needed, where they are header transmission time, data transmission time, response interframe space (RIFS), ACK transmission time, contention interframe space (CIFS), respectively. While σ, T_c, T_{RIFS}, T_{ACK}, and T_{CIFS} are constant, T_H and T_D are a function of the number of subchannels. PHY and MAC header conveys important information, such as source and destination address, frame length, and modulation and coding scheme (MCS) level, so that the header uses the whole bandwidth with robust MCS level. Since the number of data sub-carriers in each subchannel are divided by M, M

times symbols are needed to keep the same level of robustness. HPAV specification defines maximum allocated resource of one transmission as maximum transmission time T_{max}, so T_D reduces as M increases. Then, we have $T_D(m) = T_{max} - T_H(m)$ and $T_H(m) = m \cdot T_H$, where T_H is the single channel header transmission time.

The constraint in ($\mathbf{P}$) means that each node should use only one subchannels. For the utility function, we use a log function as $U(R_i) = \log R_i$, which naturally balances throughput maximization and fairness among nodes. The problem ($\mathbf{P}$) is a mixed-integer programming problem which is generally known as NP-hard. To solve the problem, we divide the problem into two subproblems and conquer them one by one. First problem is a channel division problem (selecting M) and next problem is a subchannel allocation problem (selecting $\mathbb{I}$).

3.3.3 Implementation issue

For the OFDMA CSMA/CA protocol, the OFDMA system should use a long cyclic prefix (CP) duration to avoid the inter symbol interference (ISI) while keeping the orthogonality between sub-carriers [22]. The use of CP helps to evade the inter carrier interference (ICI) as well as ISI. Since there are more than one transmitter, the time synchronization between transmitters cannot be perfect. However, when the time difference is smaller than the CP duration, the CP guarantees orthogonality between different transmitters. The condition for the orthogonality is

$$T_{cp} > \Delta T_d^{max} + \Delta T_p^{max}, \tag{3.3}$$

where T_{cp}, ΔT_d^{max}, and ΔT_p^{max} are the CP duration, the maximum time difference in the clock drift, and the maximum time difference in the propagation delay, respectively.

The CP duration of WLAN (802.11a/g/n/ac) is 0.8 μsec, which is not enough to use the OFDMA CSMA/CA. Therefore, to use it, WLAN's OFDMA CP duration should be made longer. However, HPAV can adopt the OFDMA CSMA/CA for PLC without modifying CP duration for the following reasons. At first, the CP duration of HPAV is 10.52 μsec [32]. Next, the AC line cycle can be used for the reference clock, so the time difference from the clock drift is lowered. Finally, the clock drift requirement of HPAV is ± 25 ppm. The maximum time difference from the clock drift between nodes in a AC line cycle is $\Delta T_d^{max} = 2 \times 1/60 \times 25$ ppm $= 0.83$ μsec, and that from the propagation delay is at most $\Delta T_p^{max} = 2$ μsec. Therefore, the CP duration can sufficiently handle the time difference.

3.4 Channel Division Problem

This section solves the first problem, i.e. the channel division problem which is performed at CCo. Two solutions are proposed: One is an optimal but impractical numerical solution, and the other is a simple heuristic solution.

3.4.1 Numerical solution

To maximize the sum of node utility maximization problem, overall nodes throughput level should increase through subchannel division. Dividing channels has three positive and negative factors to R_i. There are two positive factors: At first, as M increases the multi-user diversity gain increases since each node has more chance to be allocated its favorable subchannel. Next, more number of subchannels reduces collision probability because of less number of contending nodes in each subchannel. One negative factor is that an increase of M brings about protocol overhead.

We define a subchannel diversity gain $G(m)$, which is a function of number of subchannels. Then, the optimal number of subchannels m^* is that it maximizes $G(m)$. A node's rate in a single channel is $R_i = \sum_{j=1}^{m} r_{i,j} \frac{S(N,1)}{N}$. In here, $r_{i,j}$ is a random variable. We also have a node's rate in an m subchannels as $R_i^m = \sum_{j=1}^{m} I_{i,j} r_{i,j} \frac{S(N_j,m)}{N_j}$. The m subchannel dividing gain over a single channel $G(m)$ is defined as $G(m) = \mathbb{E}[R_i^m]/\mathbb{E}[R_i]$. The following lemma makes getting m^* easy.

Lemma 4. *If $r_{i,j}$ are i.i.d., $G(m)$ is a concave function of m.*

Proof. With the i.i.d. assumption of $r_{i,j}$, expectations of R_i and R_i^m are $\mathbb{E}[R_i] = m\mathbb{E}[r_{i,j}]\frac{S(N,1)}{N}$ and $\mathbb{E}[R_i^m] = d(m)\mathbb{E}[r_{i,j}]\frac{S(\overline{N},m)}{\overline{N}}$, respectively. $d(\cdot)$ is a channel allocation diversity gain. Then, we have

$$G(m) = \frac{d(m)S(\overline{N}, m)/\overline{N}}{S(N, 1)m/N}.$$

We need to investigate the characteristics of $d(m)$ and $S(n, m)$. $d(m)$ is a expectation of maximum of random variables. Let Y_k is a maximum of random variables and $F_k(y)$ is its CDF. That is, $Y_k = \max\{X_1, X_2, \cdots, X_k\}$, and $F_k(y) = P[(X_1 \leq y) \cap (X_2 \leq y) \cap \cdots \cap (X_k \leq y)]$. If $X_1, X_2, \cdots, X_k$ are i.i.d., $F_k(y) = F_X(y)^k$. The channel allocation diversity gain is formally defined as $d(m)\mathbb{E}[r_{i,j}] = \mathbb{E}[Y_m]$, where $X_1 = r_{i,1}$, $X_2 = r_{i,2}$, ..., and $X_m = r_{i,m}$. According to the order statistics [34], the $d(m)$ is a increasing and concave function of m. Also, since $r_{i,j}$ is a discrete random variable, $d(m)$ is an infinitely differentiable function.

Now, we look into $S(n, m)$. It is assumed that the effect of the collision probability is negligible since our area of interest is not more than 20 nodes in a system. The overhead from increase header data symbols linearly increases as m. Therefore, $S(n, m)$ can approximately be an affine function of m. The range of $S(n, m)$ is between 0 and 1.

Since $\overline{N}$ is average number of nodes in one subchannel, we have $\overline{N} = m/N$. Finally, we have $G(m) = d(m)S(\overline{N}, m)/S(N, 1)$. Note that $S(N, 1)$ is a positive real number. The second derivative of the

$G(m)$ twice is

$$G''(m) = \frac{1}{S(N,1)}(d''(m)S(\overline{N},m)+2d'(m)S'(\overline{N},m)+d(m)S''(\overline{N},m)).$$

There are six functions: $d(m)$, $d'(m)$, $d''(m)$, $S(\overline{N},m)$, $S'(\overline{N},m)$, and $S''(\overline{N},m)$. Since $d(m)$ is a increasing and concave function of m, $d'(m) > 0$ and $d''(m) < 0$. Also, $S'(\overline{N},m) < 0$, and $S''(\overline{N},m) = 0$ since $S(n,m)$ is an affine function or m. Therefore, $G''(m) < 0$. □

With the Lemma, we easily find the optimal number of subchannels with the gradient method. However, the i.i.d. assumption of $r_{i,j}$ does not hold in the power line environment. Power line channel generally depends on both between nodes and subchannels [35]. Therefore, the system should know all the distributions of $r_{i,j}$ plus all the joint distributions to get the $G(m)$. It is almost impossible and impractical even it is possible.

3.4.2 Heuristic solution

Due to the impracticality of the numerical solution, we propose a simple heuristic channel division algorithm. The two keys of multi-user diversity gain are number of nodes N in the network and randomness among subchannels. The more number of nodes gives the higher probability of high SNR nodes in each subchannel. However, this is not enough to capture the multi-user diversity. If all the nodes have the same channel response in each subchannel, there is no diversity gain at all regardless of the number of nodes. Therefore, the other key is how different channel response has in each subchannel, i.e., randomness among subchannels. To capture this randomness, the standard deviation σ of subchannels is used. We design a heuristic channel division algorithm with N and σ.

Our proposed heuristic algorithm only considers four number of subchannels for simplicity. The set of possible subchannels defines as $\mathcal{M} = \{M_1 = 1, M_2 = 2, M_3 = 4, M_4 = 8\}$. As we assume that each node knows its channel response gain, it feed its bit-loading standard deviation of subchannels σ back to the CCo. By being averaged over all nodes's σ, the CCo obtains σ_{avg}.

Our proposed heuristic channel division algorithm is followed. The CCo selects the maximum M_i which satisfies the two condition: i) $M_i \leq N$ and ii) $a_i - b(N - M_i) < \sigma_{avg}$, where a_i and b are positive real number. The reason for the first condition is straightforward. If $M > N$, there are $M - N$ wasted empty subchannels. The rationale behind the second condition is that the randomness should be larger than the channel division overhead. That is, σ_{avg} should be larger than a threshold. The threshold are defined by two factors: i) the larger M need the more diversity gain, i.e., $a_1 < a_2 < a_3 < a_4$ due to the increase of header overhead. ii) even if the randomness is not much, large N might cause more diversity gain, i.e., $-b(N - M_i)$. Here, the parameters a_i and b are found through simulations. We use $a_1 = 0$, $a_2 = 1.15$, $a_3 = 1.4$, $a_4 = 1.65$, and $b = 0.02$. For example, with $N = 10$ and $\sigma_{avg} = 1.5$, our proposed algorithm chooses $M = 4$ since the set of subchannels satisfied the two condition is $\{1, 2, 4\}$ and four is the maximum. If N changes to 20, $M = 8$ since the threshold of the second condition decreases.

3.5 Subchannel Allocation Problem

After choosing M, the remaining problem is that which node gets into which subchannel, i.e., the subchannel allocation problem. We propose centralized optimal and distributed heuristic solutions as first problem does.

3.5.1 Numerical solution

We revisit our original problem (**P**). Because M is fixed, we have

$$
\begin{aligned}
(\mathbf{P}') \quad \max_{\mathbb{I}} \quad & \sum_{i=1}^{N} U(R_i) \\
\text{subject to} \quad & \sum_{j=1}^{M} I_{i,j} = 1, \text{ for all } i.
\end{aligned}
$$

The problem $(\mathbf{P})'$ is identical with the association control problem in wireless networks. There are several problem solving algorithms of the utility maximization association control problem [36, 37]. According to [37], it was proven that $(\mathbf{P})'$ is NP-hard. The complexity of the exhaustive search algorithm is $O(M^N)$. If the fluctuations of relative rate are statistically identical, that is, the multi-user diversity only depends on the number of nodes in a subchannel, it is solvable with $O(N^M)$ complexity using the maximum bipartite matching algorithm. However, $O(N^M)$ is still high complexity. In [37], the authors have also proposed a simple online algorithm based on two atomic operations: 'change' and 'swap.' The algorithm locally performs the two operations to maximize the objective function. Therefore, the algorithm reaches a local optimum. We call this algorithm Local Search (LS). The 'change' operation is that a node changes its allocated subchannel to another if it increases the objective function. Similarly, the 'swap' operation is that two nodes which are allocated different subchannels switch their subchannels if it increases the objective function. The LS algorithm searches all the possible cases in the 'change' and 'swap,' and select one case which maximizes the increase of the objective function and it is larger than a predetermined threshold. The LS algorithm stops when there is no possible case. Note that the 'swap' operation cannot be made from two 'change' operations because of the LS algorithm's greedy characteristic. The complexity of the worst case of the LS algorithm is $O(NM + N^2)$. In [37], it was shown that the LS algorithm achieves the same objective function values as the optimal algorithm in almost 90% of the cases, and that only less than of 1% the performance ratios in the LS algorithm are less than 0.997 of the optimal solution.

To run the three numerical subchannel allocation algorithms, each node should feed its channel state information of each subchannel back to CCo. With the information, CCo allocate each subchannel to each node. They are centralized algorithms.

3.5.2 Heuristic solution

We also propose a heuristic distributed subchannel allocation algorithm. The algorithm independently runs at each node. CCo is only in charge of observing the number of contending nodes in each subchannel N_j, and it periodically broadcasts the beacon[2] that contains the information about M and N_j. The expected throughput of node i in subchannel j can be calculated by each node with the received information M and N_j, and with its own measured channel state information $r_{i,j}$. According to (3.2), it is $R_i = r_{i,j}\frac{S(N_j,M)}{N_j}$.

Procedures of our proposed heuristic solution for subchannel allocation is followed: At first, a newly joining node i chooses the highest SNR subchannel j among M subchannels. CCo notifies this change $N_j = N_j + 1$ through the beacon to all nodes in the network. Each node in subchannel j updates its expected throughput in each subchannel. If the expected throughput of the node i at some subchannel is higher than that at the subchannel j, the node changes the subchannel j to the new one. That is, if there is a subchannel k which satisfies

$$\frac{r_{i,j}S(N_j, M)}{N_j} < \max_k \left\{ \frac{r_{i,k}S(N_k + 1, M)}{N_k + 1} \right\}, \tag{3.4}$$

[2] The beacon period is 33.33 msec in North America and Korea.

the node i changes the subchannel j to the maximum expected throughput subchannel k. However, if the node immediately changes its subchannel, our proposed heuristic algorithm might not converge. In our algorithm, each node changes its subchannel after waiting for a certain backoff time. During the backoff, if the expected throughput of that subchannel becomes lower than the current throughput, the node gives up changing its subchannel. To give more priority to the higher gain node, each node selects its backoff counter (BC) according to inversely proportional to the gain increase of the expected throughput. In addition, to avoid the ping-pong problem between nodes with the same channel status, a random number in [0,L] is added to the BC. The unit of the BC is beacon period. The BC for node i is

$$BC_i = \frac{G_{MAX}}{G_i} + Unif(0, L), \tag{3.5}$$

where G_{MAX} is a constant and G_i is the gain increase of node i, respectively.

This is approximately the same as the 'change' operation in the centralized LS algorithm. Therefore, our proposed heuristic algorithm is a distributed LS algorithm which only has the 'change' operation.

Fig. 3.4 shows an example of our proposed heuristic subchannel allocation algorithm. Since both nodes prefer subchannel 1, they initially choose subchannel 1. They achieve 5 and 9 Mbps, respectively

	A	B
Tx rate of SC 1 (Mbps)	10	18
Tx rate of SC 2 (Mbps)	9	10

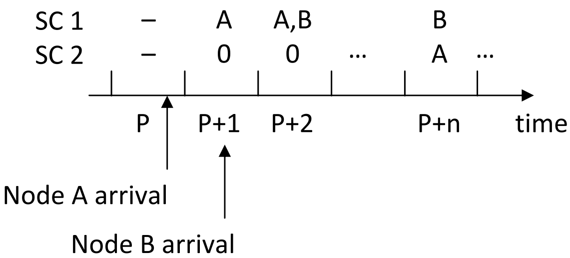

Figure 3.4: An example of our proposed heuristic distributed subchannel allocation algorithm. At period P and P+1, nodes A and B arrive in the network, respectively. In the end, our proposed algorithm allocate nodes A and B to subchannel 2 and 1, respectively.

in subchannel 1[3]. If they change its subchannel, they can achieve 9 and 10 Mbps, respectively, i.e. condition (3.4) satisfies. Therefore, they select a BC according to (3.5). Since the gain of node A (4 Mbps) is larger than that of node B (1 Mbps), node A has a smaller BC and changes its subchannel to 2 at P+n. After node A moves to the subchannel 2, the change condition (3.4) is not satisfied, so node B gives up its changing attempt. In the end, nodes A and B use subchannels 2 and 1, respectively.

3.6 Performance Evaluation

In this section, we compare the performance of our proposed OFDMA CSMA/CA for PLC with other competitive schemes, i.e., the HPAV

[3]For simplicity, CSMA/CA protocol overhead is not considered.

standard and CPLC, in terms of throughput and fairness. For simulations, we use a simulator written in C.

In CPLC, the node which wins the contention only uses its good subchannels, i.e. larger than a certain threshold. The rest nodes contend one more time for the use of remaining subchannels and the second winning node transmits its data through the remaining subchannels under a constraint of synchronized transmission with the first transmission.

3.6.1 Simulation settings

There are one CCo and the number of nodes, i.e. transmitters, varies from one to 20. The HPAV CSMA/CA parameters and other simulation parameters are listed in Table 3.1. We simulate under three channel scenarios: First, a flat channel scenario means that all the nodes have the same channel status. Next one is a random channel scenario in which each node has randomly selected channel status for each subchannels. Since the result of this scenario heavily depends on the chosen channel's status, the result is averaged by 30 independent runs. Finally, real channel scenario is used proposed by [35]. In [35], the authors provides a MATLAB functions that return frequency responses for realistic in-home and small offices channels in a simple network topology.

Table 3.1: Simulation parameters

System bandwidth	1.8-30 MHz
G_{MAX} in (3.5)	20
L in (3.5)	3
MaxFL	2501.12 μsec
Header transmission time in single channel	110.48 μsec
Beacon Period	33.33 msec
CIFS_AV	100 μsec
RIFS_AV	48.52 μsec
PRS0, PRS1	35.84 μsec
Backoff slot time	35.84 μsec
Response timeout	140.48 μsec

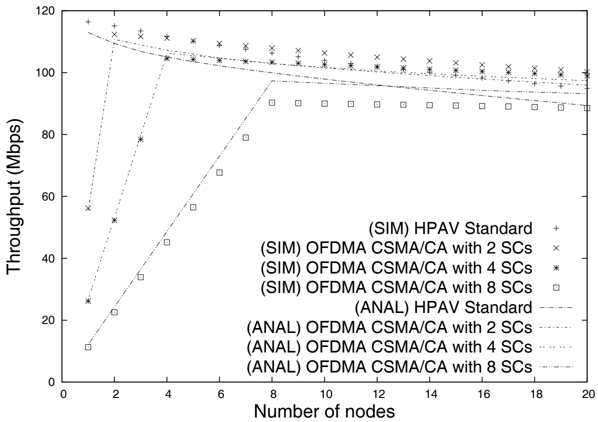

Figure 3.5: Throughput performance comparison according to the number of nodes under the flat channel scenario. The lines and dots are numerical and simulation results, respectively.

3.6.2 Diversity gain on channel division

The results of this section only shows the throughput improvement of the LS subchannel allocation algorithm[4] when M varies in [1,20].

[4]Since the other two centralized algorithms do not return the subchannel allocation result when $M = 8$ and $n > 12$ due to the computational complexity, we use the LS algorithm.

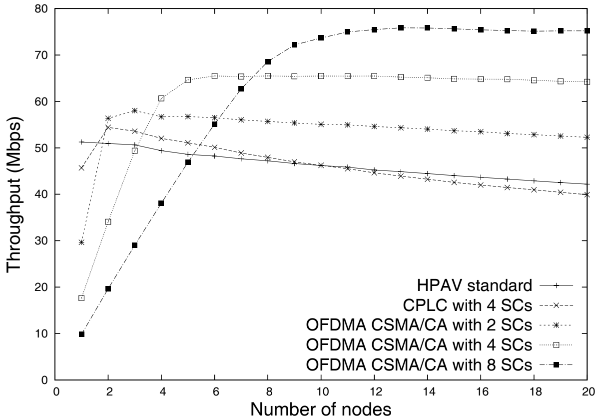

Figure 3.6: Throughput performance comparison according to the number of nodes under the random channel scenario. Our proposal shows the highest throughput when the number of nodes is larger than or equal to the number of subchannels. The result is averaged over 30 runs.

Fig. 3.5 shows the throughput performance under the flat channel scenario. The graphs are plotted by both numerical and simulation methods. The lines and dots are numerical and simulation results, respectively. The result shows that the difference between numerical and simulation results are about 4 %. Since the result of CPLC cannot be obtained by numerical method, we use simulation result only for the following results. CPLC is the same as the HPAV standard in flat channel scenario. The throughput improvement gain of our proposed scheme is marginal in the flat channel scenario since there is no diversity gain.

The throughput performance according to the number of nodes under the random channel scenario is shown in Fig. 3.6. Our proposal

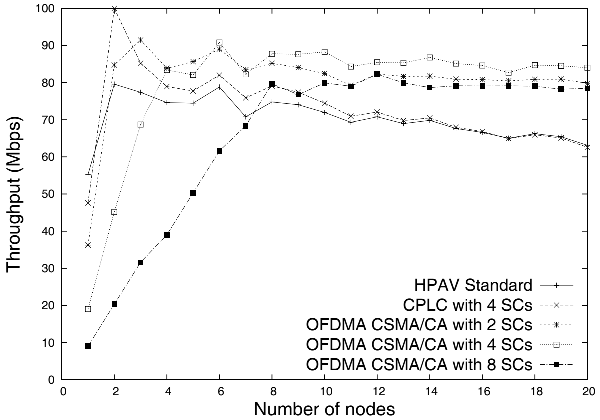

Figure 3.7: Throughput performance comparison according to the number of nodes under the real channel scenario.

gets the highest throughput performance. Because of the randomness of the channel, the channel selection diversity gain overcomes the cost of long header. CPLC shows a performance gain with small number of nodes, i.e. less than five nodes, but its performance converges to that of the HPAV with the number of nodes since the efficiency of the secondary channel decreases with the number of nodes.

Fig. 3.7 shows the throughput performance under the real channel scenario. Generally, our proposed OFDMA CSMA/CA with four subchannels show the best throughput performance when the number of nodes is larger than or equal to the number of subchannels. Due to the lack of the randomness among subchannels, the channel division gain cannot overcome the increase of header overhead. CPLC shows the best performance in 2-node case because of a severe unfairness of among two node, that is, higher node and the other achieve 90

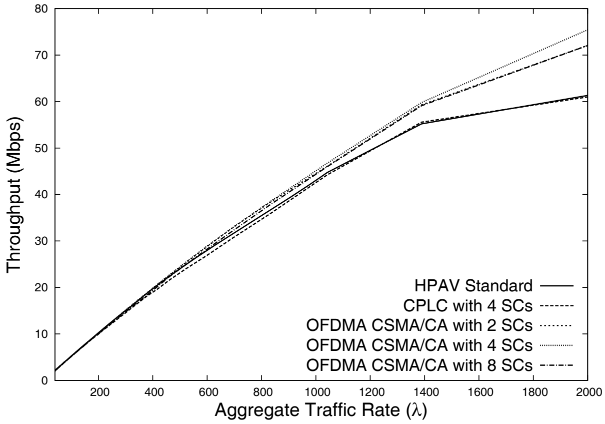

Figure 3.8: Throughput performance comparison according to the traffic rate λ. λ is the number of aggregated traffic arrival per second in the network.

and 10 Mbps, respectively. Note that from this result, we select the parameter value a_i and b in our proposed heuristic channel division algorithm in Section 3.4.2.

Fig 3.8 shows the throughput performance of non saturated traffic condition. There are 20 nodes in the network and each node receives a packet with Poisson arrival process. The size of each packet is 5,000 bytes. When traffic intensity is low ($0 < \lambda < 6$), all the schemes handle the injected traffic well. However, after $\lambda > 6$, HPAV and CPLC cannot fully handle the offered load. Our proposed OFDMA CSMA/CA with four subchannels show the best performance under the saturated condition. This coincides with the result of Fig. 3.7. Note that we use N_A instead of N in the non saturated condition. N_A is the number of active nodes[5] in the network.

[5] Active node mean a node with data in its queue.

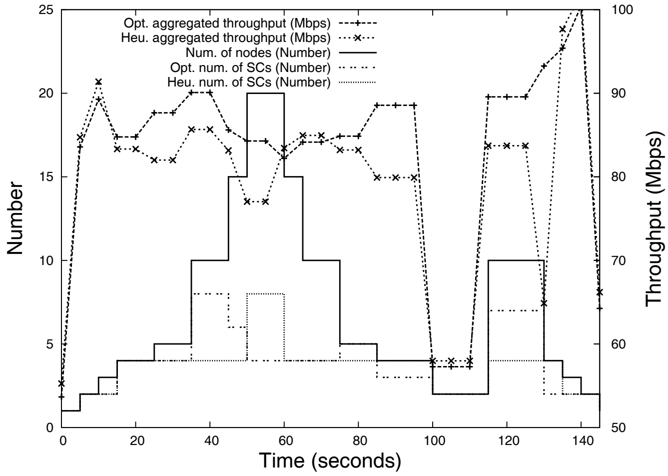

Figure 3.9: Throughput performance under the real channel scenario. The two lines from the top represent throughput performance (Mbps and right 'y' axis). The unit of the other three lines are number (left 'y' axis).

3.6.3 Dynamic scenario

To evaluate our proposed optimal and heuristic results, we make a dynamic scenario described in Fig. 3.9. Several nodes get into and leave the network as time goes, i.e. the solid line shown in Fig. 3.9. The channel response of each node is also predetermined. According to the number of nodes and its subchannel's standard deviation, optimal and heuristic number of subchannels are selected. The two lines from the bottom represents number of subchannels of optimal and heuristic algorithms, respectively. While the result of the heuristic algorithm can only have M in $\mathcal{M} = \{1, 2, 4, 8\}$, the optimal solution can have any positive integer M. Also, optimal and heuristic sub-

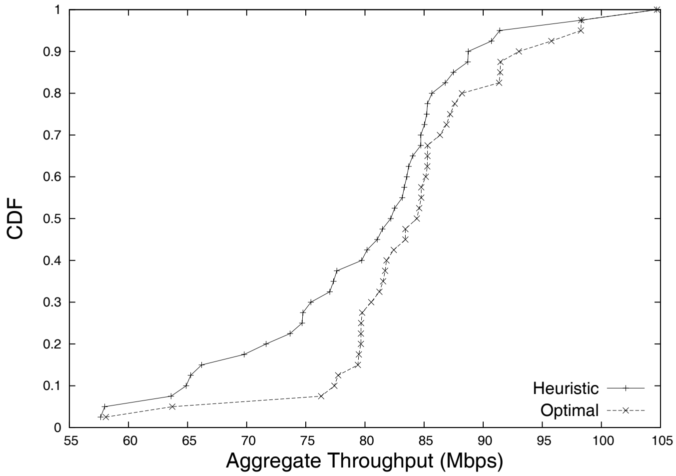

Figure 3.10: CDF of the throughput performance in optimal and heuristic solutions.

channel allocation algorithms decide subchannel of each node. The two lines from the top shows the throughput performance of optimal and heuristic algorithms, respectively. The performance gap between the two algorithms are about 4 % excluding the case at 130 sec. At the 130 sec., because of our proposed heuristic channel division algorithm's improper result, the throughput performance gap is severe. Note that the throughput performance of the heuristic algorithm is slightly higher than that of the optimal algorithm in some cases. This is because: 1) the simulation time is not enough to get a desired result, and 2) the objective function is a sum of utility maximization not a throughput maximization.

Fig. 3.10 shows a CDF of the throughput performance in optimal and heuristic solutions with 40 scenarios. This result compares the throughput performance of the optimal channel division and LS subchannel allocation algorithms with that of heuristic channel division and subchannel allocation algorithms. The average performance gap between them is about 4.7% and the maximum difference is 32.6%.

3.7 Conclusion

In this paper, a new multiple access framework for PLC was introduced, that is, OFDMA CSMA/CA for PLC. Our proposed OFDMA CSMA/CA divides the whole bandwidth into several subchannels and each node enters its favorable subchannel. In the framework, we formulated a sum of node utility maximization problem. The problem it is divided into two sub-problem: the channel division and subchannel allocation problems. We proposed optimal and heuristic solutions of each problem. Simulation results showed that our proposed OFDMA CSMA/CA framework improves the throughput performance with proper settings of the number of subchannels and subchannel allocation. Our proposed heuristic algorithm generally follows well to the optimal algorithm with much lower complexity and feedback overhead.

Chapter 4

Adaptive Rate Control and Contention Window Size Adjustment for Power Line Communication

4.1 Introduction

Traditional home appliances are being rapidly replaced by digital value-added ones and upcoming applications, such as interactive games and voice over IP (VoIP), are becoming more popular. Recently, lots of investigations on home networks have concentrated on communication between applications of multimedia and digital platforms. To provide such connectivity, various home network technologies of wireless and wired have been developed.

For wireless solutions, there are IEEE 802.11x wireless local area networks (WLANs) [38] and IEEE 802.15.x wireless personal area networks (WPANs) [39]. The major drawback of these wireless solutions is that their overall performances heavily depend on the interference from neighboring clients. For wired solutions, there are HomePlug [20], High-Definition Power Line Communication (HD-PLC) [40] and Universal Powerline Alliance (UPA) [41], which use existing power lines. The wired solutions suffer less from the interference problem than the wireless solutions. Among the power line communication (PLC) technologies, HomePlug AV (HPAV) [32] is a state of the art solution which has been standardized by HomePlug Powerline Alliance and follows the HomePlug 1.0 standard [42]. While HomePlug 1.0 was designed to distribute the Internet access, HPAV aims at supporting audio/video as well as data traffic. HPAV employs the advanced physical (PHY) layer and medium access control (MAC) layer technologies and supports the rate of up to 200 Mbps.

Previous investigations in PLC MAC have mainly focused on HomePlug. Chung et al. [31] presented a detailed analysis for HomePlug carrier sense multiple access with collision avoidance (CSMA/CA) using the Markov Chain model. In [26], Campista et al. enhanced throughput performance by simply modifying the collision avoidance parameters of HomePlug CSMA/CA. Tripathi et al. [43] worked on achieving high throughput in HomePlug CSMA/CA, assuming that every station always knows an exact number of contending stations within the network. As the above mentioned assumption was unrealistic, Yoon et al. [44] proposed a heuristic throughput optimization algorithm that can run without knowing the exact number of contending stations. These investigations assume that the channel is ideal, i.e., no transmission error due to the bad channel. This assumption is not valid either in real environments.

PLC and Ethernet use wired lines, but their channels are very different. For instance, PLC cannot detect collision while Ethernet can. Therefore, the power line channel is treated more like a wireless channel enabling PLC to use CSMA/CA which is widely used in wireless networks. However, some characteristics of the power line channel are different from those of the wireless channel and have been extensively investigated in [45, 46].

Rate adaptation has been proposed for wireless communications to enhance throughput performance under varying channel conditions. It uses multiple modulation coding schemes (MCSs) and adaptively chooses a transmitter's MCS level according to the channel condition [47, 48, 49]. As rate adaptation scheme for IEEE 802.11 WLAN cannot be applied for the PLC directly, Yoon et al. [50] proposed a scheme that reflects the characteristics of power line channel and applied this scheme to HPAV.

There are two types of adaptation schemes to combat bad channels; they are channel adaptation and rate adaptation schemes. These two types are similar in terms of changing the transmitter's modulation and coding according to the channel condition, while their targets are different. Most of adaptation schemes for PLC have mainly focused on channel adaptation [51, 52], which is designed for combating a cyclostationary characteristic of the power line channel. The cyclostationary characteristic comes from that channel and noise characteristics change along with the AC line cycle. The channel adaptation algorithms in [51, 52] are similar. After the receiver measures the channel response for a complete AC line cycle, the receiver feeds it back to the transmitter to determine proper modulation and coding schemes. However, previous investigations have not considered the case of the dynamic channel response according to joining or leaving of noise sources. On the other hand, rate adaptation schemes care for combating random and dynamic channel responses. The channel and rate adaptation schemes can be applied together since they do not contradict each other.

In this paper, we propose an enhanced MAC scheme for PLC that exploits the characteristics of the power line channel. It contains the functions of rate adaptation and contention window (CW) size adaptation. For the rate adaptation, our approach tries to be aware of the impulsive noise that often observed in the power line channel. In our scheme, the transmitter sends a packet with strong header protection, and the receiver replies with a negative acknowledgement (NACK) that indicates the error cause when the received payload is corrupted. Consequently, the transmitter chooses a proper MCS level according to this feedback. For the CW adaptation, our scheme adjusts the CW size adaptively to maximize network throughput. Depending on the congestion level, the network coordinator decides whether to increase, decrease, or keep the current CW size. The adaptive CW adjustment deals with the congestion problem while the impulsive noise aware rate adaptation handles the time varying channel problem.

4.2 Power Line Noise

The wireless channel has fast fading due to the multi-path propagation property of the transmitted signal. So the coherent time[1] is an important metric to understand the channel fluctuation [53]. The power line channel also has the multi-path problem because of power line taps, but it has no fast fading since each path length does not change with time. It has been extensively investigated in [54, 46]. In this section, we consider two types of channel noise models for PLC MAC design: background and impulsive noises [45, 55].

4.2.1 Background Noise

As wireless environments contain lots of noise sources and reflectors, so the background noise of wireless channel can be modeled as Gaussian according to the central limit theorem (CLT) [53]. On the other

[1]The channel condition is assumed fixed within the coherent time.

hand, power line environments are with a limited number of noise sources and reflectors, henceforth the background noise model does not follow Gaussian. As the noise model depends on the number of turned on noise sources [46], we assume the following: 1) there are M noise sources, and 2) on/off duration of each source is random and exponentially distributed. Then we can model the number of noise sources as an $M/M/\infty//M$ queueing system [56]. The second assumption may not hold true since the on/off duration of each electronic device is normally controlled by a human being or automatic on and off, i.e., somewhat deterministic rather than random. However, this assumption can be acceptable in our protocol design since random on-off environments of devices are more hostile compared to deterministic environments.

4.2.2 Impulsive Noise

The impulsive noise in the power line channel is generated by on-off switching of an electronic device. It is not stationary while the background noise can be assumed stationary. The duration of each impulsive noise is very short, i.e., less than 2 msec, and its power spectral density (PSD) is about 50 dB higher than that of the background noise. Thus, if the impulsive noise is generated during a data transmission, the transmitted signal will be severely damaged and fall into a burst error.

Zimmermann et al. [45] investigated the characteristics of the im-

Table 4.1: Impulsive noise scenarios

Noise Scenario	Mean IAT	Mean duration
Hardly distributed	0.015 sec	2.08msec
Moderately distributed	0.476 sec	0.87msec
Lightly distributed	1.903 sec	1.82msec

pulsive noise by measuring its inter arrival time (IAT) and modeled it as a partitioned Markov Chain. In [57], Hrasnica et al. considered the partitioned Markov Chain model with three scenarios as listed in Table 4.1, which we will use in our simulations.

4.3 HomePlug AV MAC

In this section, we briefly explain the HPAV MAC that adopts newly developed PHY and MAC layer technologies, such as orthogonal frequency division multiplexing (OFDM) and hybrid access control. HPAV uses a hybrid access mechanism to support various type of services. For the hybrid access control, each HPAV network has a coordinator named central coordinator (CCo) which periodically broadcasts a beacon message containing access control information. Fig. 4.1 shows an example of HPAV access mechanism that consists of CSMA/CA and time division multiple access (TDMA) regions. TDMA is designed for services with strict quality of service (QoS) requirements while CSMA/CA is for impromptu data transfer, control message and best effort services.

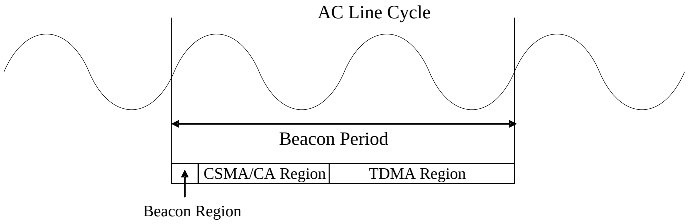

Figure 4.1: Example of the HPAV beacon period. The beacon period is synchronized with the AC line cycle for robust transmission and it consists of three regions: beacon, CSMA/CA, and TDMA.

4.3.1 CSMA/CA

HomePlug CSMA/CA[2] is similar to that in IEEE 802.11 WLAN as both use binary random backoff algorithm. Unlike IEEE 802.11 CSMA/CA, HomePlug CSMA/CA has the priority resolution period (PRP) and the deferral counter (DC).

The objective of PRP is to classify priorities among flows. It consists of two priority resolution slots (PRSs) named PRS0 and PRS1, and the duration of PRP is long enough to detect the medium state, i.e., busy or idle. Owing to the use of PRS0 and PRS1, HomePlug CSMA/CA can support four priorities[3]. If the station hears the busy signal during the PRP, it does not enter "Contention State." Only the stations with the same priority are able to enter "Contention State."

The DC is a parameter that works during the contention while the PRP does before the contention. It helps each station to perform a binary random backoff to avoid collision. When a station has a frame

[2]We use the term HomePlug CSMA/CA instead of the HPAV CSMA/CA because HPAV and HomePlug 1.0 use the same CSMA/CA protocol.

[3]The low and high priorities are (00, 01) and (10, 11), respectively.

Table 4.2: CW and DC as a function of BPC and priority

	High Priority		Low Priority	
	CW	DC	CW	DC
BPC = 0	7	0	7	0
BPC = 1	15	1	15	1
BPC = 2	15	3	31	3
BPC $\geq$ 3	31	15	63	15

to transmit, it sets its backoff procedure counter (BPC) value to 0, and chooses a random backoff counter (BC) number in [0, CW]. If the medium is idle for one slot, each station in "Contention State" decreases its BC by one, and sends a frame when its BC equals 0. If a station experiences collision, it increases the BPC by one and chooses a random BC number in [0, CW] again. Table 4.2 shows CW and DC values for each BPC.

At each BPC, each station sets the DC value to a predefined value shown in Table 4.2. The DC is decreased by one when the medium is busy. If the DC is zero and the medium is busy, the station performs a binary random backoff without attempting transmission.

4.3.2 Header CRC and ACK/NACK

HPAV has the PHY header named frame control (FC) which is similar to the physical layer convergence protocol (PLCP) header in IEEE 802.11. The FC, which contains the information about the frame format type and the MCS level, is very robust[4]. HPAV has five types

[4]The FC uses quadrature phase-shift keying (QPSK) and 1/2 coding.

of the frame format: beacon, start of frame (SOF), selective acknowledgement (SACK), request to send (RTS)/clear to send (CTS), and sound. In SOF, the FC contains transmitter and receiver addresses. Unlike the IEEE 802.11 PLCP header, the FC has its own 24 bit cyclic redundancy check (CRC), named frame control block check sequence (FCCS), to let the receiver validate it without decoding the following data part.

In HPAV, the receiver can reply to the transmitter with a NACK when it received a valid FCCS part but not the data part. Thanks to the use of NACK, HPAV transmitter can distinguish channel error from collision error. When the transmitter receives a NACK, it assumes with high probability that the frame error occurred due to the channel error. If a timeout occurs, the transmitter supposes that a collision occurred because there is no response from the receiver. This means that the receiver failed to decode the FCCS part either.

4.3.3 Rate Adaptation

For rate adaptation, the HPAV standard defines the sounding method to estimate the channel state between transmitter and receiver. At first the transmitter transmits a sound frame of 520 bytes by robust OFDM (ROBO) modulation. Then the receiver decides a specific MCS level for each subcarrier and replies with Tone-Map massage (CM_CHAN_EST.IND) to the transmitter.

If the transmitter receives a NACK, it does not decrease its transmission rate as long as the number of consecutive NACKs is smaller than Max_NACK_Retries. If the transmission failed Max_NACK_Retries times consecutively, the transmitter uses the ROBO modulation until the transmission is complete[5]. Then the transmitter initiates the sounding procedures and stores new Tone-Map. If a frame collision occurs, the transmitter retransmits it at the same rate unless the number of consecutive timeouts reaches Max_Collision_Retries.

4.4 Enhanced MAC Scheme

To fully exploit the capacity of a medium, PHY and MAC protocols need to understand its characteristics. For PLC, we devise two schemes that consider power line channel characteristics: impulse noise aware rate adaptation (INARA) and CW size adaptation.

4.4.1 INARA

The channel estimation procedures in the HPAV standard require a lot of overhead. For instance, the average time spent for the sounding procedures is 2558.72 μsec, which is almost the same as the transmission time for an ordinary data frame. The sounding procedures can be suited for TDMA transmission which guarantees periodic resource allocation, but too costly for CSMA/CA transmission. Therefore, we propose a simple rate adaptation scheme, named INARA, which uses

[5] If the frame transmission using ROBO fails consecutively, it will be discarded.

the genuine characteristics of the power line channel. The key concept in INARA is that the receiver helps the transmitter to know the channel status by simply replying with ACK or NACK frame.

NACK with noise type indication

The rate adaptation scheme in the HPAV standard distinguishes collision error from channel error, but does not impulsive noise from background noise. When the transmitter receives NACK, it simply retransmits the frame consecutively unless the number of consecutive NACK generations reaches Max_NACK_Retries[6]. This is because the transmitter cannot be sure about the cause of a transmission error by receiving only one NACK. The first NACK may come from either impulsive noise or background noise, but the consecutive failures primarily come from the background noise. If the transmitter knows the reason for the received NACK, it can avoid having consecutive transmission failures.

In INARA, we propose the receiver to use the NACK that contains one bit of the failure reason. This enables the transmitter to react to the failure appropriately. INARA uses two different NACKs according to the noise type: NACK_I for an impulsive noise error and NACK_B for a background noise error. When the transmitter receives NACK_I, it retransmits the buffered frame without rate decrease. Differently than this, on NACK_B reception, it retransmits the buffered frame

[6]The default value of Max_NACK_Retries is two.

with rate decrease. Since the impulsive noise has 50 dB larger PSD on average than the background noise, the RF hardware can easily detect the impulsive noise during the frame reception. If the receiver cannot decode the FC correctly, there will be no NACK transmission since the receiver has no information about transmitter as well as receiver addresses. Therefore, INARA cannot help performing the same as the conventional rate adaptation. However, any rate adaptation algorithm will not be effective in this case since the channel is very poor.

Rate increase ACK

While the NACK with noise type indication helps the transmitter not to decrease the transmission rate, the ACK frame contributes to rate increase. A successful frame transmission is made when the receiver decodes both the preamble and data correctly, leading the receiver to measure the current SNR. This motivates us to design the ACK frame to carry the information about SNR as well as rate increase. The receiver replies with a rate increase ACK (ACK_I) if the measured SNR is sufficient to support higher MCS level. Otherwise, it transmits a normal ACK (ACK_N). Considering there is no fast fading in the power line channel, this aggressive rate increase operates effectively.

On the other hand, in wireless environments, the SNR of a wireless channel rapidly fluctuates due to fast fading. Therefore, the rate increase right after the improved SNR may lead to the failure of the next frame transmission. In the auto rate fallback (ARF) scheme [47],

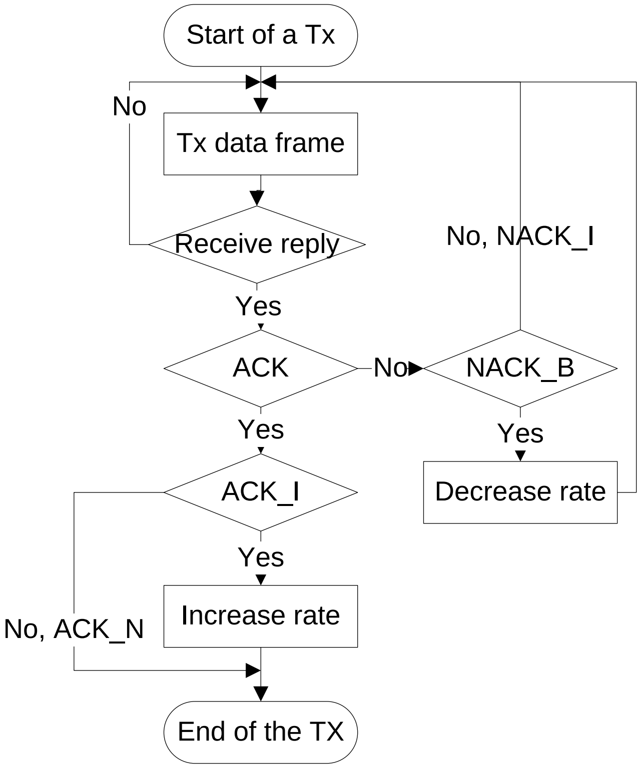

Figure 4.2: Transmitter Flow chart of INARA.

the transmitter is allowed to increase its rate after ten consecutive successful transmissions[7]. This approach is very conservative and has some problems in exploiting instantaneous channel improvement.

Figs. 4.2 and 4.3 show the flow chart of INARA in the transmitter and receiver point of view, respectively. As INARA uses one extra bit to indicate the status of NACK and ACK, it can be implemented easily in the HPAV standard. In this flow chart, we do not present

[7]The transmitter decreases its transmission rate with two consecutive transmission failures.

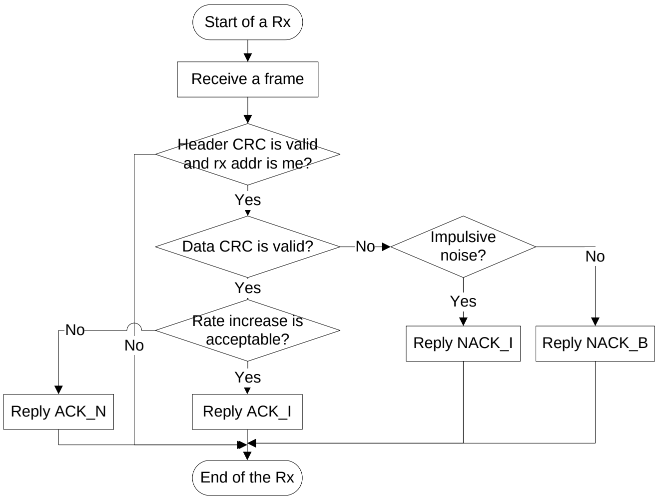

Figure 4.3: Receiver Flow chart of INARA. In INARA, the receiver returns the channel status to the transmitter by using ACK or NACK.

the CW increase algorithm of CSMA/CA and the packet dropping case for simplicity.

4.4.2 Adaptive CW Adjustment

To find a suboptimal CW size in real-time for throughput enhancement, we propose a heuristic adaptive CW adjustment algorithm. In this algorithm, the CCo collects information about the number of ACK/NACK receptions and the number of idle slots during each beacon period. Using this information, the CCo determines whether to increase or decrease the CW size, and broadcasts the adjusted CW size through the beacon frame, which is assumed robust enough to reach all the stations. Each station in the network replaces the current CW with new one. Fig. 4.4 shows the flow chart of our heuristic

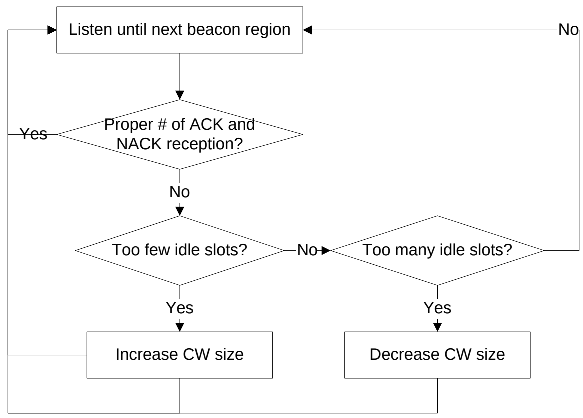

Figure 4.4: Flow chart of the adaptive CW adjustment algorithm. The CCo determines and broadcasts the new CW size.

CW adjustment algorithm where the predefined CW sets are { {7, 15, 31, 63}, {15, 31, 63, 127}, {31, 63, 127, 255}, {63, 127, 255, 511} }. The increase and decrease of CW indicate that the algorithm selects a set with larger and smaller CW size, respectively. It was found that four CW size sets are sufficient when there are less than 50 users in the network [44].

We set the threshold value for the number of successful transmissions[8] during a beacon period to 10. If there were less than 10 successful transmissions in the previous beacon period, the CCo counts the number of idle slots passed by. If it is smaller than 40, the CCo doubles the CW size. For a number larger than 80, the CCo decreases the CW size by half. Otherwise, the CW size remains the same. Here, the threshold values of 10, 40, and 80 were found through simulations.

[8]When the transmitter receives an ACK or a NACK, the CCo regards it as successful transmission since the adaptive CW adjustment only cares the collision

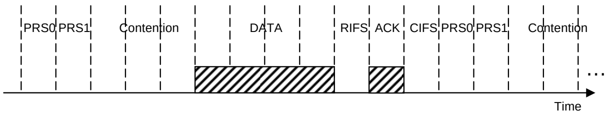

Figure 4.5: A transmission example. One transmission cycle if from PRS0 to CIFS. Except "Contention" and "DATA," the other parts have a fixed period of time.

We reason the threshold values with simple analysis. Fig. 4.5 depicts one successful data transmission of HPAV. We define the time for a successful transmission as

$$T_s = PRS0 + PRS1 + N\sigma + T_{frame} + RIFS + T_{ACK} + CIFS, \quad (4.1)$$

where PRS0, PRS1, σ, RIFS, T_{ACK} and CIFS denote the duration of PRS0, PRS1, an idle slot, response distributed spacing (RIFS), ACK and contention distributed spacing (CIFS), respectively. N and T_{frame} are a random variable denoting the number of idle slots before the transmission and one MAC frame transmission time, respectively. T_s is classified into fixed and variable periods of time. The fixed period of time consists of PRS0, PRS1, RIFS, ACK and CIFS which is 372.16 μsec as listed in Table 4.3, and the variable period of time is given by $N\sigma$ and T_{frame}. If the transmitter's queue is saturated, T_{frame} is 2640.16 μsec[9]. To get the duration for a random backoff, we assume a simple collision free scenario with only a pair of transmitter

problem.

[9]Commonly PLC systems use the maximum transmission unit for an MAC frame as time unit, so the transmission time for an MAC frame is fixed regardless of the transmission rate with saturated assumption.

and receiver in the network. An average number idle slots for one transmission in this simple network is 3.5 [44], resulting in the time for a successful transmission of 3137.76 μsec. Then, in one beacon period (33.33 msec), there are approximately 10.62 transmissions and 37.17 idle slots. The threshold value for the transmission, i.e. 10, comes from this result. If the number of transmissions is less than 10, the system considers the current CW size is not proper. However, even when the current CW size is appropriate to the network condition, there would be less than 10 transmissions because of randomness. To measure the suitability of the current CW size again, the system checks the number of idle slots within the beacon period. An appropriate number of idle slots in a beacon period is about 40, but to accommodate randomness, we use a range of 40 to 80 idle slots, which have been found through simulations.

We found the threshold values thorough simulations, but they still work properly in various conditions. In our analysis, we assume the network is saturated, i.e. all the nodes have traffic to send. When the network is not saturated, our proposed scheme runs well too since the network itself has small number of transmissions and few number of collisions. This means that without adaptively changing the CW size, our considered system operates well.

Table 4.3: System parameters for simulations

MaxFL	2501.12 μsec
FC transmission time	110.48 μsec
Average sounding time	2558.72 μsec
Beacon Period	33.33 msec
CIFS_AV	100 μsec
RIFS_AV	48.52 μsec
PRS0, PRS1	35.84 μsec
Backoff slot time	35.84 μsec
Response timeout	140.48 μsec
MAX_NACK_Retries	2
MAX_Collision_Retries	6

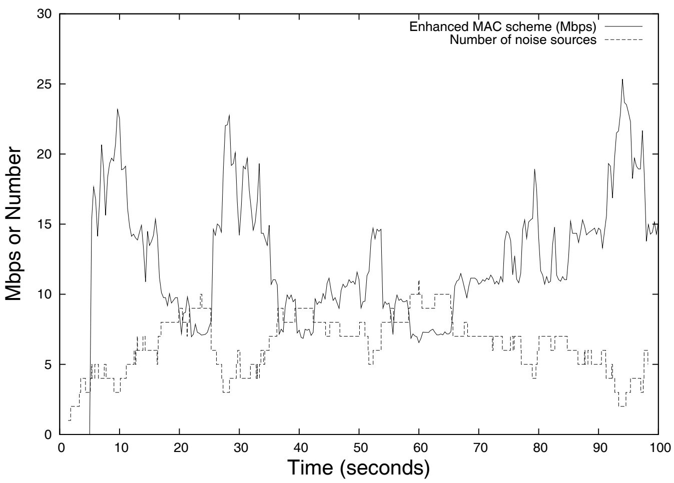

Figure 4.6: Time varying behaviors of the $M/M/\infty//M$ background noise model. The solid and dotted lines represent the throughput performance of the proposed enhanced MAC scheme and the number of noise sources turned on, respectively. In this simulation, there are five transmitters and all the traffics start at 5 [sec].

4.5 Performance Evaluation

We assume that our proposed scheme and the HPAV standard adapt to a stable channel condition somehow. The channel adaptation

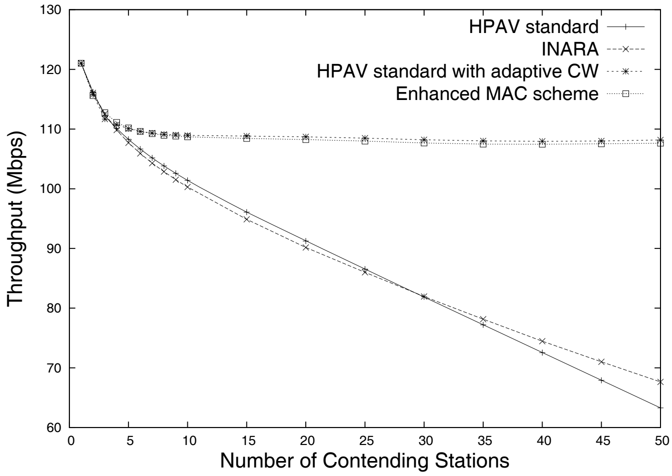

Figure 4.7: Throughput under ideal channel

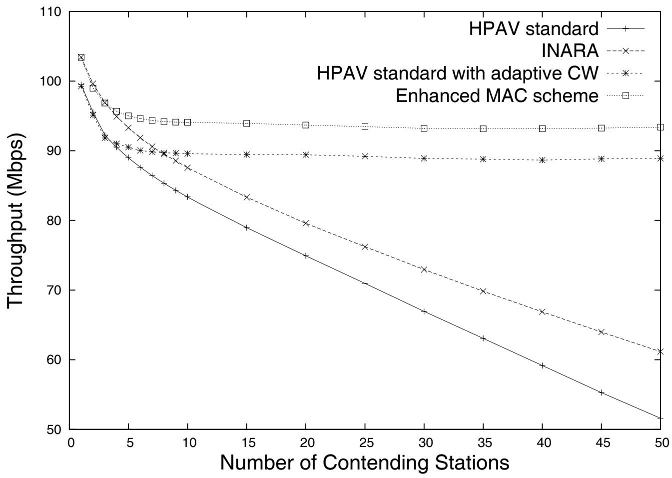

Figure 4.8: Throughput under impulsive noise

schemes in [51, 52] act the same as the HPAV standard in our simulations because they do not consider a dynamic changing channel status. Therefore, in this section, we compare our enhanced MAC scheme with the HPAV standard through simulations. In simulations,

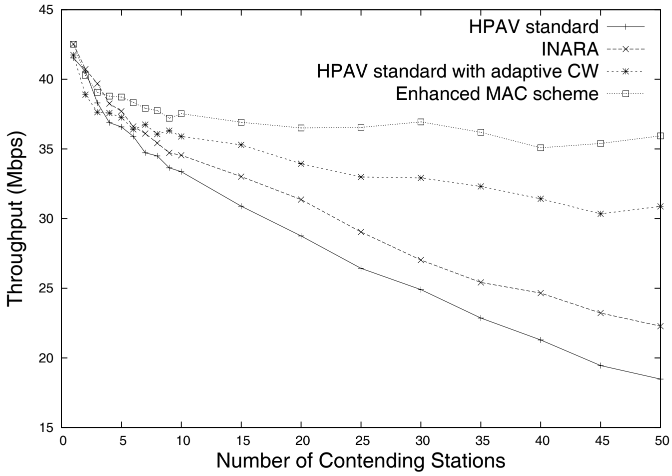

Figure 4.9: Throughput under background noise

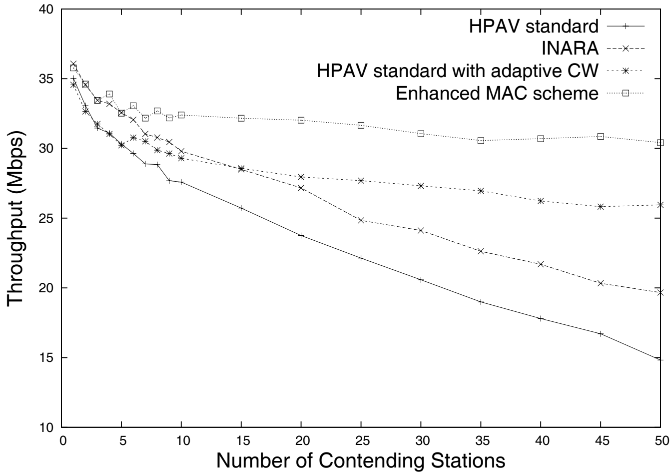

Figure 4.10: Throughput under impulsive and background noises

we use an event-driven simulator written in C++.

4.5.1 Simulation Settings

We consider a PLC network with one CCo and up to 50 stations. We assume the following three things. First, all the flows have the same priority. Second, every traffic is saturated, and the transmission time for each frame is set to MaxFL which is the maximum frame length defined in the HPAV standard. Third, all the stations are within one hop transmission range. According to the HPAV specification, the number of MCS levels is 14, and the maximum and minimum transmission rates are 150.19 Mbps and 9.856 Mbps, respectively. Table 4.3 summarizes the system parameters used in simulations [32].

4.5.2 Background Noise Model

We use an $M/M/\infty//M$ queueing model with $M = 14$ for the background noise. The average arrival rate λ at each noise source is 0.1 [arrival/sec] and the average service time $1/\mu$ is 10 [sec]. If all the noise sources are on, no transmission can be made successful. The maximum transmission rate is achievable when there is no noise source on.

Fig. 4.6 shows an example of the dynamic behaviors of a background noise environment. The average state duration time is 0.9 [sec], and the average number of noise sources is seven. It shows that a smaller number of noise sources on leads to a better channel quality as expected.

4.5.3 Saturation Throughput

We consider saturation throughput with the simulation time of 10,000 [sec], and use the hardly distributed noise scenario in Table 4.1. The two schemes of HPAV standard and INARA[10] use only the rate adaptation algorithm, so they lose some throughput with the number of contending stations.

In an ideal channel environment, a transmission error occurs only due to collision. Fig. 4.7 shows the throughput under an ideal channel according to the number of contending stations. The HPAV standard and our proposed MAC scheme distinguish collision error from channel error. The throughput performances of the HPAV standard and our scheme degrade with the number of contending stations due to the increased collision probability. With the adaptive CW adjustment, however, the throughput is virtually stable where there are more than five contending stations.

The throughput performance under the impulsive noise is shown in Fig. 4.8. The overall tendency is about the same as under the ideal channel. Our proposed MAC scheme outperforms the HPAV standard mainly owing to the proper rate adaptation. Fig. 4.9 shows the throughput performance under the background noise. The average throughput of each scheme is lowered due to the noise source, so the maximum achievable throughput is 43 Mbps. When there is only one transmitter, all the three schemes perform similarly since only the

[10] INARA is the same as proposed in [50]

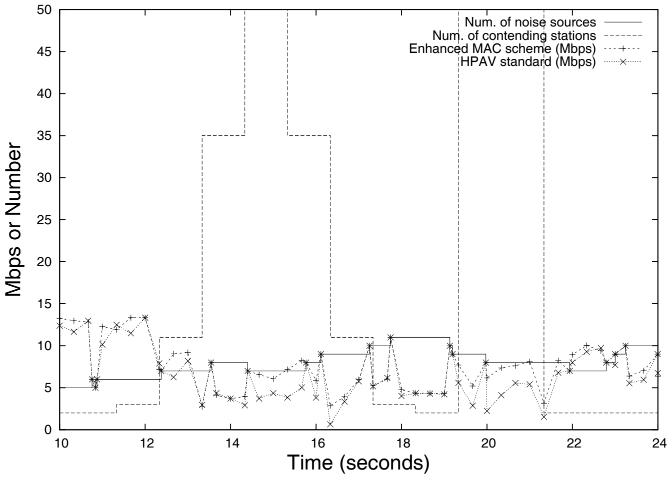

Figure 4.11: Throughput performance comparison of our proposed MAC scheme and the HPAV standard under impulsive and background noises. The solid and dotted lines represent the number of noise sources turned on and the number of contending stations, respectively. The dotted lines marked with plus and cross represent the system throughput performances of our proposed scheme and the HPAV standard, respectively.

background noise causes the transmission error.

The throughput performances under the impulsive and background noises, i.e., a more realistic scenario, are shown in Fig. 4.10. Both Figs. 4.10 and 4.9 display similar tendency. Our proposed MAC scheme achieves the highest throughput since it responds to the transmission failure reasonably well.

4.5.4 Dynamic Behaviors

Under the background and impulsive noise environment, we vary the number of contending stations according to the time. Fig. 4.11 shows the dynamic throughput performances of our proposed MAC scheme and the HPAV standard scheme. The 'y' axis represents both throughput and the number of currently active users. The number of active stations varies between 2 to 50 according to the time. Since our proposed MAC scheme is with the adaptive CW adjustment, it shows relatively stable throughput performance and obtains about 20% higher throughput than the HPAV standard scheme. It performs getting better with the number of contending stations as shown in Fig. 4.10. These results confirm that our proposed scheme outperforms the HPAV standard scheme for various scenarios.

4.6 Conclusion

The power line channel is different from the wireless channel as it has no fast fading. It has non-stationary impulsive and non-Gaussian background noises. In this paper, we proposed an enhanced MAC scheme for PLC and evaluated it via extensive simulations. To exploit the characteristics of the power line channel, we applied two algorithms to our MAC design: INARA and adaptive CW adjustment algorithms. INARA enables the transmitter to react to a transmission error properly by using one extra bit that indicates the status of ACK or NACK. The adaptive CW adjustment helps the transmitter to increase or decrease its transmission rate according to the network congestion level. The simulation results showed that our proposed

MAC scheme always outperforms the other competitive schemes under various scenarios. It can be easily implemented for any type of PLC standard since it reflects the genuine characteristics of the power line channel and requires only one extra bit from the reserved field.

Future work on this proposal can include the test bed implementation of our proposed scheme. Our proposed scheme can easily apply to a PLC modem by modifying the software algorithm on the top of PHY layer.

Chapter 5

Conclusions

In this dissertation, we design three different protocols that aim improving power line communications (PLC) performance.

Firstly, with the recent proliferation of interest in the smart grid, PLC is attracting attention again as an appropriate networking technology for an access network (AN) covering a regional area of power systems. A narrowband solution in PLC is appealing to the medium and low voltage distribution networks that demand applications of moderate data rates. Meanwhile opportunistic routing (OR) is a new routing paradigm that makes use of the broadcasting nature of the wireless channel. In this paper, we argued that, with the narrowband solution, OR can improve in routing performance by exploiting the penetrating characteristic of power line channels in PLC-AN. Then, we design a PLC customized OR, named PLC-OR, which basically uses single path route selection and simple ACK-based coordination.

It includes an algorithm to decide transmission rate, tone mapping, and forwarder set selection. Through simulations, it is shown that our proposed PLC-OR lowers the transmission time. The end-to-end delay is reduced by about 40% compared to the traditional sequential routing. A simple application of wireless OR to a PLC network has some gain over the traditional routing, but experiences delivery failure in some cases. Our future work is to develop a more enhanced OR scheme considering cooperative transmission.

Secondly, we proposed a new multiple access framework for PLC, that is, orthogonal frequency-division multiple access (OFDMA) carrier sense multiple access with collision avoidance (CSMA/CA). Our proposed OFDMA CSMA/CA divides the whole bandwidth into several subchannels and each node enters its favorable subchannel. In the framework, we formulated a sum of node utility maximization problem. The problem is divided into two sub-problem: the channel division and subchannel allocation problems. We proposed optimal and heuristic solutions of each problem. Simulation results showed that our proposed OFDMA CSMA/CA framework improves the throughput performance with proper settings of the number of subchannels and subchannel allocation. Our proposed heuristic algorithm generally follows well to the optimal algorithm with much lower complexity and feedback overhead.

Finally, we proposed an enhanced medium access control (MAC) scheme for PLC and evaluated it via extensive simulations. The power line channel is different from the wireless channel as it has no fast fading. It has non-stationary impulsive and non-Gaussian background noises. To exploit the characteristics of the power line channel, we applied two algorithms to our MAC design: impulse noise aware rate adaptation (INARA) and adaptive contention window (CW) adjustment algorithms. INARA enables the transmitter to react to a transmission error properly by using one extra bit that indicates the status of ACK or NACK. The adaptive CW adjustment helps the transmitter to increase or decrease its transmission rate according to the network congestion level. The simulation results showed that our proposed MAC scheme always outperforms the other competitive schemes under various scenarios. It can be easily implemented for any type of PLC standard since it reflects the genuine characteristics of the power line channel and requires only one extra bit from the reserved field.

To summarize, because of the unique characteristics of PLC, MAC and network layer protocols which are aware of these characteristics improve PLC system performance. Although this dissertation only covers three examples of the PLC-customized protocol, more investigations with the knowledge of power line channel are needed. This dissertation can be used as a guideline for the following PLC protocol research.

Bibliography

[1] R. Hledik, "How Green is the Smart Grid?" *The Electricity Journal*, vol. 22, no. 3, pp. 29-41, Apr. 2009.

[2] IEEE Std 1901-2010, *IEEE Standard for Broadband over Power Line Networks: Medium Access Control and Physical Layer Specifications*, 2010.

[3] G3-PLC: Open Standard for SmartGrid Implementation; http://www.maxim-ic.com/products/powerline/g3-plc/

[4] H. Liu, B. Zhang, H. Mouftah, X. Shen and J. Ma, "Opportunistic Routing for Wireless Ad Hoc and Sensor Networks: Present and Future Directions," *IEEE Communications Magazine*, vol. 47, no. 12, pp. 103-109, Dec. 2009.

[5] G. Bumiller, L. Lampe, and H. Hrasnica, "Power Line Communication Networks for Large-scale Control and Automation Systems," *IEEE Communication Magazine*, vol. 48, no. 4, pp. 106-113, Apr. 2010.

[6] M. Biagi and L. Lampe, “Location Assisted Routing Techniques for Power Line Communication in Smart Grids,” in Proc. *IEEE SmartGridComm*, Oct. 2010.

[7] M. Biagi, S. Greco1 and L. Lampe, “Neighborhood-Knowledge based Geo-Routing in PLC,” in Proc. *IEEE ISPLC*, Mar. 2012.

[8] “Pathloss as a Function of Frequency, Distance and Network Topology for Various LV and MV European Powerline Networks,” OPERA, Tech. Rep. D-05, 2005.

[9] S. Galli, A. Scaglione, and Z. Wang, “For the Grid and Through the Grid: The Role of Power Line Communications in the Smart Grid,” *Proceedings of the IEEE*, vol. 99, no. 6, pp. 998-1027, Jun. 2011.

[10] G. Bumiller, “Automated Channel and Performance Measurements for Narrowband MV- and LV-Power-Lines,” in Proc. *IEEE ISPLC*, Mar. 2007.

[11] B. Varadarajan, I.H. Kim A. Dabak, D. Rieken, and G. Gregg, “Empirical Measurements of the Low-frequency Power-line Communications Channel in Rural North America,” in Proc. *IEEE ISPLC*, Apr. 2011.

[12] K. Razazian, A. Kamalizad, M. Umari, Q. Qu, V. Loginov, and M. Navid, “G3-plc Field Trials in U.S. Distribution Grid: Initial Results and Requirements,” in Proc. *IEEE ISPLC*, Apr. 2011.

[13] IEEE: "Low-Frequency Narrow-Band Power Line Communications, munications," http://grouper.ieee.org/groups/1901/2/

[14] H.C. Ferrerira, L. Lampe, J. Newbury, and T.G. Swart, *Power Line Communications*. Wiley, 2010.

[15] *Power Systems Test Case Archive*, Univ. Washington. [Online]. Available: http://www.ee.washington.edu/research/pstca/

[16] Z. Yang, K. Zeng, and W. Lou, "FSA: A Fast Coordination Scheme for Opportunistic Routing," in Proc. *IEEE ICC*, Jun. 2009.

[17] K. Zeng, Z. Yang, and W. Lou, "Location-Aided Opportunistic Forwarding in Multirate and Multihop Wireless Networks," *IEEE Transactions on Vehicular Technology*, vol. 58, no. 6, pp. 3032-3040, Jul. 2009.

[18] K. Zeng, W. Lou, J. Yang, and D.R. Brown, "On Geographic Collaborative Forwarding in Wireless Ad Hoc and Sensor Networks," in Proc. *WASA*, Aug. 2007.

[19] R. Draves, J. Padhye, and B. Zill, "Routing in Multi-Radio, Multi-Hop Wireless Mesh Networks," in Proc. *ACM MobiCom*, Sep. 2004.

[20] http://www.homeplug.org, HomePlug PowerLine Alliance.

[21] F.J. Canete, J.A. Cortes, L. Diez, and J.T. Entrambasaguas, "Analysis of the Cyclic Short-term Variation of Indoor Power Line Channels," *IEEE Journal on Selected Areas in Communications*, vol. 24, no. 7, pp. 1327-1338, Jul. 2006.

[22] H. Kwon, H. Seo, S. Kim, and B.G. Lee, "Generalized CSMA/CA for OFDMA Systems: Protocol Design, Throughput Analysis, and Implementation Issues," *IEEE Transactions on Wireless Communications*, vol. 8, no. 8, pp. 4176-4187, Aug. 2009.

[23] D. Anastasiadou and T. Antonakopoulos, "Multipath Characterization of Indoor Power-line Networks," *IEEE Transactions on Power Delivery*, vol. 20, no. 1, pp. 90-99, Jan. 2005.

[24] D. Umehara, T. Hayasaki, S. Denno, and M. Masahiro, "Influences of Periodically Switching Channels Synchronized with Power Frequency on PLC Equipment," *Journal of Communications*, vol. 4, no. 2, pp. 108-118, Mar. 2009.

[25] S.-G. Yoon and S. Bahk, "Adaptive Rate Control and Contention Window Size Adjustment for Power Line Communication," *IEEE Transaction on Power Delivery*, vol. 26, no. 2, pp. 809-816, Apr. 2011.

[26] M.E.M. Campista, L.H.M.K. Costa, and O.C.M.B. Duarte, "Improving the Multiple Access Method of CSMA/CA Home Networks," in *Proc. IEEE CCNC*, Las Vegas, USA, Jan. 2006.

[27] H. Kwon, S. Kim, and B.G. Lee, "Opportunistic Multi-channel CSMA Protocol for OFDMA Systems," *IEEE Trans. Wireless Commun.*, vol. 9, no. 5, pp. 1552-1557, May 2010.

[28] S.W. Oh, R. Mo, Y. Ma, Y. Zeng, and A.A.S. Naveen, "Cognitive Power Line Communication System for Multiple Channel Access," in Proc. *IEEE ISPLC*, Dresden, Germany, Mar.-Apr. 2009.

[29] R. Dong, M. Ouzzif, S. Saoudi, "A Cognitive Cross-Layer Resource Allocation Scheme for In-Home Power Line Communications," in Proc. *IEEE ICC*, May 2010.

[30] R. Dong, M. Ouzzif, S. Saoudi, "A Two-dimension Opportunistic CSMA/CA Protocol for OFDMA-based In-home PLC Networks," in Proc. *IEEE ICC*, Jun. 2011.

[31] M.Y. Chung, M.-H. Jung, T.-J. Lee, and Y. Lee, "Performance Analysis of HomePlug 1.0 MAC with CSMA/CA," *IEEE Journal on Selected Areas in Communications*, vol. 24, no. 7, pp. 1411-1420, Jul. 2006.

[32] HomePlug AV System Specifications, ver. 1.0.1, Mar. 2007.

[33] HomePlug AV2 System Specifications, ver. 1.0.0, Jan. 2012.

[34] H.A. David and H.N. Nagaraja, *Order Statistics* (3rd Edition). Wiley, New Jersey, 2003.

[35] F.J. Canete, J.A. Cortes, L. Diez, and J.T. Entrambasaguas, "A Channel Model Proposal for Indoor Power Line Communications," *IEEE Communications Magazine*, vol. 49, no. 12, pp. 166-174, Dec. 2011.

[36] A. Sang, X. Wang, M. Madihian, and R.D. Gitlin, "Coordinated Load Balancing, Handoff/cell-site Selection, and Scheduling in Multi-cell Packet Data Systems," *Springer Wireless Networks*, vol. 14, no. 1, pp. 103-120, Jan. 2008.

[37] T. Bu, L. Li, and R. Ramjee, "Generalized Proportional Fair Scheduling in Third Generation Wireless Data Networks," in Proc. *IEEE INFOCOM*, Apr. 2006.

[38] IEEE 802.11 Working Group for Wireless Local Area Networks. [Online]. Available: http://grouper.ieee.org/groups/802/11

[39] IEEE 802.15 Working Group for Wireless Personal Area Networks. [Online]. Available: http://grouper.ieee.org/groups/802/15

[40] High-Definition Powerline Communication, http://www.hd-plc.org

[41] Universal Powerline Alliance, http://www.upaplc.org

[42] HomePlug 1.0 Specification, HomePlug Powerline Alliance, Jun. 2001.

[43] K. Tripathi, J.-D. Lee, H. Latchman, J. McNair and S. Katar, "Contention Window based Parameter Selection to Improve Powerline MAC Efficiency for Large Number of Users," in *Proc. IEEE ISPLC*, Orlando, USA, Mar. 2006.

[44] S.-G. Yoon, J. Yun, and S. Bahk, "Adaptive Contention Window Mechanism for Enhancing Throughput in HomePlug AV Networks," in *Proc. IEEE CCNC*, Las Vegas, USA, Jan. 2008.

[45] M. Zimmermann and K. Dostert, "Analysis and Modeling of Impulsive Noise in Broad-band Powerline Communications," *IEEE Transactions on Electromagnetic Compatibility*, vol. 44, no. 1, pp. 249-258, Feb. 2002.

[46] Y.-H. Kim, H. Song, J.-H. Lee, and S.-C. Kim, "Wideband Channel Measurements and Modeling for In-house Power Line Communications," in *Proc. IEEE ISPLC*, Athens, Greece, Mar. 2002.

[47] A. Kamerman and L. Monteban, "WaveLAN-II: a High-performance Wireless LAN for the Unlicensed Band," *Bell Labs Technical Journal*, vol. 2, no. 3, pp. 118-133, Aug. 1997.

[48] G. Holland, N. Vaidya, and P. Bahl, "A Rate-adaptive MAC Protocol for Multi-hop Wireless Networks," in *Proc. ACM MOBICOM*, Rome, Italy, Jul. 2001.

[49] J. Kim, S. Kim, S. Choi, and D. Qiao, "CARA: Collision-aware Rate Adaptation for IEEE 802.11 WLANs," in *Proc. IEEE INFOCOM*, Barcelona, Spain, Apr. 2006.

[50] S.-G. Yoon and S. Bahk, "Rate Adaptation Scheme for Power Line Communication," in *Proc. IEEE ISPLC*, Jeju Island, Korea, Apr. 2008.

[51] S. Katar, B. Mashbum, K. Afkhamie, H. Latchman, and R. Newrnan, "Channel Adaptation based on Cyclo-Stationary Noise Characteristics in PLC Systems," in *Proc. IEEE ISPLC*, Florida, USA, Mar. 2006.

[52] K.-H. Kim, H.-B. Lee, Y.-H. Kim, and S.-C. Kim, "Channel Adaptation for Time-varying Powerline Channel and Noise Synchronized with AC Cycle," in *Proc. IEEE ISPLC*, Dresden, Germany, Mar.-Apr. 2009.

[53] A. Goldsmith, *Wireless Communications*, New York: Cambridge University Press, 2005.

[54] M. Zimmermann and K. Dostert, "A Multipath Model for the Powerline Channel," *IEEE Transactions on Communications,* vol. 50, no. 4, pp. 553-559, Apr. 2002.

[55] D. Middleton, "Statistical-physical Model of Electromagnetic Interference," *IEEE Transactions on Electromagnetic Compatibility,* vol. EMC-19, no. 3, pp. 106.126, Aug. 1977.

[56] L. Kleinrock, *Queueing Systems*, vol. 1. New York: Wiley, 1975.

[57] H. Hrasnica, A. Haidine, and R. Lehnert, "Reservation MAC Protocols for Powerline Communications," in *Proc. IEEE ISPLC*, Malmö, Sweden, Apr. 2001.

초 록

전력선을 매질로 하여 통신을 하는 전력선 통신은 이미 구축된 전력망을 사용한다는 장점이 있다. 최근 들어 스마트 그리드라 칭하는 차세대 전력망에서 노후한 전력망을 최신의 에너지 기술과 정보통신 기술을 통해 교체하려는 움직임이 있다. 스마트 그리드가 등장함에 따라 전력선 통신에 대한 관심이 고조되고 있다. 전력선 통신은 액세스 네트워크와 댁내 망 두 가지 방향으로 발전되어 왔다. 액세스 네트워크를 위한 전력선 통신은 인터넷을 전력선 통신으로 사용하려는 높은 데이터 전송률을 필요로 하는 기술과 제어 정보를 주고받을 용도의 낮은 데이터 전송률과 긴 전송거리를 필요로 하는 기술이 있다. 홈네트워크의 백본 네트워크로 사용하려는 목적인 댁내 망을 위한 전력선 통신은 매우 높은 데이터 전송률을 요구한다. 이와 같은 요구 사항을 맞추기 위해 전력선 매질의 특성을 인지하는 전력선 통신 프로토콜의 디자인이 필요하다.

본 논문에서는 전력선 통신의 성능을 향상시키는 세 가지 프로토콜을 설계한다. 첫째로, 스마트 그리드에서 사용되는 전력선 액세스 네트워크에서의 라우팅 알고리즘을 설계한다. 협대역 주파수를 사용하는 전력선 통신의 신호는 전력기기를 관통하는 특성이 있기에 기회적 라우팅(OR, opportunistic routing)을 적용할 수 있다. 본 연구에서는 전력선 통신 하에서의 OR의 적용 가능성을 조사해본 후 전력선 통신 맞춤 OR(PLC-OR)을 설계한다. 제안하는 PLC-OR은 위치정보를 활용하여 경로를 설정한다. 본 연구에서는 단위시간 당 비트-미터 극대화 문제를 만들고 그 문제를 분산 방식으로 해결하는 알고리즘을 제시한다. 모의실험을 통해 제안하는 PLC-OR이 기존의 순차적인 라우팅 기법에 비해 동일한 안정성을 가지면서 송신자와 수신자 사이의 패킷 전송시간을 줄여주는 것을 확인하였다.

둘째로, 직교 주파수 분할 다중 접근(OFDMA, orthogonal frequency-division multiple access)을 사용하는 전력선 통신에서 반송파 감지 다중 접근/충돌 회피(CSMA/CA, Carrier Sense Multiple Access with Collision Avoidance) 기법을 제안한다. 상대적으로 변화가 적고 AC 주파수 변화와 동기화된 전력선 채널의 특성을 이용하면 전력선 통신에서의 OFDMA는 임의 접근 방식에서도 다중 사용자 다이버시티를 얻을 수 있다. 본 연구에서는 제안하는 OFDMA CSMA/CA 프레임워크 하에서의 사용자 유틸리티 합을 극대화시키는 문제를 만들었다. 제시한 문제는 전체 대역을 몇 개의 부대역으로 나눌 것이냐를 정하는 문제와 각 사용자를 어떤 부대역에 할당하는 것에 대한 문제로 나누어 푼다. 이 문제들에 대하여 최적의 해와 근사 해를 구하는 방법을 제시한다. 다양한 모의실험을 통해 제안하는 알고리즘이 단일 채널 CSMA/CA에 비해 시스템 유틸리티를 향상시키는 것을 보였다.

마지막으로, 전력선 임펄스 잡음과 배경 잡음을 고려한 매체 접근 제어(MAC, medium access contorl) 프로토콜을 설계한다. 제안하는 MAC은 적응적 전송률 조절 기법과 경쟁 윈도우 조절 기법으로 구성되어 있다. 적응적 전송률 조절 기법에서는 수신자가 데이터 전송이 실패했을 때 그 이유를 한 비트 정보로 NACK 패킷을 통해 송신자에게 전달한다. 송신자는 그 정보를 가지고 적절하게 전송률을 조절한다. 또한 현재 네트워크의 사용자 수를 고려한 적응적 경쟁 윈도우 조절 방식도 제안한다. 모의실험을 통해 다양한 환경에서 제안하는 MAC 기법이 네트워크 수율을 올리는 것을 보였다.

주요어 : 전력선 통신, 스마트 그리드, 최적화, 기회적 라우팅, OFDMA, CSMA/CA, 매체 접근 제어, 전송률 조절, 경쟁 윈도우

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지난 6년 반 동안의 대학원 생활을 되돌아 볼 때 하나님을 제외하고는 할 말이 별로 없음을 다시 생각하게 됩니다. 석사 2년차 때 예수님을 구주로 영접한 후 삶의 동반자 되시고, 보호하시며 어려울 때 위로해주신 하나님께 감사드립니다.

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캠퍼스 QT 모임 멤버들인 원보, 진우, 지호, 태섭, 태준에게도 감사를 전합니다. 이들과 함께 하기에 대학원 생활을 더욱 풍성히 보낼 수 있었습니다. 하나교회 공동체인 상훈, 성구, 형수, 지훈, 성한, 정훈이가 함께하는 스룹바벨 셀과 상래, 복유, 태영, 예찬, 태진, 태훈 철헌, 동렬, 준우, 대한이가 있는 세븐일레븐 셀에 감사드립니다. 이들의 기도와 지지가 큰 힘이 되어주었습니다. 이성열 목사님과 하순회 교수님, 강찬구 전도사님의 영적인 후원에 감사를 전합니다.

사랑하는 아버지께서는 아들이 학위 과정을 마무리하는 것을 함께하시진 못하셨지만, 그 넘치는 사랑 기억하며 감사를 드립니다. 아들에게 참으로 많은 기도와 사랑으로 후원해주신 어머니, 항상 그 은혜 기억하며 살겠습니다. 삶의 큰 틀을 늘 함께한 사랑하는 형과 동생 그리고 매부에게도 감사를 전합니다. 사위를 아들처럼 여겨 주셔서 많은 사랑을 베풀어 주시는 장모님, 처제, 가족들 감사합니다.

늘 남편을 지지해주고 많은 것을 함께 하였고 앞으로 평생을 같이 걸어갈 돕는 배필인 사랑하는 아내에게 사랑과 감사를 전합니다.

이제 사회로의 디딜 한 발을 눈앞에 두었습니다. 혼자서는 할 수 있는 일이 참 적지만, 도움을 주고받을 수 있는 좋은 분들이 많기에 그리고 무엇보다 저를 가장 잘 아시고 모든 것을 공급해주시며 사랑해주시는 하나님께서 동행하시기에 용기를 잃지 않을 수 있습니다. 하나님 사랑합니다.

잠언 9:10
주님을 경외하는 것이 지혜의 근본이요, 거룩하신 이를 아는 것이 슬기의 근본이다.

2012년 7월,
윤성국 드림.