Multichannel CSMA/CA Protocol for OFDMA-Based Broadband Power-Line Communications

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***Abstract*—Channel response and noise in the in-home power-line channel are time varying, and show periodic patterns since electric devices, which are major noise sources, synchronously run with the ac-line cycle. Using the relatively stable channel characteristic of the power line, orthogonal frequency-division multiple access (OFDMA) schemes in power-line communications (PLCs) can achieve multiuser diversity gain even in random access. In this paper, we propose a carrier-sense multiple access with a collision-avoidance (CSMA/CA) protocol for OFDMA-based broadband PLC. To achieve the maximum diversity gain, we formulate a utility maximization problem for our considered framework. Then, we solve this problem by dividing it into two subproblems. The first one divides the whole bandwidth into a certain number of subchannels appropriately, and then the second one allocates a subchannel to each node according to the channel condition. To solve each subproblem, we first consider optimal algorithms and then heuristic algorithms to overcome the complexity. Through extensive simulations, we show that our proposal greatly improves the overall system utility compared to the single-channel CSMA/CA scheme. The performance improvement of our proposal over the single channel scheme is mainly achieved by lowering collision probability and exploiting multiuser diversity.**

***Index Terms*—Carrier-sense multiple access with collision avoidance (CSMA/CA), multiuser diversity, network utility maximization, orthogonal frequency-division multiple access (OFDMA), power-line communications (PLCs), subchannel allocation.**

I. INTRODUCTION

POWER-LINE communication (PLC) systems are potential candidates in many applications, such as outdoor internet access, inhome, in-vehicle, and smart grid. Among those, inhome broadband PLC aims to provide a backbone network for a home network system. To accommodate the traffic demand explosively increasing in robust home networking, inhome PLC should provide high bandwidth and good quality of service (QoS). For instance, HomePlug AV2 (HPAV2) [2], which is one of newly developed broadband PLC standards, uses a very wide frequency band, that is, 2–85 MHz, and a hybrid medium-access control (MAC) of time-division multiple access (TDMA) and CSMA/CA to support various QoS requirements, that is, best effort and prioritized QoS. This enables gigabit-class transmission for multiple HDTV streaming and online gaming. HPAV2 adopts state-of-the-art techniques for wireless communications, such as orthogonal frequency-division multiplexing (OFDM) and multiple-input and multiple-output (MIMO) with beamforming, to achieve high throughput performance.

To apply new wireless communication techniques to PLC, understanding the unique characteristics of the power-line channel is important. The power line is a wired communication medium, but its channel characteristics are very different from the conventional wired media, such as telephone and Ethernet lines, because it is not designed for communications. Channel response and noise in the inhome power-line channel are time varying, and show periodic patterns since electric devices, which are major noise sources, synchronously run with the ac line cycle. Some characteristics of the power-line channel are similar to those of the wireless channel, but their details are different. For instance, both power line and wireless channels are fading channels and have several frequency notches. Frequency notches in the power-line channel, however, do not fluctuate very much because of their static topology, while those in the wireless channel changs frequently due to their topology dynamics.

Recently, a new carrier-sense multiple access with collision avoidance (CSMA/CA) protocol using orthogonal frequency-division multiple access (OFDMA) has been discussed for wireless communications [3]–[5]. In wireless OFDMA CSMA/CA protocols, the entire bandwidth is divided into multiple subchannels, and more than one subchannel can be used at the same time, resulting in reduced collision probability. Owing to the relatively stable characteristic of the power-line channel and the use of several independent subchannels in OFDMA CSMA/CA, PLC systems can achieve multiuser diversity gain even in CSMA/CA operation. To this end, we propose an OFDMA-based multichannel CSMA/CA protocol for broadband PLC systems that aims to achieve high throughput by exploiting the multiuser diversity.

Our proposal divides the entire bandwidth into multiple subchannels to reduce collision probability and allocates each node an appropriate subchannel to maximize the multiuser diversity. To do this, we first formulate this as a problem of maximizing the sum of node utilities. Then, we divide the problem into two subproblems: the channel-division subproblem and subchannel allocation subproblem. To solve these subproblems, we consider optimal and heuristic solutions and investigate their performances through simulations. Due to reduced collision prob-

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ability and increased multiuser diversity gain, our multichannel CSMA/CA outperforms the conventional single channel one in PLC networks.

The rest of this paper is organized as follows. We first review the related work for the power-line channel and newly developed multiple access schemes in Section II. Then, we propose our multichannel CSMA/CA protocol for OFDMA-based broadband PLC and formulate the problem in Section III. Sections IV and V present algorithms to solve this problem. After evaluating our proposal in Section VI, we conclude this paper in Section VII.

II. RELATED WORK

A. Power-Line Channel

The power-line channel has a frequency-selective characteristic [6]. Since there are many branches and taps in a power network, the transmitting signal is split so that the receiver receives multiple signals along with time differences, which makes the power-line channel frequency selective. In addition, since each power-line route between a pair of transmitters and receivers has different impedances and a various number of taps, each power-line channel has its own parameters, such as frequency-dependent response and rms delay spread.

There are two major noises in the power-line channel. One is the background noise from low-power noise sources, and the narrowband noise from wireless or wired sinusoidal signals. This type of noise shows a short-term time-varying behavior, but it shows periodicity because noise sources are normally synchronous with the main ac frequency [7]. This noise is relatively stable and can be regarded as stationary for several minutes or even hours [8]. The other one is the impulsive noise generated by electrical appliances, and it severely affects the communication signals [8].

Many researchers have investigated cancelling out the impulsive noise by using error-correcting codes with automatic repeat request, channel estimation, and impulse detection and iterative noise cancellation [1], [2], [9], [10]. Since our work does not deal with the physical layer, we assume that a proper impulsive noise cancellation scheme in the physical layer is applied and each node is aware of the periodic time-varying channel response. So it is possible to assume that the channel is stable for several minutes or even hours.[1]

B. OFDMA CSMA/CA

Thanks to the advantage of OFDMA, communication systems can use a wide frequency band such as that greater than 10 MHz. To use the broadband medium efficiently, multichannel MACs have been proposed in [11] and [12]. And the CSMA/CA protocol has been proposed to control the shared medium in an efficient and distributed manner. In a recent study [3], Kwon *et al.* argued that combining the two techniques can be a good approach to use the wireless channel more efficiently. In OFDMA, a node can obtain the status of each subcarrier with a single fast Fourier transform (FFT) processing the received OFDMA symbol. Using this, they designed a multichannel MAC called the OFDMA CSMA/CA protocol where each transmitter contends with others over many subchannels, leading to reduced collision probability.

Moreover, the authors in [4], have developed their scheme as an opportunistic multichannel CSMA/CA protocol. In this scheme, the multiuser diversity gain was achieved by scheduling each node to transmit on its favorable subchannel, assuming the channel is stationary. However, in wireless systems, the stationary channel assumption is not generally acceptable.

Inspired by the multiuser diversity gain obtained from subchannelization in the OFDMA system, several investigations [13]–[15] have been done for PLC networks. Oh *et al.* [13] proposed a cognitive power-line communication (CPLC) system which allows a secondary node to reuse unused frequency bands of a primary node. A maximum of two nodes can transmit simultaneously in the CPLC system. In [14], the authors proposed a heuristic subchannel allocation scheme for the OFDMA CSMA/CA protocol without considering subchannel division and optimal solutions. A 2-D opportunistic CSMA/CA protocol was proposed in [15] to exploit the multiuser diversity gain. However, their scheme shows severe temporal unfairness according to each node's channel state.

All of the previous research on OFDMA CSMA/CA protocols did not properly investigate the negative effect of subchannelization, such as increased header overhead. Since subchannels are created by dividing the entire spectrum into smaller pieces, the number of required OFDMA symbols for header transmission is increased, resulting in low data-transmission throughput. There is an in-depth discussion about the subchannelization effect in Section III-B.

III. MULTICHANNEL CSMA/CA FOR OFDMA-BASED BROADBAND PLC

Our proposed multichannel CSMA/CA protocol has two advantages over the conventional CSMA/CA protocol. First, the collision probability in the multichannel CSMA/CA protocol is lower since the number of contending nodes in each subchannel has decreased [16], [17]. Second, our proposal can exploit the multiuser diversity gain by allocating each node its favorable subchannel. This is a main difference between the wireless OFDMA CSMA/CA protocol and our proposed multichannel CSMA/CA protocol for PLC. The wireless OFDMA CSMA/CA system creates a subchannel by spreading it over the entire frequency band to average out its randomness to overcome the fast fading characteristic of the wireless channel [3]. Different from this, our proposal allocates a particular frequency band to a subchannel to achieve the multiuser diversity gain since the power-line channel shows relatively stable channel response.

A. System Model

We consider an inhome power-line network consisting of N nodes. It is assumed that all of the nodes in the network have an infinite number of packets in their queues and that the system uses the HPAV MAC protocol [1], [2]. Between the TDMA and the CSMA/CA in the HPAV hybrid MAC protocol, our proposed

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[1] The period of several minutes is a very long time scale from the viewpoint of MAC-layer design.

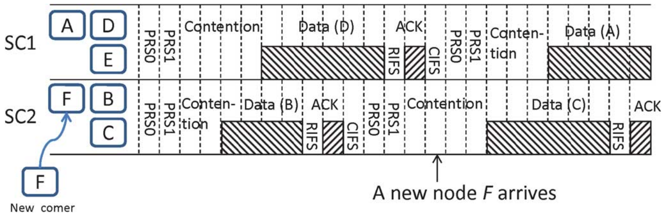

Fig. 1. Example of our multichannel CSMA/CA protocol operation. In this example, there are two subchannels and five nodes, and a new node arrives. Each node is allocated a subchannel and independently performs the CSMA/CA protocol on the allocated subchannel. Newcomer F is initially allocated subchannel 2.

scheme focuses on the CSMA/CA part[2] only. Each HPAV network has a special node, called the central coordinator (CCo), which takes charge of the network control. We also assume that channel responses between nodes are relatively stable for several minutes and each transmission pair knows their channel gain through a channel estimation scheme, such as the sounding method in the HPAV standard [1], [2].

The conventional PLC CSMA/CA protocol uses the entire bandwidth as a single contending channel while our proposal has several contending subchannels. Our proposal divides the entire frequency band into M subchannels, each of which consists of concatenated subcarriers to exploit the multiuser diversity gain. In our framework, the CSMA/CA protocol independently operates on each subchannel, and each node is allocated a subchannel in a centralized or distributed manner.

Fig. 1 shows a sample operation of our multichannel CSMA/CA protocol. One transmission cycle of the HPAV CSMA/CA protocol is composed of two priority resolution slots (PRSs), contention, data transmission, response distributed spacing (RIFS), ACK transmission, and contention distributed spacing (CIFS) [18]. In the considered example, subchannels 1 and 2 show similar signal-to-noise ratio (SNR) gains to the new node F. When the node F arrives, there have been three and two nodes in subchannels 1 and 2, respectively. So node F is allocated subchannel 2 to achieve higher throughput by the centralized controller or its own decision.

B. Problem Formulation

Our objective is to maximize the sum utility of nodes by using an appropriate number of subchannels and allocating a proper 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 that is equal to 1 when node i is associated with subchannel j, and 0 otherwise.

Then, we can formulate the problem as

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

where R_i represents the throughput of node i, expressed as

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

where $r_{i,j}$ is the feasible PHY rate of node i on subchannel j, and N_j is the number of nodes on subchannel j, that is, $N_j = \sum_{i=1}^{N} I_{i,j}$. Here, $S(n,m)$ denotes the saturated throughput of the CSMA/CA protocol for n nodes and m subchannels, which is a time fraction of the successful data transmission. The reason for using N_j is for each node on subchannel j to equally share the successful data-transmission period from the long-term perspective, considering the saturated traffic assumption and the long-term fairness of the CSMA/CA protocol.

Using the results in [16], we have

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

where $P_{tr}(n)$ and $P_s(n)$ are the probabilities that at least a node transmits and that a node successfully transmits in the case of n nodes, respectively. $T_D(m)$, δ, T_s, and T_c denote the data-transmission time, idle slot time, the required time for successful transmission, and the wasted time due to a frame collision, respectively. For successful transmission, the required time is given as $T_s = T_H(m) + T_D(m) + T_{\text{RIFS}} + T_{\text{ACK}} + T_{\text{CIFS}}$ where they represent the header transmission time, data-transmission time, RIFS time, ACK transmission time, and CIFS time, respectively.

The maximum transmission time of a frame is $T_{\max}$ in the HPAV specification. Under the saturated traffic condition, a transmission time of a frame, that is, $T_H(m) + T_D(m)$, is always $T_{\max}$, resulting in constant T_s. However, $T_H(m)$ and $T_D(m)$ are functions of the number of subchannels. PHY and MAC headers convey the information about source and destination addresses, frame length, as well as modulation and coding scheme (MCS) level. These transmissions use the whole bandwidth and the robust MCS level to protect the header information. This means that the number of symbols for the header transmission should be increased by M fold to maintain the same level of robustness since the number of subcarriers in each subchannel is decreased by a factor of $1/M$. In other words, T_H increases with M while T_D decreases. We have $T_D(m) = T_{\max} - T_H(m)$ and $T_H(m) = m \cdot T_H$, where T_H is the header transmission time in a single channel environment.

The constraint in $(\mathbf{P})$ indicates that each node should be allocated only one subchannel. As the utility function, we choose $U(R_i) = \log R_i$ to balance throughput and fairness among nodes. The problem $(\mathbf{P})$ is a mixed-integer programming problem which is generally known to be NP-hard. To solve this, we divide it into two subproblems and conquer them one by one. The first subproblem is for subchannelization (selecting M) and the next one for subchannel allocation (selecting $\mathbb{I}$).

C. Implementation Issues

The OFDMA system should use a sufficiently long cyclic prefix (CP) duration to avoid intersymbol interference (ISI) while keeping the orthogonality between subcarriers [3]. The use of CP helps to evade intercarrier interference (ICI) as well

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[2] The CSMA/CA protocols of HPAV and HPAV2 are backward compatible with each other.

as ISI. Since the OFDMA CSMA/CA protocol allows more than one node to transmit simultaneously, 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 given as

$$T_{\mathrm{cp}} > \Delta T_d^{\max} + \Delta T_p^{\max} \tag{2}$$

where T_{cp}, $\Delta T_d^{\max}$, and $\Delta T_p^{\max}$ 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 μs [19], which is not long enough to satisfy the condition (2). Therefore, it should be set longer to be used. Fortunately, HPAV can use the OFDMA CSMA/CA protocol without modifying CP duration due to the following three reasons. First, the CP duration in HPAV is much longer than that in the wireless local-area network (WLAN), that is, 10.52 μs [1]. Second, the ac line cycle can be the reference clock, so the time difference due to the clock drift is lowered. Finally, the clock drift requirement of HPAV is ±25 ppm, so the maximum time difference due to the clock drift between nodes in an ac line cycle is $\Delta T_d^{\max} = 2 \times 1/60 \times 25\ \mathrm{ppm} = 0.83$ μs, and that due to the propagation delay is $\Delta T_p^{\max} = 2$ μs at most. Therefore, the CP duration in HPAV is sufficiently long enough to satisfy the orthogonality condition (2).

IV. CHANNEL-DIVISION PROBLEM

This section solves the first problem of channel division which is performed at the CCo. Our objective is to maximize the sum utility of nodes by dividing the entire channel into multiple subchannels. To achieve this, we consider two types of solutions: One is an optimal but impractical numerical solution, and the other is a simple heuristic solution.

A. Numerical Solution

For subchannelization, there are two strengths and one weakness concerned with R_i. The first advantage is that with the number of subchannels M, the multiuser diversity gain increases since each node has a greater chance to be allocated its favorable subchannel. The second advantage is that with M, the collision probability lowers because there are a smaller number of contending nodes in each subchannel. The weakness is the increase in the header transmission time with M. Therefore, finding an optimal number of subchannels is important.

We define a subchannel diversity gain $G(\cdot)$, which is a function of the number of subchannels. This motivates us to find an optimal number of subchannels m^* that maximizes $G(\cdot)$. For an m subchannel environment, each node i has $R_i^m = \sum_{j=1}^{m} I_{i,j} r_{i,j} (S(N_j, m)/N_j)$ while for a single channel environment, each node has $R_i = \sum_{j=1}^{m} r_{i,j}(S(N,1)/N)$. The diversity gain of using m subchannels over a single channel is defined as $G(m) = \mathbb{E}[R_i^m]/\mathbb{E}[R_i]$, where $\mathbb{E}[\cdot]$ represents the expectation operator. Then, the following lemma leads us to obtain m^* easily.

Lemma 1: If $r_{i,j}$'s are i.i.d., $G(m)$ is a concave function of the number of subchannels m.

Proof: With the i.i.d. assumption of $r_{i,j}$, we obtain $\mathbb{E}[R_i] = m\mathbb{E}[r_{i,j}](S(N,1)/N)$ and $\mathbb{E}[R_i^m] = d(m)\mathbb{E}[r_{i,j}](S(\overline{N},m)/\overline{N})$, where $d(\cdot)$ denotes channel allocation diversity gain. Then, we have

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

Let us investigate the characteristics of $d(m)$ and $S(n,m)$. Y_k denotes a random variable that chooses 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 $F_k(y) = P[(X_1 \le y) \cap (X_2 \le y) \cap \cdots \cap (X_k \le y)]$. 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 given as $d(m)\mathbb{E}[r_{i,j}] = \mathbb{E}[Y_m]$, where $X_1 = r_{i,1}$, $X_2 = r_{i,2}, \ldots$, and $X_m = r_{i,m}$. According to the order statistics in [20], $d(m)$ is an increasing and concave function of m. Also, since $r_{i,j}$ is a discrete random variable, $d(m)$ is an infinitely differentiable function.

Regarding $S(n,m)$, it is assumed that the impact of the collision probability is negligible since our considered system does not cover more than 20 nodes. The overhead due to the increased number of header data symbols increases linearly with m. Therefore, $S(n,m)$ can approximately be an affine function of m in [0, 1].

Since $\overline{N}$ is the average number of nodes in one subchannel, we have $\overline{N} = N/m$ under the assumption of i.i.d. channel response. Finally, we have $G(m) = d(m)S(\overline{N},m)/S(N,1)$. Since $S(N,1)$ is a constant positive real number, we have the second derivative of $G(m)$ as

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

Since $d(m)$ is an 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 of m. Therefore, we have $G''(m) < 0$, which means $G(m)$ is a concave function. ■

From this Lemma and the gradient method, we can easily find an optimal number of subchannels. However, the i.i.d. assumption of $r_{i,j}$ does not hold in power-line environments since the power-line channel state generally depends on each node's location and allocated subchannel [21]. Therefore, the system should know all of the distributions of $r_{i,j}$'s and their joint distributions to obtain $G(m)$, which is impractical.

B. Heuristic Solution

Due to the impracticality of obtaining the numerical solution, we propose a simple heuristic channel-division algorithm. The two keys to obtain the multiuser diversity gain are the number of nodes in the network N and the randomness of each subchannel. Clearly, we obtain higher probability of having high SNR nodes for a larger N in each subchannel. However, this is not enough to capture the multiuser diversity. If all of the nodes have the same channel response in each subchannel, there is no diversity gain at all regardless of N. In order to exploit the randomness of subchannels, we need to capture it by the standard deviation σ of each subchannel's MCS level.

Since each node in the network should be associated with the CCo, the CCo basically knows N. Since we assume that each node knows its channel response gain, node i feeds back its MCS level's standard deviation σ_i to the CCo. By averaging out all of the σ_i's, the CCo obtains σ_{avg}. Then, our heuristic channel-division algorithm uses N and σ_{avg} at the CCo to obtain an appropriate number of subchannels. For simplicity, our proposed algorithm only considers four cases of channel-division sets, that is, $M_1 = 1$, $M_2 = 2$, $M_3 = 4$, and $M_4 = 8$.

Algorithm 1 Heuristic channel-division algorithm

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1: Input: $N$ and $\sigma_i, i = \{1, \cdots, N\}$
2: State Output: $M$
3: // Initialization
4: $\sigma_{\text{avg}} = \frac{1}{N}\sum_{i=1}^{N}\sigma_i$
5: for $i = 1$ to 4 do
6:   if $M_i \leq N$ and $(a_i - b \cdot N) < \sigma_{\text{avg}}$ then
7:     $M = M_i$
8:   end if
9: end for
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Our proposed heuristic channel-division scheme running at CCo is presented in Algorithm 1, where a_i and b are given as positive real numbers. The CCo selects a maximum M among M_i's which satisfies the conditions in line 6. The reason for using the first condition is straightforward. If $M_i > N$, there are $(M_i - N)$ wasted subchannels. The rationale behind the second condition is that the randomness level σ_{avg} should be larger than a certain threshold of $(a_i - bN)$ that indicates the channel-division overhead.

The threshold is defined by two factors: 1) a higher number of subchannels requires a higher diversity gain, that is, leading to $a_1 < a_2 < a_3 < a_4$ due to the increase in the header overhead, and 2) even when the randomness is not high, a higher number of nodes gives higher probability of a higher diversity gain, so we have a minus term which is proportional to N, that is, $-b \cdot N$. Here, the parameter values of a_i and b are found through simulations. We use $a_1 = 0$, $a_2 = 1.19$, $a_3 = 1.48$, $a_4 = 1.81$, and $b = 0.02$. For example, our proposal chooses $M = M_3$ for $N = 10$ and $\sigma_{\text{avg}} = 1.5$ since M_1, M_2, and M_3 satisfy those conditions and M_3 is the maximum among those. For the case of $N = 20$ and $\sigma_{\text{avg}} = 1.5$, we obtain $M = M_4$ since the threshold value for the second condition decreases.

After deciding the number of subchannels, the CCo keeps paying attention to the channel status. If any subchannel is empty for a predetermined time, the CCo lowers the number of subchannels used.

V. SUBCHANNEL ALLOCATION PROBLEM

After choosing an M, we need to decide which node gets into which subchannel, called the subchannel allocation problem. To solve this problem, we consider a centralized optimal approach and propose its distributed heuristic version as we have done with the first problem.

A. Numerical Solution

We revisit our original problem $(\mathbf{P})$. For a fixed M, we have

$$(\mathbf{P}') \quad \max_{\mathbb{I}} \quad \sum_{i=1}^{N} U(R_i)$$

$$\text{subject to} \quad \sum_{j=1}^{M} I_{i,j} = 1, \ \text{for all } i.$$

The problem $(\mathbf{P}')$ is identical to the association control problem in wireless networks. There are several centralized solutions to this type of utility maximization association control problem [22], [23]. In [23], it was proven that $(\mathbf{P}')$ is an NP-hard problem. Clearly, the complexity of the exhaustive search algorithm is $O(M^N)$. If fluctuations of relative data rates are statistically identical, that is, the multiuser diversity gain only depends on the number of nodes in each subchannel, we obtain the solution with the complexity $O(N^M)$ by using the maximum bipartite matching algorithm. However, this complexity is still too high.

In [23], 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 gets to a local optimum. We call this algorithm "Local Search (LS)." The "change" operation makes a node change its allocated subchannel to another one if some gain is achievable in the objective function. Similarly, the "swap" operation makes two nodes, which are allocated as different subchannels, switch their subchannels if some gain is achieved.[3] The LS algorithm searches all possible cases of "change" and "swap" operations, and selects the best case that maximizes the objective function. The worst case complexity of the LS algorithm is $O(NM + N^2)$. It was shown that the LS algorithm shows the same performance values as the optimal algorithm in about 90% of the cases, and comparable performance to the optimal solution in the other cases [23].

To run the three numerical subchannel allocation algorithms, each node should feed each subchannel state back to the CCo. Then, the CCo allocates a subchannel to each node. That is, these are centralized algorithms.

B. Heuristic Solution

We now consider a heuristic distributed subchannel allocation algorithm that runs at each node. The CCo has the information about N_j, and periodically broadcasts the beacon[4] that contains the information about M and N_j. This algorithm does

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[3] The "swap" operation cannot be made by two "change" operations because of the LS algorithm's greedy characteristic.

[4] The beacon period is 33.33 ms in North America and Korea.

not require the channel state information of each node. Node i can calculate its expected throughput R_i in subchannel j, using the information about M and N_j and its measured channel state information $r_{i,j}$. From (1), we obtain the node i's throughput as $R_i = r_{i,j}(S(N_j, M)/N_j)$.

The procedures of our proposed heuristic solution for subchannel allocation are given as follows: At first, a newly joining node i chooses a subchannel j with the highest SNR. The CCo broadcasts the increment of N_j using the beacon. Each node updates its expected throughput over subchannel j. If a subchannel k exists, which satisfies

$$\frac{r_{i,j} S(N_j, M)}{N_j} < \max_{k \neq j} \left\{ \frac{r_{i,k} S(N_k + 1, M)}{N_k + 1} \right\} \tag{3}$$

node i changes its allocated subchannel from subchannel j to k. However, if all of the nodes satisfying this condition change their subchannels at the same time, our proposed heuristic algorithm may not converge.

To prevent such an event, each node needs to wait for a certain backoff time before changing its allocated subchannel. In this algorithm, the unit of backoff time is the beacon period. During the backoff, if it is expected throughput over the subchannel of interest becomes lower than its currently achievable throughput, it gives up changing its allocation. To give high priority to a node with higher gain, each node selects its backoff counter (BC) according to a certain number that is inversely proportional to the increment gain of the expected throughput. In addition, to avoid the ping-pong problem[5] between nodes with the same channel state, we add a random number in [0,L] to calculate the BC of each node, which has the unit of beacon period. Then we can express the BC of node i as

$$\mathrm{BC}_i = \frac{G_{\mathrm{MAX}}}{G_i} + \mathrm{Unif}(0, L) \tag{4}$$

where G_{MAX} is a constant and G_i is the increased gain of node i. This is similar to the "change" operation in the centralized LS algorithm. Therefore, our proposed heuristic algorithm can be considered as a distributed LS algorithm which only uses the "change" operation, that is, no "swap" operation.

Fig. 2 shows the flowchart for our proposed heuristic algorithm. This algorithm runs at each node. When a new node i enters the network, it chooses a subchannel with the highest SNR, say j. Each node continuously updates N_j and $r_{i,j}$ according to the broadcasted beacon and the channel measurement, respectively. If the node i finds a subchannel which satisfies (3), it sets BC_i as a number given by (4). For each beacon period, the BC_i is decreased by one. If the condition (3) holds true until the BC_i reaches 0, the node changes its allocated subchannel from j to k that satisfies (3).

VI. Performance Evaluation

In this section, we compare the performance of our proposed multichannel CSMA/CA protocol for PLC with the other competitive schemes in terms of throughput; they are the HPAV standard CSMA/CA protocol and the cognitive power-line communication (CPLC) system [13]. In simulations, we use a simulator written in C.

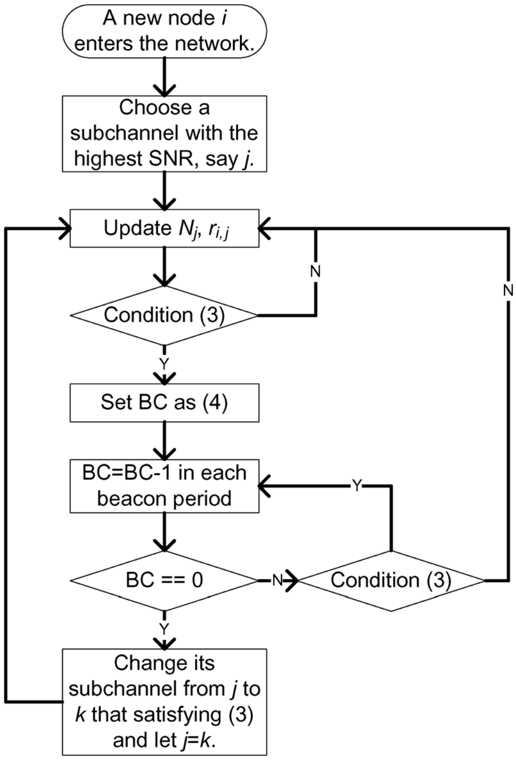

Fig. 2. Flowchart for our heuristic distributed subchannel allocation algorithm. When a new node enters the network, each node runs this algorithm.

TABLE I
SIMULATION PARAMETERS

System bandwidth	1.8-30 MHz
G_{MAX} in (4)	20
L in (4)	3
T_{max}	2501.12 μsec
T_H	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

While the HPAV standard does not have subchannelization, it uses a bit-loading algorithm. That is, a node uses the entire bandwidth and sets its best MCS level to each subchannel. In CPLC, a node that wins the contention uses good subchannels that have greater SNRs than a certain threshold. The other nodes contend once again to become a second winning node that will transmit data through the remaining subchannels and end its transmission synchronously with the first node.

A. Simulation Settings

In the considered topology, we have one CCo and vary the number of nodes from 1 to 20. The CSMA/CA protocol parameters in the HPAV standard and other simulation parameters are listed in Table I. We simulate three channel state scenarios: The first is a flat channel scenario where all of the nodes have the same channel state. The second is a random channel scenario where each node has a randomly selected channel state for each subchannel. Since the results of this scenario heavily depend

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[5] Nodes change their allocated subchannels back and forth.

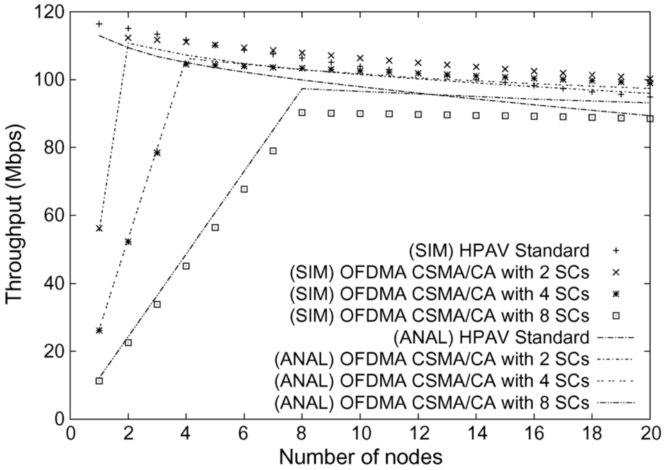

Fig. 3. Throughput performance comparison according to the number of nodes under a flat channel scenario. The dotted lines and symbols represent numerical and simulation results, respectively.

on the chosen channel state, they are averaged over 30 independent runs. The last is a real channel scenario used in [21], where the authors provided MATLAB functions that return frequency responses for realistic inhome and small office channels in a simple network topology.

B. Diversity Gain by Channel Division

The results of this section only show the throughput improvement of the LS subchannel allocation algorithm over the other competitive schemes[6] according to M.

Fig. 3 shows the throughput performance under a flat channel scenario. The dotted lines and symbols represent numerical and simulation results, respectively. The results explain that numerical and simulation results show a similar tendency and that the gap between them is smaller than 4%. We use the simulator in the following results since the results for CPLC cannot be obtained by the numerical method. CPLC shows the same performance as the HPAV standard in the flat channel scenario. The throughput gain improvement of our proposal is marginal since there is no diversity gain in the flat channel scenario.

The throughput performance according to the number of nodes under a random channel scenario is shown in Fig. 4. Our proposal gets the highest throughput performance. Because of the channel randomness, the channel selection diversity gain overcomes the cost of the long header. CPLC shows some performance gain for the number of nodes smaller than five. But its throughput 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.

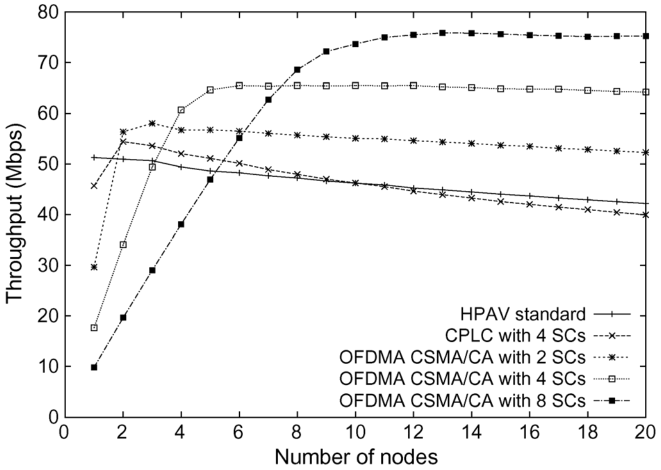

Fig. 4. Throughput performance comparison according to the number of nodes under a random channel scenario. Our proposal shows the highest throughput when the number of nodes is not smaller than the number of subchannels. The results are averaged over 30 runs.

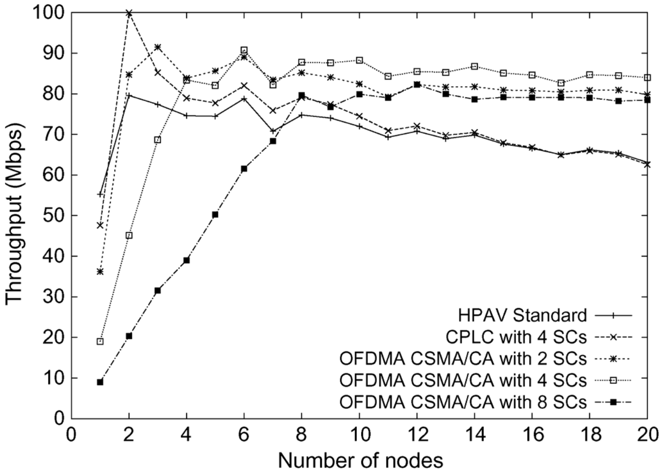

Fig. 5. Throughput performance comparison according to the number of nodes under a real channel scenario.

Fig. 5 shows the throughput performance under a real channel scenario. Generally, our proposal with four subchannels shows the best throughput performance for $N \geq 4$. Due to the lack of the randomness among subchannels, the channel-division gain for the case of eight subchannels cannot overcome the increase in the header overhead. CPLC shows the best performance in the case of two nodes because of severe unfairness between them, where they achieve 90 and 10 Mb/s, respectively. From this result, we select the channel-division parameter values of a_i and b for our heuristic algorithm in Section IV-B.

Fig. 6 shows the throughput performance of a nonsaturated traffic condition. There are 20 nodes in the network and each node receives packets with Poisson arrival. The packet size is fixed at 5000 B. When the traffic intensity is low ($0 < \lambda < 6$), all of the schemes operate well. However, for $\lambda > 6$, HPAV and CPLC cannot fully accommodate the offered load. Our proposal with four subchannels shows the best performance under the saturated condition. This result coincides with that of Fig. 5 where the “x” axis indicates the number of active nodes.[7]

C. Dynamic Scenario

To evaluate our proposed optimal and heuristic proposals, we consider a dynamic scenario described in Fig. 7. In this scenario, the number of nodes in the network is time varying. The

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[6] 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.

[7] An active node indicates a node with packets in its queue.

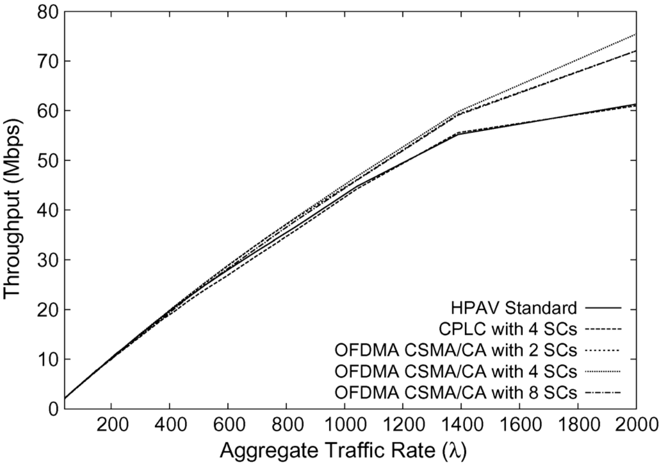

Fig. 6. Throughput performance comparison according to the aggregated arrival rate λ that indicates the number of packet arrivals per second.

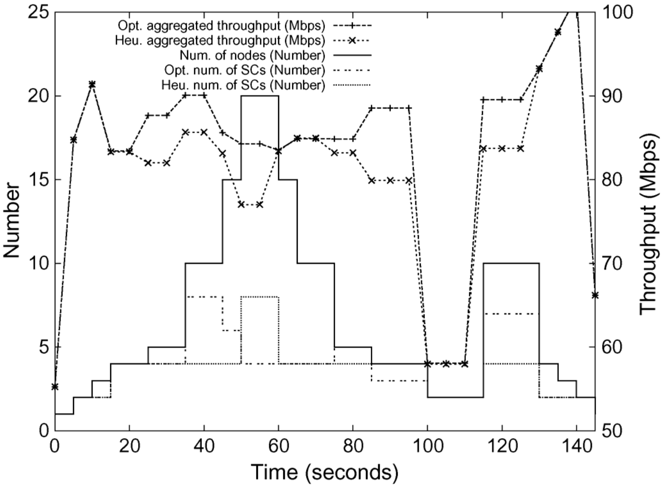

Fig. 7. Throughput performance under a real channel scenario. The two lines at the top represent throughput performance (right "y" axis), and three lines at the bottom represent the numbers of nodes and subchannels (left "y" axis).

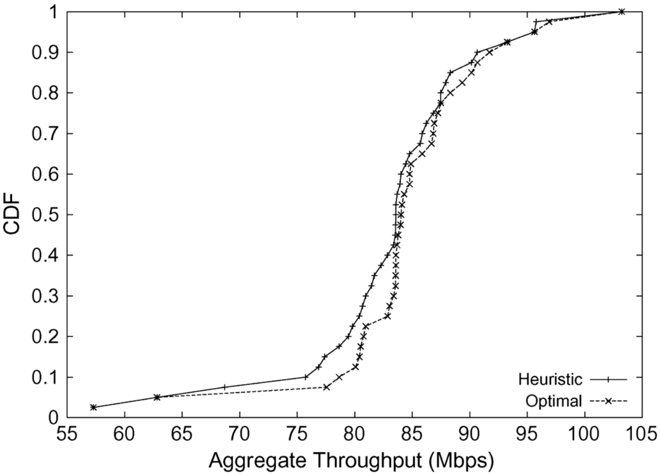

Fig. 8. CDF of the throughput in optimal and heuristic solutions.

channel response of each node is predetermined. According to the number of nodes and the standard deviation of subchannel states, optimal and heuristic numbers of subchannels are selected. The two lines at the bottom represent the numbers of subchannels obtained by optimal and heuristic algorithms, respectively. While the heuristic algorithm only selects a value from the set $\mathcal{M} = \{1, 2, 4, 8\}$, the optimal one can have any positive integer M.

The two lines at the top show the throughput performances of optimal and heuristic algorithms, respectively. The performance gap between the two algorithms is about 3.4% on average. If the heuristic channel-division algorithm returns the same number of subchannels with that of the optimal one (57% of the simulation period), the performance gap is 0.8% on average. However, if the two algorithms choose different numbers of subchannels (43% of the simulation period), the performance gap is 6.4% on average. We can conclude that channel division is more influential than subchannel allocation in throughput performance.

Fig. 8 shows the CDF of the throughput in optimal and heuristic solutions, which was obtained from 40 scenarios. This result compares the throughput performance of the optimal channel division and LS subchannel allocation algorithms with that of the heuristic channel division and subchannel allocation algorithms. The average performance gap between these two is about 1.4% and the maximum is 15.6%. For 24 scenarios, our proposed heuristic solution achieves almost the same throughput performance, that is, less than 1% performance gap, as the optimal one. It can be concluded that our proposed heuristic solution achieves very similar performance gain as the optimal solution with much smaller overhead.

VII. CONCLUSION

In this paper, we proposed a new multiple-access framework for PLC, named the multichannel CSMA/CA protocol for OFDMA-based broadband PLC. Our proposed protocol divides the whole bandwidth into multiple subchannels and allocates each node a good subchannel. In the framework, we formulated the problem as a network utility maximization problem. To solve this, we divided the problem into two subproblems: 1) a channel-division subproblem to find an appropriate number of subchannels and 2) a subchannel allocation subproblem to allocate a subchannel to each node. To solve each subproblem, we considered optimal and heuristic approaches. Our heuristic solution to the channel-division subproblem runs in a centralized manner with little feedback information, and that to the subchannel allocation problem runs in a distributed manner. The simulation results showed that our proposed framework improves throughput performance by selecting a proper number of subchannels and assigning each node a favorable subchannel. Our proposed heuristic algorithm approximately follows the optimal algorithm in throughput performance with the benefits of low complexity and reasonably low feedback overhead.

In future work, we need to develop a smooth conversion algorithm for the subchannelization and the subchannel allocation when the power-line channel state varies greatly.

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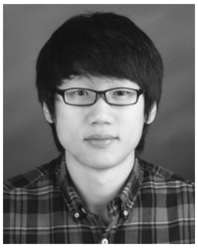

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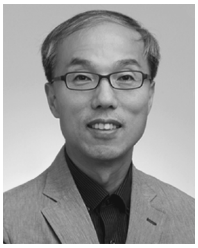

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