OFDMA CSMA/CA Protocol for Power Line Communication

Sung-Guk Yoon
INNMC, School of EECS
Seoul National University
Email: sgyoon@netlab.snu.ac.kr

Daeho Kang
INMC, School of EECS
Seoul National University
Email: dhkang@netlab.snu.ac.kr

Saewoong Bahk
INMC, School of EECS
Seoul National University
Email: sbahk@snu.ac.kr

***Abstract*—The channel response and noise in the power line channel show periodic behaviors since electric devices, which are major noise sources, synchronously run with the AC line cycle. Using the multichannel characteristics of orthogonal frequency-division multiple access (OFDMA) for the random access scheme, the power line communication (PLC) can improve system throughput. In this paper, we propose a carrier sense multiple access with collision avoidance (CSMA/CA) protocol for OFDMA based PLC systems. Our proposed protocol divides the whole bandwidth into several sub-channels, and each station joins its best sub-channel. Each sub-channel performs CSMA/CA independently reducing the collision probability and enhancing the system throughput. Through extensive simulations, we verify our proposed protocol improves the system throughput under various environments.**

I. Introduction

The power line is a wired communication medium, but its channel characteristics are very much different from conventional wired media such as telephone and Ethernet lines since it is not designed for communications. On the contrary, some characteristics of the power line channel are similar with those of the wireless channel; they are fading and frequency notch, but their style of fading and notch are different. The frequency notch in the power line channel does not fluctuate very much because of static channel environments while that in the wireless channel changes dynamically due to variously moving objects.

To overcome the fading problem of frequently changing channel according to time and frequency in wireless communications, many diversity techniques have been proposed, such as time or frequency diversity. Recent investigations, however, regard the fading as a positive factor. For instance, if a station meets a bad channel status due to the fading, on the other hand, there might be a station with a good channel status for the same reason. To exploit the fading, adaptive modulation and coding (AMC) in physical (PHY) layer and opportunistic scheduling in media access control (MAC) layer are proposed.

Electrical devices installed in the power line, which are major noise sources in the power line communications (PLCs), operate with the AC line cycle. Therefore, the channel and noise characteristics change along with this cycle. This unique periodic characteristic of the power line channel is called cyclostationary.

Because of different channel characteristics of the fading in the wireless and power line channels, combating techniques should be different. HomePlug AV (HPAV) carrier sense multiple access with collision avoidance (CSMA/CA) uses the tone map, which is obtained by channel measurement. After filtering frequency notches, the transmitter only uses good frequency bands [1]. In [2], Katar et al. investigated a channel adaptation scheme based on the cyclostationary characteristic. Oh et al. [3] proposed a cognitive power line communication (CPLC) system which allows the secondary station to reuse the unused frequency bands from the primary station. However, two stations at most can be simultaneously active in the CPLC system. In [4], the authors found an optimal size of time slot in the time division multiple access (TDMA) region using the cyclostationary characteristic of the power line channel.

Recently, a new CSMA/CA protocol using orthogonal frequency-division multiple access (OFDMA) was discussed in wireless communications [5]. The main benefit of using OFDMA comes from that each station 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 sub-channels resulting in reduced collision probability. However, since the characteristics of the power line channel are different from those of the wireless channel, we need to design a PLC customized OFDMA CSMA/CA protocol to enhance overall performance.

In this paper, we propose a CSMA/CA protocol for PLC systems which use OFDMA. Like in [3] and [5], our proposal divides the whole bandwidth into several sub-channels. Since the power line channel keeps its channel gain for a long period, our proposal tries to associate each station with its best sub-channel. The two main reasons for throughput enhancement of our proposed scheme are: i) the collision probability is lowered by spreading stations over multiple sub-channels, and ii) each station chooses its best channel of maximum rate, that is, maximizing the diversity gain.

The rest of the paper is organized as follows. We first describe the characteristics of the power line channel and OFDMA CSMA/CA in Section II. Then, we design our

This work was supported by the Korea Science and Engineering Foundation (KOSEF) grant funded by the Korea government (MEST) (No. 09-043 (0423-20090043)).

OFDMA CSMA/CA for PLC in Section III. After evaluating the proposed protocol in Section IV, we conclude our paper in Section V.

II. System Model

In this section, we briefly overview the characteristics of the power line channel and OFDMA CSMA/CA proposed in [5].

A. 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 line, the channel between transmitter and receiver experiences impedance mismatching. Therefore, the signal generates multipath, which causes the frequency selective channel response. In a fixed power line topology, each channel has unique parameters, such as frequency dependant response and root-mean-square (RMS) delay spread. In [6], 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. [7] 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. [8] 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

$$H(t,f) = \begin{cases} H_{Low}(f) & |v_{ac,\theta}(t)| \leq V_{thr} \\ H_{High}(f) & |v_{ac,\theta}(t)| \geq V_{thr} + \Delta V \end{cases}, \quad (1)$$

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. In the MAC layer point of view, this result implies that the power line channel has regular and periodic properties.

B. OFDMA CSMA/CA

The CSMA/CA protocol efficiently controls the shared medium in a distributed manner. To enhance the throughput efficiency of PLC CSMA/CA, many investigations have been made [9]–[11] and focused on lowering the collision probability.

Recently, Kwon et al. [5] presented a new OFDMA CSMA/CA for wireless communications. In OFDMA, a station 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 sub-channels, resulting in reduced collision probability.

Fig. 1 shows an example of the OFDMA CSMA/CA protocol operation. While each station 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 sub-channels 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.

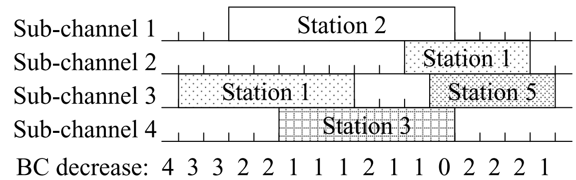


Fig. 1. Example of the OFDMA CSMA/CA protocol operation. Because of the advantage of the OFDMA, more than one station can transmit simultaneously. In the protocol, each station decreases its own BC by the number of idle sub-channels rather than one, and transmits a frame through a randomly chosen sub-channel among the idle sub-channels.

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. 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

$$T_{cp} > \Delta T_d^{max} + \Delta T_p^{max}, \quad (2)$$

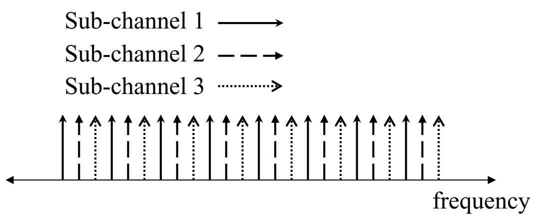
where T_{cp}, ΔT_d^{max}, and ΔT_p^{max} are the CP duration, the maximum time difference in the clock drift, and the maximum time difference in the propagation delay, respectively.

III. OFDMA CSMA/CA for PLC

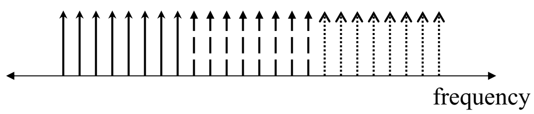
This section explains our proposed OFDMA CSMA/CA for PLC. We assume that the system uses the HPAV MAC protocol [12] which is standardized by the HomePlug Powerline Alliance. HPAV adopts newly developed PHY and MAC layer techniques, such as orthogonal frequency-division multiplexing (OFDM) and hybrid MAC. Each HPAV network has a special station, named central coordinator (CCo), which takes charge of the control of the network. Our system also assumes that there is a special coordinator in the network.

A. Motivation

The main difference between the conventional OFDMA CSMA/CA and the OFDMA CSMA/CA for PLC comes from the genuine characteristics of the power line channel, i.e., cyclostationary. The wireless OFDMA CSMA/CA system creates a sub-channel by spreading it over the whole frequency band to average its randomness, which is called diversity mode in WiMAX standard [13] and shown in Fig. 2(a). However, to enhance the throughput performance, allocating a particular frequency band to a sub-channel would be better, which is



(a) Diversity mode



(b) AMC mode

Fig. 2. Two methods for channel division.

called AMC mode in WiMAX standard [13] and shown in Fig. 2(b) As the power line channel shows somewhat stable channel response, we can use the latter approach for channel division.

Chung et al. [14] 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 stations. This opens a possibility of throughput enhancement by spreading contending stations over different sub-channels and using the channel condition for each transmission.

B. Channel allocation

In our proposed OFDMA CSMA/CA, the CCo divides the bandwidth into multiple sub-channels and each station chooses its own sub-channel. Each sub-channel operates the CSMA/CA protocol independently. The CCo is in charge of sub-channelization and observes the number of contending stations in each sub-channel. The CCo broadcasts the beacon that contains the information about the number of stations in each sub-channel. After hearing the beacon, each station switches its sub-channel to maximize its achievable throughput.

The expected throughput of each sub-channel can be calculated by using the information about the number of stations and the channel condition. Assume that there are N stations in the network. Let S_{sat} denote the saturated throughput, and it is the time fraction of the successful data transmission. Then, using the result in [14], we have

$$S_{sat} = \frac{P_{tr} P_s T_s}{(1 - P_{tr})\sigma + P_{tr}(P_s T)s + (1 - P_s)T_c)}, \quad (3)$$

where P_{tr} and P_s are the probabilities that at least one station transmits and that a station successfully transmits, respectively. σ, T_s, and T_c denote the duration of an idle slot time, the required time for the successful transmission of a frame, and the wasted time due to a frame collision, respectively. From the long-term fairness nature of HPAV CSMA/CA and the saturation assumption, each station in the network equally shares the duration of the successful data transmission. Therefore, the time fraction taken by each station for the data transmission is S_{sat}/N, and then the expected throughput of station i is given as

TABLE I
AN EXAMPLE SCENARIO

Sub-channel index	# of stations	R_i (Mbps)	R^{ex} (Mbps)
1	4	45	6.15
2	1	30	10.94
3	6	99	9.38
4	3	79	13.72

$$R_i^{ex} = \frac{S_{sat}}{N} R_i, \quad (4)$$

where R_i is the maximum achievable transmission rate of user i.

Each contending station updates its expected throughput at each sub-channel according to the congestion information. When the expected throughput of a station at some sub-channel is higher than that at the current sub-channel, the station leaves the current sub-channel.

Table I shows an example scenario. There are four sub-channels and 14 stations in the network. The number of contending stations in each sub-channel is shown in the second column. When a new station joins the network, the station measures the channel status of all the sub-channels, which is given in the third column, and receives the contending information from the beacon. The station calculates the expected throughput and it is shown in the fourth column. In this case, the station chooses sub-channel 4 which gives 13.72 Mbps and tries to transmit through this sub-channel. Note that after joining the new station, some stations in sub-channel 4 may change their sub-channel to achieve higher throughput.

C. Potential problems

Since each station in our proposal chooses a sub-channel in a heuristic manner, it has two potential problems: ping-pong and non-optimal sub-channel association.

1) Ping-pong problem: Fig. 3 shows an example of the ping-pong problem. The transmission rates of stations A and B are depicted at the top of the figure and used for Figs. 4 and 5 too. The ‘x’ axis represents time in unit of beacon period, i.e., 33.33 msec. In this scenario, stations A and B enter the network at the same beacon period P and measure the channel. Since both stations expect high throughput at the sub-channel 1, they join the sub-channel 1 at period P+1. At the next period P+2, both stations find that sub-channel 2 is better now, so they switch to sub-channel 2 together. They repeat this process and this is called ping-pong problem in our OFDMA CSMA/CA.

2) Non-optimal sub-channel association: Fig. 4 shows an example of the non-optimal sub-channel association problem. Station A is associated with sub-channel 1 from period P+1, and station B with sub-channel 2 since the expected rate of sub-channel 2 (7.53 Mbps) is higher than that of sub-channel 1 (6.56 Mbps)[1]. In this example, the total throughput

[1]The expected rates are from (4)

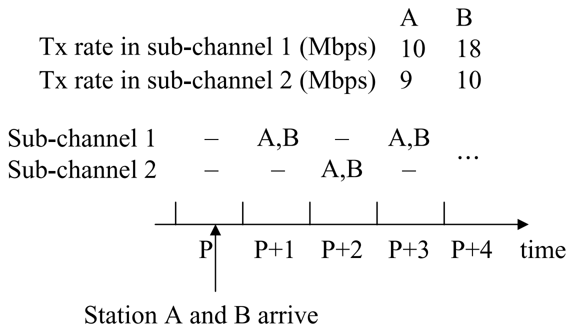


Fig. 3. An example of the ping-pong problem. Stations A and B choose the same sub-channel continuously, so one sub-channel is always vacant.

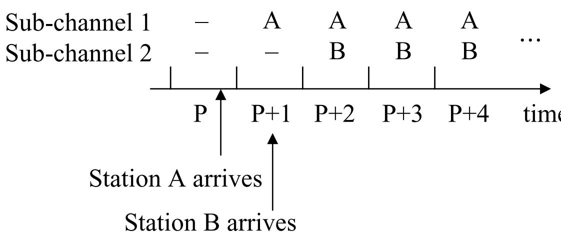


Fig. 4. An example of the non-optimal sub-channel association. In this example, stations A and B operate in the sub-channels 1 and 2, respectively. From the total throughput point of view, they need to be allocated at the opposite sub-channel of each other.

is 7.53(Station A)+7.53(Station B)=15.06 Mbps, but it can be 20.32 Mbps when they exchange the allocated sub-channels. The total throughput in our proposed OFDMA CSMA/CA heavily depends on the incoming order of each station.

D. Supplementary methods

To resolve the above potential problems, we consider two supplementary methods: prioritized sub-channel change and the highest transmission rate entrance.

1) Prioritized sub-channel change: In the prioritized sub-channel change, each station does not change its sub-channel immediately after having the information about some good sub-channel, instead waits for a certain backoff time. During the backoff, if the expected throughput of that sub-channel becomes lower than the current throughput, the station gives up changing its sub-channel. As for priority assignment, each station selects the backoff counter (BC) that is inversely proportional to the gain increase of the expected throughput. In addition, to avoid the ping-pong problem between stations with the same channel status, a random number in [0,L] is added to the BC. The unit of the BC is beacon period. Then, we express the BC for station i as follows:

$$BC_i = \frac{G_{MAX}}{G_i} + Unif(0, L), \tag{5}$$

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

2) Highest transmission rate entrance: In this scheme, a newly joining station does not choose a sub-channel with the maximum expected throughput but with the maximum transmission rate. After the station joins, there might be a contention in the sub-channel. Among the contending stations, a station which gains the most by changing its sub-channel leaves.

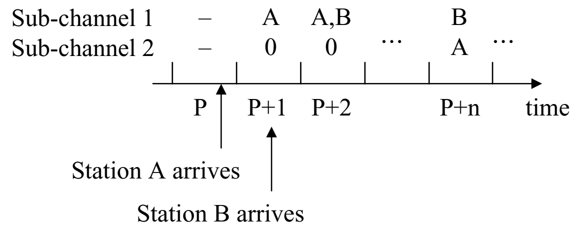


Fig. 5. An example of our proposal to resolve the ping-pong and non-optimal association problems.

Fig. 5 shows an example of our proposed OFDMA CSMA/CA with supplementary schemes that use the same scenario in Fig. 4. At period P+2, station B chooses sub-channel 1 since it is the best. Both stations achieves higher throughput by changing the sub-channels, so they select a BC according to (5). Since the gain of station A (3.12 Mbps) is larger than that of station B (0.97 Mbps), station A has a smaller BC and changes its sub-channel to 2 at P+n. Then, both stations stay at their own sub-channels.

E. Discussion

To transmit the frame header in our proposal, the more number of symbols is needed since the number of usable data carriers is lowered by dividing bandwidth. For instance, in the HPAV specification, the first two OFDM symbols contain the header information, named frame control (FC). If the network operates our proposal with two sub-channels, four symbols are needed to transmit the FC. Increasing the number of sub-channels has a trade-off between less collision probability and larger frame header overhead.

In [5], the authors pointed out that the OFDMA symbol should have longer CP duration to adopt the OFDMA CSMA/CA, and the proper CP duration condition for using OFDMA CSMA/CA is (2). The reason for longer CP duration is timing difference between stations due to the clock drift and propagation delay. However, HPAV can adopt the OFDMA CSMA/CA for PLC without modifying CP duration. At first, the CP duration of HPAV is 10.52 μsec [12] which is much larger than that of 802.11a, 0.8 μsec. 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 $\pm$25 ppm. The maximum time difference from the clock drift between stations 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.

IV. Simulations

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

TABLE II
SIMULATION PARAMETERS

Number of data sub-carriers	917
G_{MAX} in (5)	20
L in (5)	3
MaxFL	2501.12 μsec
FC transmission time in conventional CSMA/CA	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

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

CPLC is a frequency notch combating scheme. In CPLC, the station which wins the contention only uses its good sub-channels, i.e., larger than a certain threshold. The rest stations contend one more time for the use of remaining sub-channels and the second winning station transmits its data through the remaining sub-channels under a constraint of synchronized transmission with the first transmission.

A. Simulation settings

There are one CCo and the number of stations, i.e. transmitters, varies from one to 30. The simulation parameters are displayed in Table II, and the CSMA/CA parameters are from the HPAV specification [12]. The CCo divides the bandwidth into several sub-channels as equal as possible. For instance, when the CCo divides to two sub-channels, sub-channel 1 and 2 have 458 and 459 sub-carriers, respectively. We simulate under the three channel scenarios: First, flat channel scenario means that all the stations have the same channel status. Next one is asymmetric channel scenario in which half of the frequency band is good and the other half is bad. Finally, random channel scenario is that each station has randomly selected channel status for each sub-channels. Since the result of the random channel scenario heavily depends on the chosen channel's status, the result is averaged by 30 independent runs.

B. Throughput performance

Fig. 6 shows the throughput performance under the flat channel scenario. As the number of stations increases, the throughput performances of the HPAV standard and the CPLC decrease while our proposal does not. Since there are less number of contending stations in our proposed OFDMA CSMA/CA, the collision probability is low. However, even OFDMA CSMA/CA with 8 sub-channel has the lowest collision probability, it cannot achieve the highest throughput performance because of the large header overhead. The CPLC is identical to the HPAV standard since the primary station uses all the sub-channels.

The throughput performance according to the number of stations under the asymmetric channel scenario is shown in Fig. 7. Our proposal always shows the best throughput performance when the number of stations is larger than or equal to the number of sub-channels. The OFDMA CSMA/CA with

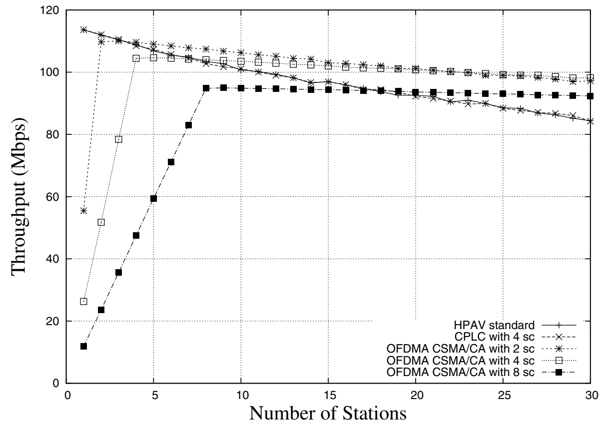


Fig. 6. Throughput performance comparison according to the number of stations under the flat channel scenario. Our proposed OFDMA CSMA/CA achieves the highest throughput after 3 stations.

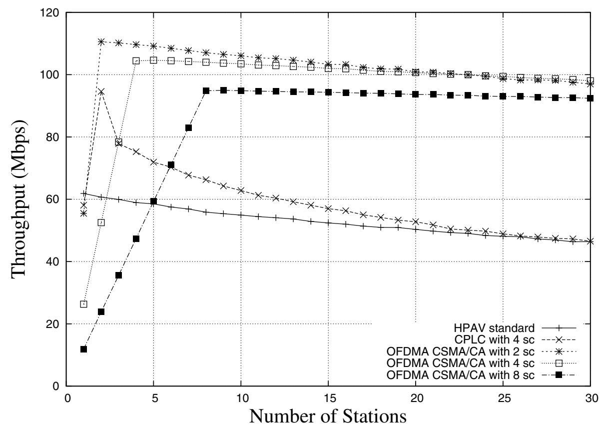


Fig. 7. Throughput performance comparison according to the number of stations under the asymmetric channel scenario. Our proposal always achieves the highest throughput performance except only one station.

8 sub-channels still suffers from the header overhead. Since there is at most one active station in the HPAV, it achieves the lowest throughput. The CPLC shows good performance with small number of stations, i.e., less than five stations, but its performance converges to that of the HPAV with the number of stations since the efficiency of the secondary channel decreases with the number of stations.

Fig. 8 shows the throughput performance under the random channel scenario. Our proposal gets the highest throughput performance except only one station, and it with 8 sub-channels achieves the highest throughput with over 7 stations. Because of the randomness of the channel, the channel selection diversity gain overcomes the cost of long header.

C. Fairness

We use the Jain's fairness index [15] to measure how the resource is allocated in a fair manner. As the index approaches to one, the system allocates its resource fairly and vice versa. Fig. 9 shows the fairness index under the random channel scenario. Our proposal shows good fairness performance with

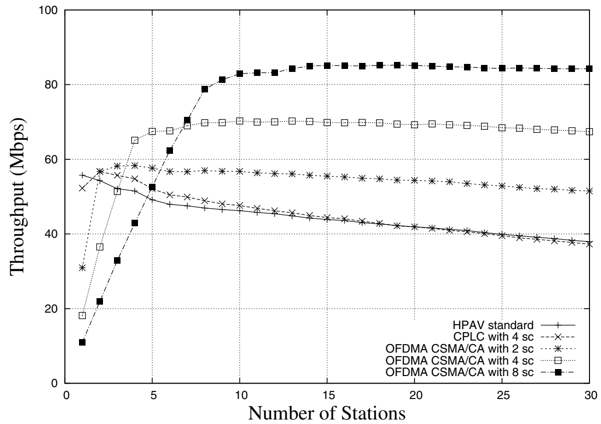


Fig. 8. Throughput performance comparison according to the number of stations under the random channel scenario. Our proposal shows the highest throughput when the number of stations is larger than or equal to the number of sub-channels. The result is averaged over 30 runs.

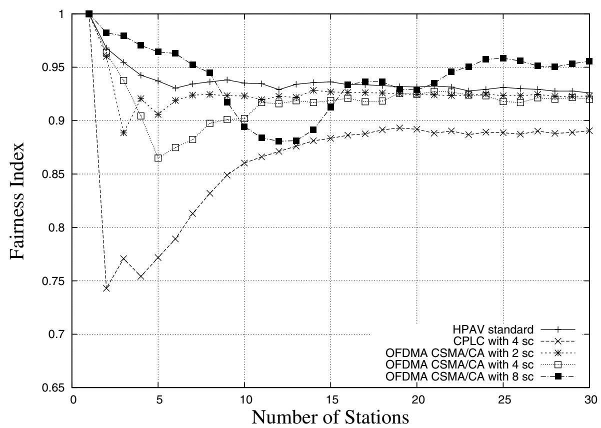


Fig. 9. Fairness performance comparison according to the number of stations under the random channel scenario. The result is averaged over 30 runs.

the number of stations (> 15) while it shows fluctuation with relatively small number of stations. Especially, when the number of stations are in the middle of multiples of the number of sub-channels[2], the fairness is low. However, even our proposal gets lower fairness performance, the minimum throughput station achieves better throughput performance than that of the HPAV standard. For instance, when there are 5 stations in the OFDMA CSMA/CA with 4 sub-channels, the station which gets the minimum throughput has 7.19 Mbps, but the minimum station in the HPAV standard has 6.39 Mbps. Therefore, our proposed OFDMA CSMA/CA improves the network throughput while the minimum throughput station also enhances its throughput.

V. Conclusion

In this paper, we proposed a new CSMA/CA for PLC, that is, OFDMA CSMA/CA. Our proposed OFDMA CSMA/CA divides the whole bandwidth into several sub-channels and each station enters its best sub-channel which gives the maximum expected throughput. The two major reasons for the throughput enhancement of our proposed protocol are that it reduces collision probability by distributing the load over multiple sub-channels and tries to select the best sub-channel by using the multiuser diversity. When the network does not have sufficient number of stations, our proposal shows lower fairness than the conventional protocol. However, the minimum throughput station of our proposal gets higher throughput than that of the conventional protocol. In other words, our proposal improves the throughput performance of all the stations.

For the future work, we will consider more realistic power line channel to verify our proposed protocol and find an optimal number of sub-channels according to the number of stations.

[2] 12, 20 stations in 8 sub-channels

References

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

[2] 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*, Orlando, USA, Mar. 2006.

[3] 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.

[4] A. Tonello, J. A. C. Arrabal, and S. D'Alessandro, "Optimal Time Slot Design in an OFDM-TDMA System over Power-line Time-variant Channels," in Proc. *IEEE ISPLC*, Dresden, Germany, Mar.-Apr. 2009.

[5] Hojoong Kwon, Hanbyul Seo, Seonwook Kim, and Byeong Gi 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.

[6] 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.

[7] 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.

[8] 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.

[9] 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.

[10] 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.

[11] 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.

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

[13] IEEE Std 802.16-2009, *IEEE Standard for Local and Metroploitan area networks Part16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems*, IEEE Press, May 2009.

[14] 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.

[15] R. Jain, D. Chiu, and W. Hawe, "A Quantitative Measure of Fairness and Discrimination for Resource Allocation in Shared Systems," *Technical Report*, DEC TR-301, Littleton, MA, 1984.