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

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***Abstract*—Even though the power line is a wired medium, its channel characteristics are very different from that of conventional wired media, such as telephone and Ethernet as it is not designed for communications. Some characteristics of the power-line channel are that of the wireless channel, so most power-line communication (PLC) schemes use the carrier-sense multiple access with collision-avoidance protocol, which is popular in wireless communications, for random access. In addition, the power-line channel has some characteristics that are absent in wired and wireless channels. In this paper, we design a new PLC media-access control (MAC) protocol considering two different types of power-line noise models: 1) impulsive noise (generated by on-off switching of electronic devices) and 2) 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 size appropriately according to the current loading. Through extensive simulations, we verify that our proposed MAC scheme improves network throughput under various scenarios.**

***Index Terms*—Contention window, HPAV, media-access control (MAC), power-line communication (PLC), rate adaptation.**

I. INTRODUCTION

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

For wireless solutions, there are IEEE 802.11x wireless local-area networks (WLANs) [1] and IEEE 802.15.x wireless personal-area networks (WPANs) [2]. 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 [3], high-definition power-line communication (HD-PLC) [4] and universal powerline alliance (UPA) [5], 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) [6] is a state-of-the art solution which has been standardized by HomePlug Powerline Alliance and follows the HomePlug 1.0 standard [7]. 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 media-access control (MAC) layer technologies and supports the rate of up to 200 Mb/s.

Previous investigations in PLC MAC have mainly focused on HomePlug. Chung *et al.* [8] presented a detailed analysis for HomePlug carrier-sense multiple access with collision avoidance (CSMA/CA) using the Markov Chain model. In [9] and [10], Campista *et al.* enhanced throughput performance by simply modifying the collision-avoidance parameters of HomePlug CSMA/CA. Tripathi *et al.* [11] worked on achieving high throughput in HomePlug CSMA/CA, assuming that every station always knows an exact number of contending stations within the network. Since the aforementioned assumption was unrealistic, Yoon *et al.* [12] 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, the 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 [13] and [14].

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 [15]–[17]. Since the rate adaptation scheme for IEEE 802.11 WLAN cannot be applied for the PLC directly, Yoon *et al.* [18] proposed a scheme that reflects the characteristics of the power-line channel and applied this scheme to HPAV.

There are two types of adaptation schemes to combat bad channels: they are 1) channel adaptation and 2) 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 adaptation schemes for PLC have mainly focused on channel adaptation [19], [20], which is designed for combatting a cyclostationary

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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 [19] and [20] 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 noise sources. On the other hand, rate adaptation schemes care for combatting 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 is often observed in the PLC. 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.

The rest of this paper is organized as follows: In Section II, we briefly describe the noise model for PLC. In Section III, we review the HPAV MAC protocol. We propose an enhanced MAC scheme in Section IV. Through simulations, we evaluate the performance of our proposed scheme in Section V, followed by concluding remarks in Section VI.

II. POWER-LINE NOISE

The wireless channel has fast fading due to the multipath propagation property of the transmitted signal. So the coherent time[1] is an important metric to understand the channel fluctuation [21]. The power-line channel also has the multipath 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 [14], [22]. In this section, we consider two types of channel noise models for PLC MAC design: 1) background and 2) impulsive noises [13], [23].

A. Background Noise

Sinice wireless environments contain lots of noise sources and reflectors, the background noise of wireless channel can be modeled as Gaussian according to the central limit theorem (CLT) [21]. On the other hand, power-line environments have a limited number of noise sources and reflectors; hence, the background noise model does not follow Gaussian. Since the noise model depends on the number of turned-on noise sources [14], 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 [24]. 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.

TABLE I
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

B. 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 ms), and its power spectral density (PSD) is about 50 dB higher than that of background noise. Thus, if the impulsive noise is generated during data transmission, the transmitted signal will be severely damaged and fall into a burst error.

Zimmermann *et al.* [13] investigated the characteristics of the impulsive noise by measuring its inter arrival time (IAT) and modeled it as a partitioned Markov Chain. In [25], Hrasnica *et al.* considered the partitioned Markov chain model with three scenarios as listed in Table I, which we will use in our simulations.

III. 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 called the central coordinator (CCo) which periodically broadcasts a beacon message containing access-control information. Fig. 1 shows an example of the 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 messages, and best effort services.

A. CSMA/CA

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

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

[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.

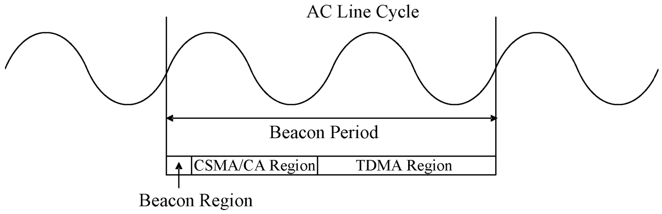

Fig. 1. Example of the HPAV beacon period. The beacon period is synchronized with the ac line cycle for robust transmission and it consists of three regions: 1) beacon, 2) CSMA/CA, and 3) TDMA.

TABLE II
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

The objective of PRP is to classify priorities among flows. It consists of two priority resolution slots (PRSs), called 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 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 is equal to 0. If a station experiences collision, it increases the BPC by one and chooses a random BC number in [0, CW] again. Table II shows CW and DC values for each BPC.

At each BPC, each station sets the DC value to a predefined value shown in Table II. 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.

B. *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 of frame formats: 1) beacon, 2) start of frame (SOF), 3) selective acknowledgement (SACK), 4) request to send (RTS)/clear to send (CTS), and 5) sound. In SOF, the FC contains transmitter and receiver addresses. Unlike the IEEE 802.11 PLCP header, the FC has its own 24-b cyclic redundancy check (CRC), called the 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 an NACK when it received a valid FCCS part but not the data part. Thanks to the use of NACK, the HPAV transmitter can distinguish channel error from collision error. When the transmitter receives an NACK, it assumes with high probability that the frame error occurred due to the channel error. If a timeout occurs, the transmitter assumes that a collision occurred because there is no response from the receiver. This means that the receiver failed to decode the FCCS part either.

C. *Rate Adaptation*

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

If the transmitter receives an 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 a 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.

IV. 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: 1) impulse noise aware rate adaptation (INARA) and 2) CW size adaptation.

A. *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 μs, which is almost the same as the transmission time for an ordinary data frame. The sounding procedures can be suited for time-division multiple access (TDMA) transmission, which guarantees periodic resource allocation, but is too costly for CSMA/CA transmission. Therefore, we propose a simple-rate adaptation scheme, called INARA, which uses 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 the ACK or NACK frame.

1) NACK with Noise-Type Indication: The rate adaptation scheme in the HPAV standard distinguishes collision error from channel error, but does not differentiate impulsive noise from background noise. When the transmitter receives NACK, it simply retransmits the frame consecutively unless the number

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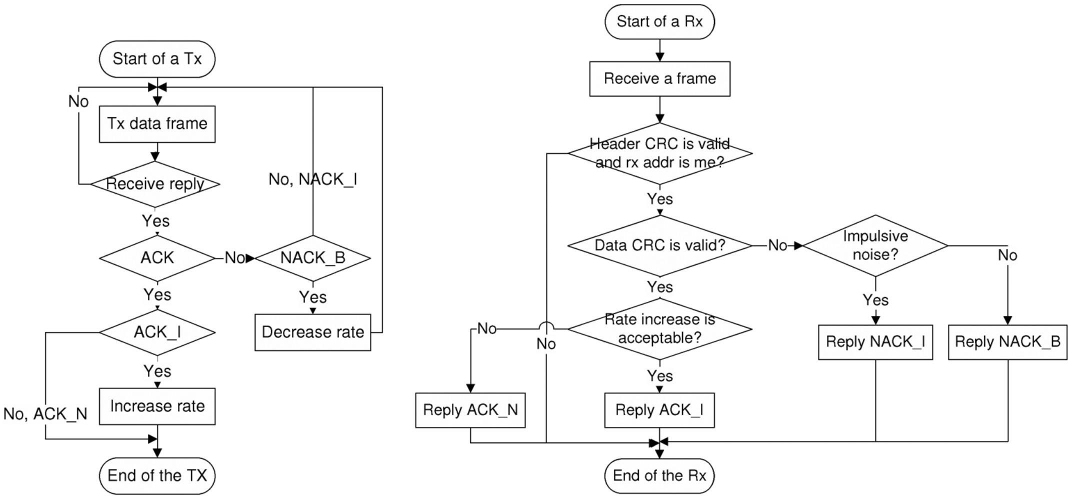
[3] The low and high priorities are (00, 01) and (10, 11), respectively.

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

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



(a) (b)

Fig. 2. Flowchart of INARA. In INARA, the receiver returns the channel status to the transmitter by using ACK or NACK. (a) Transmitter. (b) Receiver.

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 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. Different than this, on NACK_B reception, it retransmits the buffered frame 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 perform 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.

2) Rate Increase ACK: While the NACK with noise-type indication helps the transmitter not to decrease the transmission rate, the ACK frame contributes to a rate increase. A successful frame transmission is made when the receiver decodes 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 a 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.

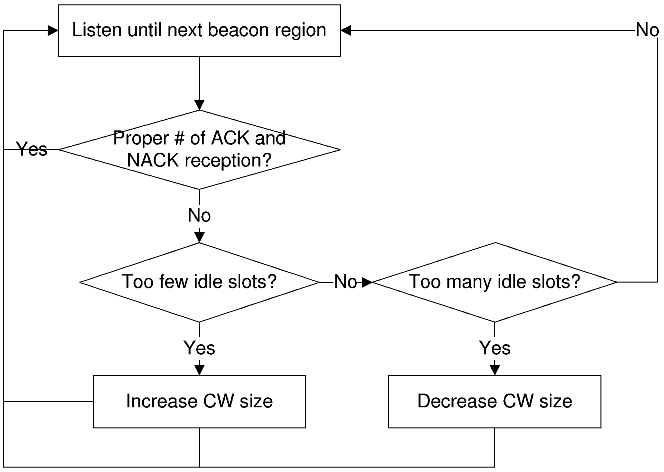


Fig. 3. Flowchart of the adaptive CW adjustment algorithm. The CCo determines and broadcasts the new CW size.

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 [15], 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.

Fig. 2 shows the flowchart of INARA. Since INARA uses one extra bit to indicate the status of NACK and ACK, it can be implemented easily in the HPAV standard. In this flowchart, we do not present the CW increase algorithm of CSMA/CA and the packet dropping case for simplicity.

B. Adaptive CW Adjustment

To find a suboptimal CW size in real time for throughput enhancement, we propose a heuristic adaptive CW adjustment al-

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[6] The default value of Max_NACK_Retries is two.

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

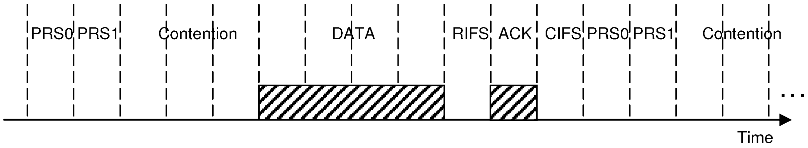

Fig. 4. Transmission example. One transmission cycle if it is from PRS0 to CIFS. Except for "Contention" and "DATA," the other parts have a fixed period of time.

gorithm. 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 of the stations. Each station in the network replaces the current CW with a new one. Fig. 3 shows the flowchart of our heuristic 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 [12].

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.

We reason the threshold values with simple analysis. Fig. 4 depicts one successful data transmission of HPAV. We define the time for a successful transmission as

$$T_s = PRS0 + PRS1 + N\sigma + T_{\text{frame}} + RIFS + T_{\text{ACK}} + CIFS \tag{1}$$

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 μs as listed in Table III, and the variable period of time is given by $N\sigma$ and T_{frame}. If the transmitter's queue is saturated, the T_{frame} is 2640.16 μs.[9] To obtain the duration for a random backoff, we assume a simple collision-free scenario with only a pair of transmitters and receivers in the network. An average number of idle slots for one transmission in this simple network is 3.5 [12], resulting in the time for a successful transmission of 3137.76 μs. Then, in one beacon period (33.33 ms), 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 to not be 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 through simulations, but they still work properly in various conditions. In our analysis, we assume the network is saturated (i.e., all nodes have traffic to send). When the network is not saturated, our proposed scheme runs well too since the network itself has a small number of transmissions and few collisions. This means that without adaptively changing the CW size, our considered system operates well.

TABLE III
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

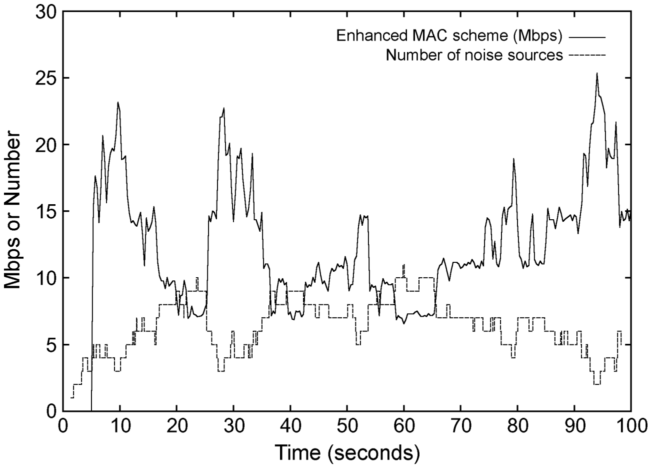

Fig. 5. Time-varying behaviors of the $M/M/\infty//M$ background noise model. The solid and dotted lines represent the throughput performance of the proposed enhanced MAC scheme and the number of noise sources turned on, respectively. In this simulation, there are five transmitters and all of the traffic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

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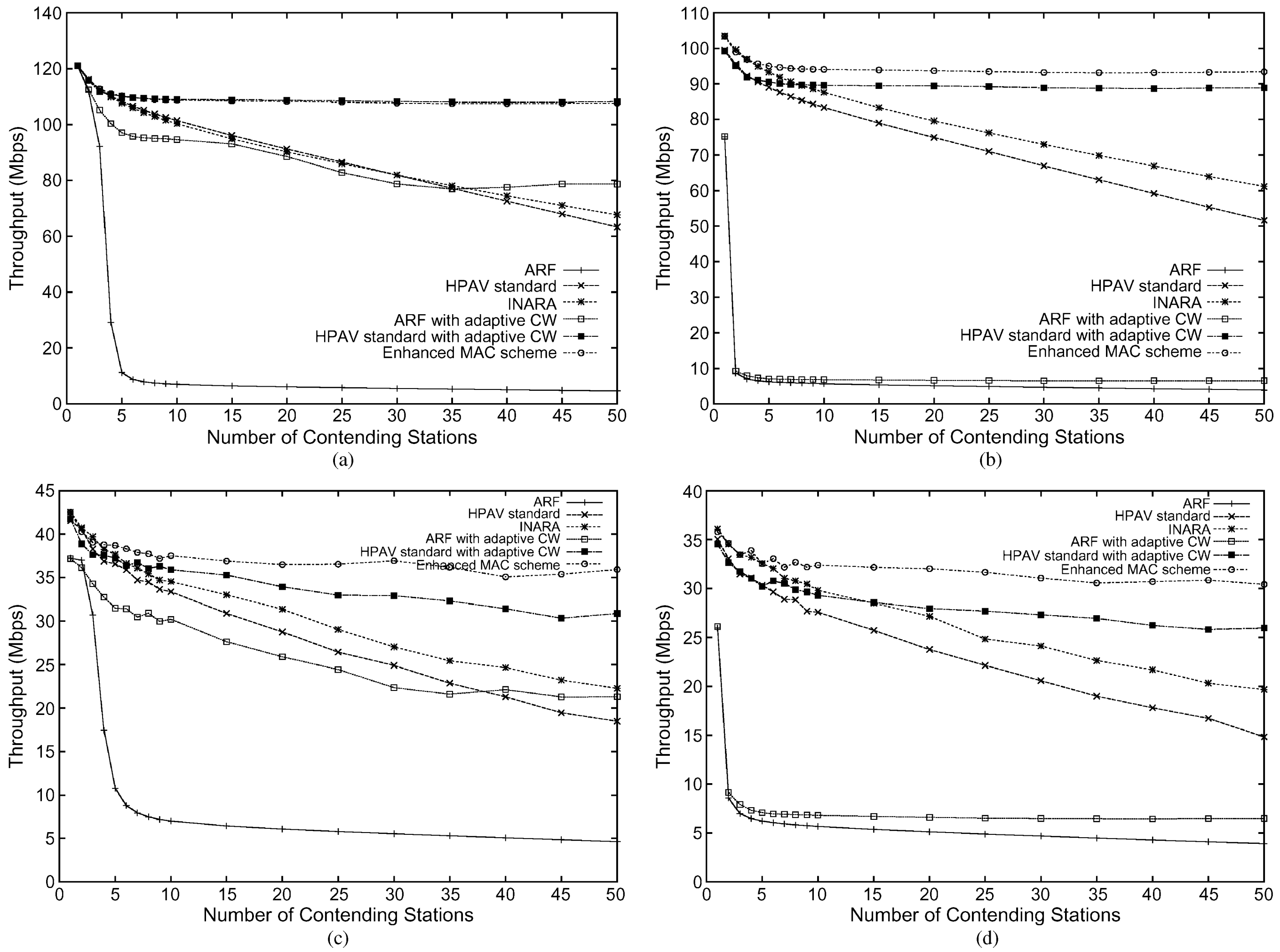
[8] When the transmitter receives an ACK or a NACK, the CCo regards it as successful transmission since the adaptive CW adjustment only cares about the collision problem.

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



(a) (b) (c) (d)

Fig. 6. Saturation throughput performance according to the number of contending stations. Our proposed MAC scheme, which uses INARA and adaptive CW adjustment, always shows the best performance under various noise scenarios. (a) Throughput under the ideal channel. (b) Throughput under impulsive noise. (c) Throughput under background noise. (d) Throughput under impulsive and background noises.

V. PERFORMANCE EVALUATION

We assume that our proposed scheme and the HPAV standard adapt to a stable channel condition somehow. The channel adaptation schemes in [19] and [20] 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, we use an event-driven simulator written in C++.

A. Simulation Settings

We consider a PLC network with one CCo and up to 50 stations. We assume the following three things. First, all of 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 of 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 Mb/s and 9.856 Mb/s, respectively. Table III summarizes the system parameters used in simulations [6].

B. 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/s] and the average service time $1/\mu$ is 10 [s]. If all of the noise sources are on, no transmission can succeed. The maximum transmission rate is achievable when there is no noise source on.

Fig. 5 shows an example of the dynamic behaviors of a background noise environment. The average state duration time is 0.9 [s], and the average number of noise sources is seven. It shows that a smaller number of noise sources on leads to better channel quality as expected.

C. Saturation Throughput

We consider saturation throughput with the simulation time of 10 000 [s], and use the hardly distributed noise scenario in Table I. Fig. 6 shows the saturation throughput according to the number of contending stations under various noise scenarios. The three schemes of ARF, HPAV standard, INARA[10] only use the rate adaptation algorithm, so they lose some throughput with the number of contending stations.

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[10] INARA is the same as that proposed in [18].

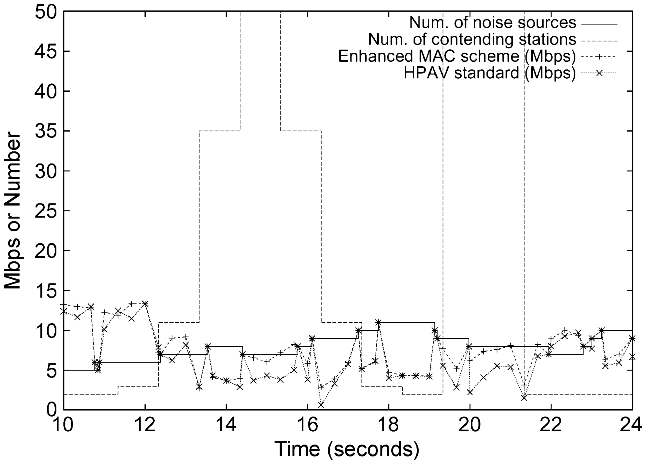

Fig. 7. Throughput performance comparison of our proposed MAC scheme and the HPAV standard under impulsive and background noise. The solid and dotted lines represent the number of noise sources turned on and the number of contending stations, respectively. The dotted lines marked with plus and cross represent the system throughput performances of our proposed scheme and the HPAV standard, respectively.

In an ideal channel environment, transmission error occurs only due to collision. Fig. 6(a) shows the throughput under an ideal channel according to the number of contending stations. Since the ARF scheme has no idea about the transmission error, it achieves very low throughput compared to the others. The HPAV standard and our proposed MAC scheme perform better than the ARF scheme since they 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 increased collision probability. With the adaptive CW adjustment, however, the throughput is virtually stable where there are more than five contending stations. The ARF scheme with the adaptive CW adjustment also works well because the adaptive CW adjustment significantly lowers the collision probability.

The throughput performance under the impulsive noise is shown in Fig. 6(b). 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. The throughput performance of ARF with or without the adaptive CW adjustment does not show much difference since the successful transmission probability is already low due to the impulsive noise, leading most packets to be transmitted at the lowest rate. Fig. 6(c) 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 Mb/s. When there is only one transmitter, all three schemes perform similarly since only the background noise causes the transmission error.

The throughput performances under the impulsive and background noises, that is, a more realistic scenario, are shown in Fig. 6(d). Figs. 6(c) and (d) display a similar tendency. Our proposed MAC scheme achieves the highest throughput since it responds to the transmission failure reasonably well.

D. Dynamic Behaviors

Under the background and impulsive noise environment, we vary the number of contending stations according to the time. Fig. 7 shows the dynamic throughput performances of our proposed MAC scheme and the HPAV standard scheme. The "y" axis represents 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. 6(d). These results confirm that our proposed scheme outperforms the HPAV standard scheme for various scenarios.

VI. CONCLUSION

The power-line channel is different from the wireless channel since it does not have fast fading. It has nonstationary 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: 1) INARA and 2) 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 the PHY layer.

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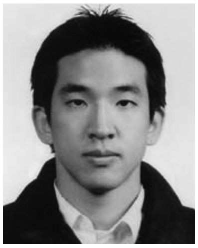

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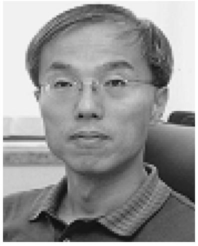

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