Mutual Preamble Detection for Full Duplex Broadband Power Line Communications

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***Abstract*—In this paper, we introduce a new scheme called Mutual Preamble Detection (MPD) to reduce the collision recovery time in broadband power line communication (BB-PLC) networks. Although latest BB-PLC products deliver a physical layer data rate of over 1000 Mbps, this is not efficiently translated into the medium access control (MAC) layer throughput due to several factors, including the long time intervals taken to recover from collisions. To address this, we use in-band full duplex operation to enable network nodes to transmit and simultaneously detect preambles, making them aware of a potential frame collision. With the detection of such a potential collision, we compel the network nodes to refrain from frame transmission in order to avoid the lengthy collision recovery time. The near-zero values of detection error and false alarm probabilities ensure the feasibility of our scheme in typical in-home BB-PLC networks. We present OMNeT++ simulation results to demonstrate the considerable increase in MAC efficiency obtained by using our proposed MPD scheme, over a traditional BB-PLC protocol.**

I. Introduction

Power line communication (PLC) has evolved greatly since the time it was employed by utility companies for monitoring, controlling, and maintaining the power grid [1], [2]. Recent advances in signal processing techniques have enabled PLC to combat the harsh communication environment, to provide high-speed data communication through broadband PLC (BB-PLC) [3]. BB-PLC is attractive due to the throughput and penetration it promises without requiring additional installation costs. The most successful and appealing application of BB-PLC has been in in-home multimedia communication, where it provides high-speed communication over the existing home wiring for applications such as high-definition video streaming, gaming, etc.

The HomePlug AV (HPAV) BB-PLC standard has been quite successful and also been consolidated in the IEEE 1901 standard [3], [4]. HPAV devices promise a physical layer (PHY) data rate of up to 200 Mbps that has further been extended to 1012 Mbps by the HPAV2 standard [5]. However, these high data rates are not reflected in the medium access control (MAC) layer as several overheads reduce the MAC efficiency. For example, in a carrier sense multiple access with collision avoidance (CSMA/CA) operation, overheads like inter-frame spaces (IFS), transmission of frame control (FC), selective acknowledgment (SACK) mechanism, priority resolution slots (PRSs), and back-off time slots consume additional time [4]. Additionally, CSMA/CA operation is also associated with lengthy collision recovery times, which further restricts the achieved MAC throughput. In HPAV, the collision recovery takes a duration of time called the extended inter-frame space (EIFS), which is set to the total duration required to transmit the longest MAC frame and is thus rather long. Despite this, typical BB-PLC protocols, like HPAV, use CSMA/CA mode, since collision detection (CD) requires a station to transmit and sense the channel simultaneously [6, Ch. 5], which was not achieved until recently [7], [8]. The development of in-band full-duplex (IBFD) in BB-PLC offers us an opportunity to implement CD in BB-PLC. Specifically, we propose a mutual preamble detection (MPD) scheme in an attempt to reduce this collision recovery time.

Although IBFD has long been in use, it has only very recently been successfully applied in a BB-PLC system [7], [8]. In our proposed MPD scheme, we enable network nodes with IBFD operation, to simultaneously transmit a preamble, as well as detect one transmitted by other network nodes. Therefore, when two or more nodes transmit a preamble after gaining access to the channel through contention, all the nodes can hear each other and detect a potential collision. In such cases, we enforce the nodes to refrain from transmission to avoid a collision and a long recovery time associated. As a result, the MAC layer overhead can be significantly reduced and the MAC throughput can be effectively increased. We employ typical self-interference cancellation gain values reported in [7] to verify the feasibility of this scheme by calculating the detection error and false alarm probabilities under different channel conditions.

The rest of the paper is organized as follows. An introduction to the composition of a MAC frame interval in CSMA/CA mode as well as concepts of MAC efficiency and throughput are provided in Section II. Our proposed MPD is explained in Section III, where we calculate the preamble detection error rate as well as false alarm rate, and show how MPD is deployed to enable fast collision recovery. In Section IV, simulation results are presented and analyzed. Finally, conclusions as well as some discussions are carried out in Section V.

II. HomePlug AV MAC Frame

MAC frames take various forms when the network is operated under different modes. The CSMA/CA mode, which is employed in HPAV and IEEE 1901, is very efficient in throughput maximization when there is no strict latency constraint for network frame delivery. We focus on the network operation in CSMA/CA mode, and briefly introduce the MAC

Fig. 1. MAC Frame Format of HomePlug AV in CSMA/CA mode

Fig. 2. Activity on the Medium in Case of Collision

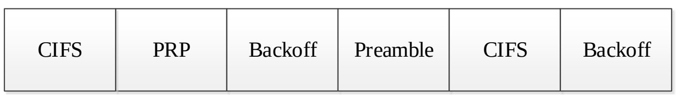

Fig. 3. Activity on the Medium in Case of Collision with our Deployment of MPD

frame structures of HPAV along with the MAC mechanism of HPAV CSMA/CA in Subsection II-A, for the purpose of understanding the benefits of introducing MPD in an HPAV setting. Subsequently, we introduce the concepts of MAC throughput and MAC efficiency in Subsection II-B, which we intend to improve through our deployment of MPD.

A. *MAC Frame Intervals in CSMA/CA Mode*

When an HPAV network is operated under CSMA/CA mode, the MAC frame format is as shown in Fig. 1. A station with data packets to transmit will continuously sense the PLC channel. When the channel is sensed idle for a duration of contention inter-frame space (CIFS), the station will initiate a priority resolution procedure (PRP). The PRP is composed of two priority resolution slots (PRSs). Each data packet is associated with a priority level ranging from 3 (highest) to 0 (lowest). Each PRS corresponds to one priority bit and the priority is resolved bit-by-bit.

Network nodes winning the PRP will start the back-off stage, while the ones losing will continue to listen to the channel. At the start of the back-off stage, if the back-off counter (BC) has not been initialized, BC will be initialized to a random value that is uniformly distributed between zero and a maximum of contention window (CW). The back-off stage is run through several back-off time slots. At every time slot the channel is sensed idle, BC will be decreased by one. If the BC of any node reaches zero, a preamble is transmitted by the node in the subsequent back-off time slot. Network nodes still in back-off, detect the busy channel, stop the random back-off, and continue to listen to the channel. The nodes transmitting the preamble, gain access to the channel, and transmit frame control (FC) of type start of frame (SOF), subsequently followed by the data payload.

When the destination node receives the data payload, it waits for a duration of response inter-frame space (RIFS) before transmitting a preamble, followed by FC of type selective acknowledgment (SACK). In SACK, the network node will transmit an acknowledgment (ACK) or a negative acknowledgment (NACK), depending on whether the payload is decoded successfully or not, respectively. After an interval of SACK, the PLC channel turns idle again.

During the back-off stage, it is possible to encounter a scenario where the BCs of more than one network node are reduced to zero simultaneously. In such a case, all such nodes will transmit preambles in the following back-off time slot, gain access to the channel, and transmit SOF followed by data payload subsequently. These simultaneously transmitted signals collide with each other and are all corrupted. No destination station can detect the data payload, and the PLC channel is kept busy until time-out. As shown in Fig. 2, it takes an interval of extended inter-frame space (EIFS) for the network to recover from such a collision.

When the network recovers from the collision, all the network nodes with packets to transmit are assumed to have won the priority check regardless of priority level. The channel state is deemed idle and all the network nodes start to back-off right away.

It is worth noting, that in Fig. 2, the EIFS is deliberately drawn with an increased length as

$$\mathsf{EIFS} = 2t_p + 2t_{FC} + \mathsf{MaxFL} + \mathsf{RIFS} + \mathsf{CIFS}, \qquad (1)$$

where t_p is time interval of preamble, t_{FC} is the time interval of FC, and MaxFL is the maximum time interval of MAC protocol data unit (MPDU) payload.

B. MAC Throughput and Efficiency

In a typical operation, an MPDU is only transmitted during the time interval when the data payload is sent, and therefore, the peak physical data rates claimed, would be effective only during that interval. In addition to MPDU, there are several overheads constituting a MAC frame interval, as indicated in Section I. We therefore define the MAC throughput to be the average MPDU transmission rate over total time. If in a period of time T, N packets are successfully transmitted, with the physical data transmission rate of those N packets being r_1, r_2, ..., r_N and the data payload transmission durations being t_1, t_2, ..., t_N, we can express the MAC throughput S as

$$S = \frac{1}{T}\sum_{i=1}^{N} r_i t_i. \tag{2}$$

Further, we also define the MAC efficiency to be the ratio of the MAC throughput to the average physical data rate P, with P defined as

$$P = \frac{\sum_{i=1}^{N} r_i t_i}{\sum_{i=1}^{N} t_i}. \tag{3}$$

Thus we can express the MAC efficiency η to be

$$\eta = \frac{S}{P} = \frac{1}{T}\sum_{i=1}^{N} t_i. \tag{4}$$

From (4), we can see that the MAC efficiency is also the ratio of the time taken for MPDU transmission to the total time. The more the time utilized for MPDU transmission, the higher is the MAC efficiency. We know that an increase in the average physical data rate, P, relies on the improvement of PLC channel environment and the evolution of PLC technology in the physical layer. Through the years, the physical data rate of PLC has been considerably increased. However, in order to effectively translate this into increase in MAC throughput, we need to improve η, which is the focus of this paper.

The maximum efficiency of an HPAV network can be computed with the asymptotic assumption, where every network node always has some packets to transmit and the network reaches its saturation throughput. Further, by considering an ideal case where each transmission attempt is successfully acknowledged by the destination node without retransmission, the maximum MAC efficiency, η, of HPAV is obtained with no collisions. Under such conditions, $\max(\eta)$ can be written as

$$\max(\eta) = \frac{\mathsf{MaxFL}}{\mathsf{EIFS} + 2t_{SLOT}}, \tag{5}$$

where $2t_{SLOT}$ is the time interval for two PRSs. With the parameters specified in HPAV [9], we get $\max(\eta) = 78.24\%$. However, practical values of η are much less than $\max(\eta)$ even when the data payload frame length is chosen to be MaxFL. This is due to the fact that there are transmission errors, collisions, as well as back-off time slots associated with transmitting MAC frames.

There are two possible ways to alleviate this degradation. One is to reduce the probability of collision so that collisions occur less frequently, and the other is to reduce the additional time interval introduced by a collision. We address this issue by taking the second approach as explained in the next section.

III. Mutual Preamble Detection

Conventionally, in case of a collision, network nodes have no knowledge of the channel status, and it takes EIFS for the network to recover. However, the introduction of IBFD in BB-PLC provides an opportunity for CD through MPD. The recent work in [7] applied echo cancellation (EC) to suppress the self-interference (SI) caused by the transmitted signal in a BB-PLC system. Based on the specific requirements and constraints in BB-PLC, the authors proposed an implementation of an analog hybrid/circulator for initial isolation, cascaded with a digital canceler for canceling the remaining SI.

With EC applied at the network nodes, the nodes transmitting a preamble are able to detect the presence of preamble transmissions by other network nodes, in which case the nodes gaining access to the channel can be informed of a potential collision beforehand. However, if the SI cancellation achieved by EC is not satisfactory, the MPD may be subject to detection failure and false alarm.

A. Detection Error and False Alarm Rates

We consider a scenario where there are two network nodes A and B, with node A continuously transmitting preambles slot-by-slot, while in each time slot, node B either transmits a preamble or does not transmit one. The behavior of node B can be described as a source continuously transmitting information bits using on-off keying with the preamble signal being the transmission pulse. In a time slot, if node B transmits the preamble, it sends bit ‘1’ to node A while if node B does not transmit a preamble, it sends a bit ‘0’. EC is applied at node A to enable it to continuously detect the information bit sent by node B in each time slot.

We know that the bit error rate (BER) of on-off keying is given as [10, Ch. 5],

$$\mathrm{BER} = Q\left(\sqrt{\frac{E_b}{N_{0,\mathrm{HD}}}}\right), \tag{6}$$

where E_b is the received energy per bit, $N_{0,\mathrm{HD}}$ is the noise power spectral density and $Q(\cdot)$ refers to the Q-function, which is the tail probability of the standard normal distribution. However, note that (6) applies only to half-duplex transmissions. When IBFD is applied, EC may not cancel the SI to the noise floor of $N_{0,\mathrm{HD}}$.

The effective noise floor under IBFD operation can be represented in logarithmic scale as

$$N_{0,\mathrm{FD}} = N_{0,\mathrm{HD}} + (\mathsf{SNR_{HD}} - \mathsf{SCINR}), \tag{7}$$

where the new noise floor is $N_{0,\mathrm{HD}}$ raised by ($\mathsf{SNR}_{\mathsf{HD}}$ – SCINR), where $\mathsf{SNR}_{\mathsf{HD}}$ is the signal-to-noise-ratio (SNR) when the network node is operated in half duplex mode and SCINR is the signal-to-canceled-interference-plus-noise-ratio after the EC, both in dB [7]. Further, the received bit energy $E_b = P_R \cdot t_{pd}$, where P_R is the power of the received signal and t_{pd} is the time interval used for preamble detection excluding roll-off intervals (RIs) on both sides of a preamble interval. Shaped by a roll-off window, RI is used for reducing inter-symbol interference, and the signal detection is not effective in the RI. Hence we only consider $t_{pd} = t_p - 2 \cdot RI$. The received signal power can be expressed as

$$P_R = \int_{f_1}^{f_2} \widetilde{P_R}(f)\mathrm{d}f, \tag{8}$$

where $\widetilde{P_R}(f)$ is the power spectral density (PSD) of the received signal on a frequency f, and f_1 and f_2 are the lower and upper limits of the transmission frequencies, respectively. For HPAV systems, $f_1 = 1.8$ MHz and $f_2 = 30$ MHz [3]. $\widetilde{P_R}(f)$ in turn can be expressed as $\widetilde{P_R}(f) = \widetilde{P_T}(f)|H(f)|^2$, where $\widetilde{P_T}(f)$ is the PSD of the transmitted signal and $|H(f)|^2$ is the channel gain. Further, HPAV and IEEE 1901 devices use a relatively large fast fourier transform (FFT) size for orthogonal frequency division multiplexing (OFDM), producing a small sub-carrier spacing, Δf, in which the power line channel can be safely assumed to be relatively flat [3]. Therefore, we can now write (8) as

$$P_R = \sum_{n \in \mathscr{N}} \widetilde{P_T}(f_n)|H(f_n)|^2 \cdot \Delta f, \tag{9}$$

where f_n is the frequency of the nth OFDM sub-carrier, and $\mathscr{N}$ is the set of all sub-carriers that are used for preamble transmission. We know that power line channels are frequency selective and $H(f_n)$ varies significantly for different n. However, $\widetilde{P_T}(f_n) = \widetilde{P_T}$ is constant for all $n \in \mathscr{N}$ [3], [4]. Therefore, by considering a flat minimum channel gain of $|H_{min}|^2$, we obtain the lower bound of the received power as

$$P_R \geq \widetilde{P_T}|H_{min}|^2 \Delta f |\mathscr{N}|. \tag{10}$$

This received power gives us the received energy as $E_b = P_R \cdot t_{pd}$. With $Q(\cdot)$ being a monotonically decreasing function, and the ratio $\frac{|H_{min}|^2}{N_{0,\mathrm{FD}}}$ decaying with decrease in $|H_{min}|^2$ [7], we obtain the upper bound of BER for IBFD,

$$\mathrm{BER} \leq Q\left(\sqrt{\mathsf{SNR}_{\mathsf{pr}}}\right), \tag{11}$$

$$\text{where } \mathsf{SNR}_{\mathsf{pr}} = \frac{\widetilde{P_T}|H_{min}|^2 \Delta f |\mathscr{N}| t_{pd}}{N_{0,\mathrm{FD}}},$$

and $N_{0,\mathrm{FD}}$ is the effective IBFD noise floor for a channel gain of $|H_{min}|^2$.

To ascertain the exact values of BER for different $|H_{min}|^2$, we consider $\widetilde{P_T} = -50$ dBm/Hz, $\Delta f = 195$ kHz, and $|\mathscr{N}| = 153$ for the preamble signal, in accordance to HPAV [9]. The specification also suggests the preamble detection time as $t_{pd} = t_p - 2RI = 35.84\mu s - 2 \cdot 4.96\mu s = 25.92\mu s$. For the half-duplex case, we let $N_{0,\mathrm{HD}} = -120$ dBm/Hz. As a result, we obtain the values listed in Table I. It is clear from Table I that even in the worst case, $\mathsf{SNR}_{\mathsf{pr}}$ is calculated to be 30 dB and thus, the BER is very small.

TABLE I
PREAMBLE SNR UNDER VARYING MINIMUM CHANNEL GAINS

$\lvert H_{min}\rvert^2$ (dB)	$\mathsf{SNR}_{\mathsf{HD}}$ (dB)	SCINR[1] (dB)	$N_{0,\mathrm{FD}}$ (dBm/Hz)	$\mathsf{SNR}_{\mathsf{pr}}$ (dB)
-5	65	32	-87	60
-10	60	30	-90	58
-20	50	27	-97	56
-30	40	27	-107	56
-40	30	21	-111	50
-50	20	12	-112	40
-60	10	2	-112	30

In particular, we can define the probability of false alarm, P_{FA}, at a network node, to be equal to the probability of detecting a '1' when a bit '0' is transmitted. Thus,

$$P_{FA} = \mathrm{BER}. \tag{12}$$

Similarly, when two network nodes transmit a preamble, the MPD requires each network node to be able to detect the preamble transmitted by the other. Thus the probability of detection error, P_{DE}, in the network, can be defined as

$$P_{DE} = 1 - (1 - \mathrm{BER})^2 = 2\mathrm{BER} - \mathrm{BER}^2 < 2\mathrm{BER}. \tag{13}$$

With typical BER values obtained from $\mathsf{SNR}_{\mathsf{pr}}$ in Table I, we observe from (12) and (13) that both P_{FA} and P_{DE} are near-zero. When more than two network nodes transmit a preamble at the same time, the received signal power at each node is further raised, and the error rates are only smaller.

B. Network Operation with MPD

In our MPD scheme, when more than one node transmit preambles to gain access to the PLC channel, each network node is able to detect the preamble transmitted by the other nodes. If a network node transmitting a preamble detects the presence of a preamble transmitted by any other network node(s), the network node simply relinquishes its access to the channel and stops transmission.

Since all the network nodes are capable of MPD, in cases of multiple preambles transmitted to the power line medium, all the nodes stop their transmission, and the PLC channel becomes idle. On one hand, according to the HPAV protocol, after an idle channel is detected for a duration of CIFS, a new

[1] SCINR values are computed from the echo cancellation gain values reported in [7].

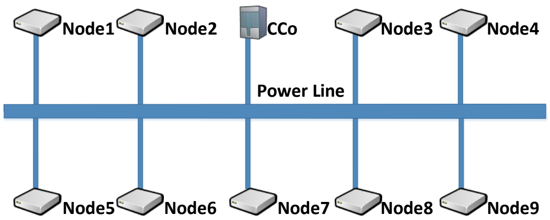

Fig. 4. Network Simulation Topology

TABLE II
SIMULATION PARAMETERS

Parameter	Value
Simulation time T_S	30 s
Number of network nodes	10
CIFS	100 μs
PRS and Back-off time slot t_{SLOT}	35.84 μs
t_p	35.84 μs
t_{FC}	133.92 μs
MaxFL	2341.12 μs
RIFS	140 μs
EIFS	2920.64 μs

MAC frame will be initiated, beginning with PRP. On the other hand, a collision recovery in HPAV requires all the network nodes with packets to transmit to immediately start the back-off without PRP as shown in Fig. 2. Therefore, in our MPD deployment, when the network recovers from collision after $t_p + \text{CIFS}$, we let the network nodes with packets to transmit begin the back-off stage immediately, as shown in Fig. 3. We thereby cut down the time interval required for the network to recover from collision without altering the counters associated with the back-off procedure.

IV. PERFORMANCE EVALUATIONS

We set up a simulation model using a discrete event simulator, OMNeT++ [11], to verify the effectiveness of our deployment of MPD. We first specify the simulation configurations and then present and analyze the simulation results.

A. Simulation Configuration

The simulation topology is shown in Fig. 4. Ten network nodes including the central coordinator (CCo) are interconnected to each other through the power line medium. The network nodes are assumed to always have packets to transmit, consistent with our asymptotic assumption. Half of network nodes are set to transmit packets with priority level 2, and the other half with priority level 1. The simulation parameters are summarized in Table II.

We perform two different simulations. In the first, we change the MPDU interval from 10%MaxFL to MaxFL with a step size of 10%MaxFL. In reality the MPDU interval must be an integral multiple of a physical block. But the simulation settings are intended for the purpose of demonstration. In the second simulation, we change the number of stations from 2 to 10, which is a fair estimate of the number of stations in an in-home scenario at the present. We still keep half of network nodes transmitting packets with priority level 2 and the other half with priority level 1.

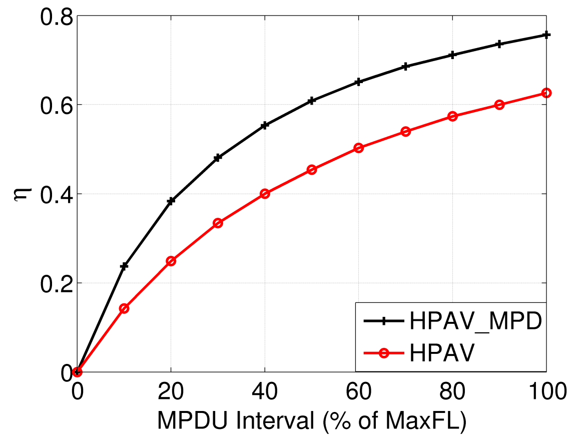

Fig. 5. MAC Efficiency as a function of MPDU Interval.

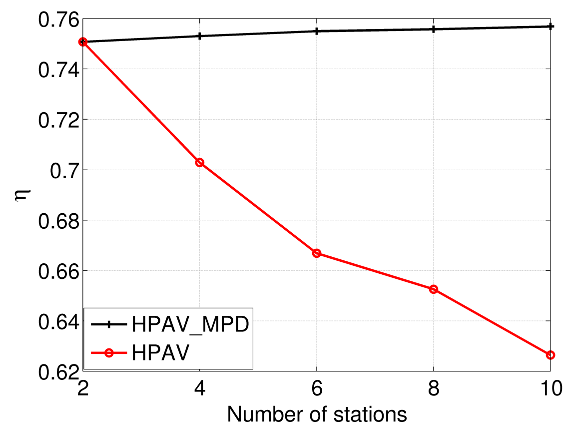

Fig. 6. MAC Efficiency as a function of number of stations.

In our simulations, the total number of transmitted frames with successful acknowledgments is counted as n_{ACK}, and the MPDU time interval of each transmitted frame is noted as t_{FL}. We can therefore calculate the MAC efficiency η in the simulation as

$$\eta = \frac{n_{ACK} t_{FL}}{T_S}, \tag{14}$$

where T_S is the total simulation time (see Table II).

B. Simulation Results and Analysis

The results of the two simulations are shown in Fig. 5 and Fig. 6. In both these, HPAV corresponds to the MAC efficiency performance measured in the original HPAV protocol, and HPAV_MPD is measured when our proposed MPD is employed in HPAV.

The results in Fig. 5 can be comprehended by considering the analysis from [12], according to which the MAC efficiency η is calculated as

$$\eta = \frac{t_{FL}}{(1-P_c)(t_{FL}+\mathsf{TO})+P_c E[t_c]}. \quad (15)$$

where t_c is the total time cost of a collided frame, P_c is the probability of transmission collision and $\mathsf{TO} = E[t_s] - t_{FL}$ is the transmission overhead, with t_s as the total time interval of a successful transmission. Since P_c, $E[t_c]$, and TO are all independent of t_{FL}, in Fig. 5, η increases as t_{FL} gets larger. However, when our MPD is deployed, $E[t_c]$ is reduced considerably. Hence, when MPD is deployed, the MAC efficiency increases significantly, which exhibits the effectiveness of MPD.

As the number of stations increases, the probability of collision P_c also increases. As a result, η in (15) should generally be reduced. This explains the performance with original HPAV shown in Fig. 6, where η drops as the number of stations increases. Since the collision recovery in HPAV is fairly time-costly, the increase of P_c degrades η drastically [13]. It is interesting that, in our deployment of MPD, η marginally increases as the station number increases as can be seen in Fig. 6. In comparison to traditional HPAV, the cost of collision recovery has been greatly reduced. As the number of stations increases, the increase of P_c has very little effect on η, while the increase of η may be attributed to the random back-off procedure of CSMA/CA. The BCs of different network nodes are randomly initialized and those random initialized values are concurrently decremented by one in each idle back-off time slot, which may be a factor contributing to the marginal improvement of η as the number of stations increases. For the same number of stations, the counters associated with back-off procedures evolve the same way in HPAV and in HPAV_MPD. Therefore, HPAV and HPAV_MPD have the same probability of collision for the same number of stations. However, the large difference in Fig. 6 between η in HPAV and η in HPAV_MPD is attributed to the decrease in collision cost when our proposed MPD is deployed. This again proves the effectiveness of MPD.

V. Conclusion

In this paper, we have proposed the deployment of a novel scheme called MPD, to decrease the cost of collision and improve MAC efficiency. We have applied in-band full-duplex operation to HPAV devices and enabled network nodes to detect preambles transmitted by the other nodes, while transmitting preambles themselves. The network nodes are thus made aware of a potential collision beforehand, and are forced to refrain from frame transmission. In this way, we save the lengthy collision recovery time associated with each collision in a CSMA/CA operation, and improve the MAC efficiency significantly, thereby assisting in translating the increase in physical layer data rates into the MAC layer more effectively. Furthermore, by using realistic self-interference cancellation gain values reported for IBFD BB-PLC systems, we formulated the probability of detection error and false alarm for our MPD scheme, and showed them to be near-zero. We have also presented simulation results to demonstrate the effectiveness of MPD in a typical in-home BB-PLC setting. We acknowledge that the shift of traditional half-duplex PLC systems to IBFD operation is a gradual process. When a PLC network contains any device not operating in full-duplex mode, the network could still require a time duration of EIFS for collision recovery. This depends on how many of the contending devices that gain simultaneous access to the channel are IBFD enabled. In such a transition phase, we note that we might not always be successful in avoiding collisions.

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