Rate Adaptation Scheme in Power Line Communication

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***Abstract*—The power line channel is similar to the wireless channel as both are shared medium, thereby transmitting and receiving can not happen simultaneously. However they have different dynamic characteristic. The power line channel does not have fast fading while the wireless channel has. It has impulsive noise while the wireless channel does not have. To reflect these characteristic, we propose a novel rate adaptation scheme in power line communication. Our proposed scheme consists of three procedures: NACK with reason, increase ACK, and fast retransmission. The key idea of our proposed scheme is that the receiver feedbacks the channel information through NACK or ACK message, which makes the transmitter choose proper rate according to the channel condition. The simulation result shows that our proposed scheme adjusts the transmission rate very well to achieve high throughput under various scenarios.**

I. Introduction

Various traditional home appliances are being rapidly replaced by digital value-added ones, and upcoming applications, such as interactive games and voice over IP (VoIP), need communication among the applications. Recently, lots of researches on home networks have concentrated on communication between the applications on multimedia and digital platforms in the local area network environments. In order to provide such connectivity, various home network technologies of wireless and wired have been developed. For wireless solutions, there are IEEE 802.11x wireless local area networks (LANs) [1] and IEEE 802.15.x wireless personal area networks (PANs) [2], which data rates vary from 250kbps to 54Mbps. The drawback of the wireless solutions is that overall performance heavily depends 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. Because they use already existing lines, the wired solutions are suffering less from the interference problem compared to the wireless solutions. Among the power line communication technologies, HomePlug AV (HPAV) is the most promising, which has been standardized by HomePlug Powerline Alliance and follows the HomePlug 1.0 standard. While HomePlug 1.0 was designed to distribute the Internet access, HPAV aims at supporting Audio/Video as well as data traffic within the home. HPAV employs the advanced PHY and MAC technologies and provides up to the PHY rate of 150 Mbps. It uses the same MAC protocol of CSMA/CA as HomPlug 1.0.

Both power line and Ethernet communications use wired line channel, but they have different characteristics. For instance, power line communication cannot detect the collision while Ethernet communication can. Due to the characteristics of power line channel, it is more like wireless channel even if it is wired line. Thus, power line communication cannot use carrier sense multiple access with collision detection (CSMA/CD) which is used in Ethernet. Instead it uses carrier sense multiple access with collision avoidance (CSMA/CA) which is used in wireless communication as a distributed communication protocol.

Past researches of HomePlug have been based on HomePlug 1.0 which is followed by HPAV. Chung et al. [6] presented a detailed analysis for MAC performance of HomePlug 1.0 by using the Markov Chain model. In [7] and [8], Campista et al. proposed throughput enhancement techniques by simply modifying the collision avoidance algorithm in CSMA/CA. These works focused on throughput rather than fairness. Tripathi et al. in [9] worked on achieving the optimal throughput of HomePlug 1.0 MAC protocol, assuming that every station always knows the exact number of contending stations. As this assumption is unrealistic, the optimal throughput is not achievable in real world. Yoon et al. [10] proposed a heuristic throughput optimization algorithm that runs without knowing the exact number of contending station in the network.

Previous researches assumed that the channel is ideal, since these works focused on enhancing or analyzing CSMA/CA protocol. In other words, they assumed that there is no transmission error due to the bad channel. So if the transmission error occurred, it must be due to collision. However this assumption is unrealistic. A state of the art technology in wireless communication to enhance throughput performance under varying channel condition is rate adaptation. It is based on multiple modulation coding scheme (MCS) and achieves high throughput by changing the transmitter's MCS level according to the channel condition properly. It has an issue of how the transmitter changes their rate quickly when the channel is changed.

A lot of researches on rate adaptation have been done for IEEE 802.11 WLANs, i.e. ARF [11], RBAR [12], CARA [13]. To the best of our knowledge, there is no research of the rate adaptation algorithm in power line communication until now. Although the power line channel has similar in characteristic to the wireless channel, the dynamic characteristics are different.

TABLE I
IMPULSIVE NOISE SCENARIOS

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

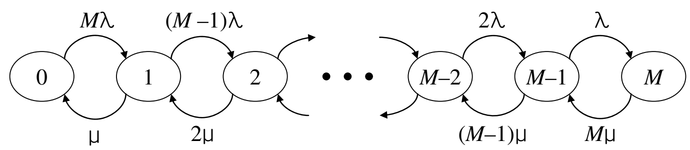

Fig. 1. M/M/∞//M queueing system

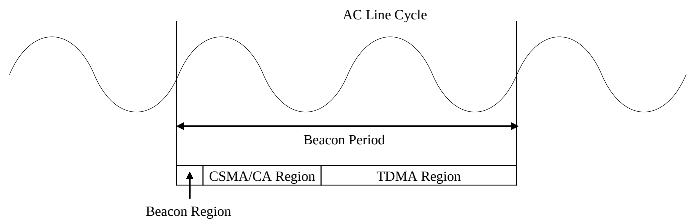

Fig. 2. An Example of HPAV Beacon Period. The Beacon Period is synchronized with AC line cycle and the Beacon Period consists of Beacon Region, CSMA/CA Region and TDMA Region

So the rate adaptation algorithm based on 802.11 cannot be applied for the power line communication directly. Bianchi et al. [14] designed a new MAC using reservation and polling for power line communication, but they did not define a rate adaptation algorithm. In this paper, we propose a rate adaptation scheme that reflects the characteristics of power line channel and apply it to the HPAV standard. As proposed scheme does not assume any underlying protocol structure, it can be used for any architecture of power line communication.

The rest of this paper is organized as follows. Section II reviews and models the characteristic of power line channel. In Section III we briefly review the HPAV standard. Section IV explains our proposed scheme. Through simulations, we evaluate the performance of the proposed rate adaptation scheme in Section V, followed by concluding remarks in Section VI.

II. POWER LINE CHANNEL

Since the purpose of power line is for power delivery, power line channel has lots of noises and suffers from extreme state change. Many researches were carried out investigating the channel characteristics and found that the noise of power line channel can be divided into two things: impulsive noise and background noise.

A. Impulsive noise

Impulsive noise is caused by switching or power supplies, such as switching of rectifier diodes, switching transients. Zimmermann et al. [15] investigated the characteristic of impulsive noise. Duration of impulsive noise is quite short, i.e. around 1 msec, and its power spectral density (PSD) is about 50 dB higher than that of the background noise. Thus, if an impulsive noise occurs while data transmitting, the OFDM symbol within the impulsive noise is damaged and the symbol can not be decoded at the receiver.

Generally, the background noise is regarded as stationary process but the impulsive noise is not due to the short duration. Zimmermann modeled the impulsive noise in partitioned Markov Chain. That is, the inter arrival time (IAT) of impulsive noise has exponential random variable. In [16], Hrasnica et al. simplified the partitioned Markov Chain model into three scenarios as listed in Table I. We used the simplified model in our simulations.

B. Background noise

Unlike the impulsive noise the background noise is stationary process. However the background noise is not additive white Gaussian noise (AWGN) which is generally accepted for background noise in wireless channel. Although transmission under power line channel experiences multipath due to the tab, power line channel does not have fast fading since the multipath effect in power line channel is almost static. The major factor in the power line background noise is noise sources [17] such as refrigerator, personal computer, air conditioner, TV and so on. In order to model the background noise, we use M/M/∞//M queueing model [18] that uses three assumptions. First, each noise source is independent and it has exponentially distributed on/off duration. Second, when a noise source is on, it injects noise into power line immediately. Third, the maximum number of noise sources is limited to M. The states 0, 1, n, and M represent the number of noise sources on, respectively. The PSD of the background noise is in proportion to the number of noise sources.

III. HOMEPLUG AV MAC

A. Hybrid Access Control

The HPAV uses a hybrid access mechanism in order to support various type of services. Fig. 2 shows an example of the HPAV access mechanism that consists of CSMA/CA and TDMA. TDMA can support some services like VoIP that require strict QoS level by allocating resources periodically. On the other hand, CSMA/CA is suitable for urgent data transfer, control message and best effort service. The HPAV and HomePlug 1.0 use the same protocol of CSMA/CA, so two different versions of HomePlug can communicate with each other.

For the hybrid access control, each HPAV network has a coordinator, named Central Coordinator (CCo). The CCo broadcasts a beacon message periodically that contains some information for access control. Every station in the HPAV network can understand the access mechanism by hearing the beacon. Practically, the CCo generates a beacon every two AC line cycles.[1] The beacon indicates, like a map, when

[1]The AC line cycle is 60 Hz in North America and in Republic of Korea. So, the beacon period is 33.33 msec. In Europe, it is 40 msec as the AC line cycle is 50 Hz.

CSMA/CA region and TDMA region start.

B. Header CRC

Like physical layer convergence protocol (PLCP) header of IEEE 802.11, HPAV has PHY header which is named frame control (FC). The FC contains important information such as what kinds of frame[2] this frame is and what kinds of MCS level this frame uses. If the frame is SOF, the FC also includes transmitter and receiver address. The FC is made up of one or two OFDM symbol, and MCS of the FC is very robust since it always sets to QPSK and 1/2 coding. The important difference with IEEE 802.11's PLCP header, the FC has its own 24-bits long cyclic redundancy check (CRC) which is named frame control block check sequence (FCCS). Thus the FC can validate by itself using FCCS without decoding the other part.

C. ACK and NACK

A receiver of IEEE 802.11 cannot reply the CRC error data frame since the receiver cannot decode transmitter address as well as receiver address. However a receiver of HPAV can reply negative acknowledgement (NACK) to transmitter when the FCCS is valid and data CRC is wrong since the FC includes address of transmitter and receiver. As long as the FC is decoded, up to decode data frame's CRC, receiver can reply ACK or NACK to transmitter. The HPAV standard defines that the receiver must reply when transmitter requires the result of frame transmission.

D. Sounding

The HPAV standard defines sounding method in order to estimate exact channel state between transmitter and receiver. At first the transmitter transmits 520-byte sounding frame, which is already known by receiver, using ROBust OFDM (ROBO) modulation, then receiver decides the MCS level of each subcarrier and reply with Tone-Map massage to the transmitter. In following transmissions, the transmitter uses the Tone-Map for data transmitting and the FC indicates which Tone-Map is used for current transmission.

IV. Rate Adaptation Algorithm

Even though the IEEE 802.11 standard does not specify any algorithm or protocol for using multiple transmission rates, most of commercial WLAN devices implement ARF [11] which was originally developed by Lucent Technologies. The HPAV standard also defines a simple rate adaptation scheme. In this section, we review the rate adaptation scheme of the HPAV standard and ARF, then propose out rate adaptation scheme in power line communication.

[2]HPAV has 5 kinds of frame: Beacon, Start of frame (SOF), selective acknowledgement (SACK), request to send (RTS)/clear to send (CTS), and sounding

A. HPAV standard

Unlike IEEE 802.11, in HPAV, collision and channel error can be distinguished at the transmitter with NACK. When the transmitter receives NACK, it can suppose with high probability that the frame error occurred due to the channel error, since the receiver can decode the FC correctly. Thus, the transmitter sets the Backoff Procedure Counter (BPC) value to 0, and chooses a random number between 0 and Contention Window (CW) at the given BPC, and sets the Backoff Counter (BC) at the chosen number. When the timeout occurs, i.e. there is no ACK or NACK for some period, the transmitter supposes a collision occurred, since the receiver cannot decode the FC despite the robustness of the FC. Thus, the transmitter increases BPC by one and sets the BC value at a random number in (0, CW) at the given BPC.

The rate adaptation of the HPAV standard procedure is as follows. If the transmitter receives a NACK, it re-transmits without decreasing the rate until the number of consecutive NACKs reaches Max_NACK_Retries. After Max_NACK_Retries, the transmitter changes the rate to ROBO modulation and completes the buffered frame. At the end of buffered frame transmission the transmitter performs the sounding procedure, and takes new Tone-Map. In case collision occurs, the transmitter retries transmit without decreasing rate until the number of consecutive timeouts reaches Max_Collision_Retries. Then the other procedures are the same as the NACK case. The standard also defines that when the channel SNR becomes better, the receiver tells the transmitter to increase the rate.

B. ARF

ARF is an open loop rate adaptation scheme, and most of the commercial WLAN devices implement it owing to the simplicity. In ARF, the transmitter decreases its rate when there are two consecutive transmission failures and the transmitter increases its rate when there are ten consecutive transmission successes. If right after transmission, after increasing rate, fails the transmitter decreases the rate. Jongseok et al. [13] indicated that the ARF performs poorly since it cannot distinguish transmission error between collision and channel error.

C. Proposed rate adaptation scheme for PLC

The channel estimation procedures (sounding) of the HPAV standard incur a lot of overhead. The detail procedures of sounding is as follows: PRS0, PRS1, backoff, sounding MPDU, RIFS, sounding ACK, CIFS, PRS0, PRS1, backoff, FC, CM_CHAN_EST.IND, CIFS. The average time consumption of sounding procedure is 2558.72 usec which is almost the same as normal data transmission time. The sounding procedure is suitable for TDMA transmission however it is a costly solution for the CSMA/CA with frequent data in/out. Thus we propose a simple rate adaptation scheme for CSMA/CA.

1) NACK with reason: The rate adaptation scheme of the HPAV standard does not suffer the throughput from misleading between collision and channel error, however it suffers the throughput from misleading the reasons of channel error: impulsive noise and background noise. In the rate adaptation scheme of the HPAV standard, the reason why the transmitter should retry until the number of consecutive NACK reaches Max_NACK_Retries[3] is that the transmitter cannot be sure reason of transmission error with one NACK. The reason of one NACK might be the impulsive noise or the background noise. However the reason of Max_NACK_Retries consecutive NACK might be the background noise with high probability. If the transmitter knows the reason of NACK the loss, consecutive transmission failure, does not exist. As our proposed scheme, the receiver sends the NACK with its transmission failure reason, so the transmitter can react quickly. Thus, in our proposed scheme there are two NACK: NACK due to the impulsive noise (NACK_I), NACK due to the background noise (NACK_B). When the transmitter receives NACK_I it retries the buffered frame without decreasing rate. And when the transmitter receives NACK_B it retries the buffered frame with decreasing rate immediately. Since the impulsive noise has average 50 dB larger PSD then the background noise, the RF hardware can detect the impulsive noise while receiving frame.

2) Increase ACK: While 'NACK with reason' deals with when the rate decreases, this scheme deals with when the rate increases. A successful frame transmission stands for the receiver decoded the preamble and data correctly, so the receiver knows current SNR exactly. Like NACK contains the reason, the ACK contains some information that is not the exact SNR but indication of rate increasing. The receiver transmits increase ACK (ACK_I) if the current SNR can support higher MCS level and it transmits normal ACK (ACK_N) if the current SNR is suitable for current MCS level. The transmitter increase its rate if the received ACK is ACK_I, and it holds its rate if the received ACK is ACK_N.

Since there is no fast fading in power line channel, this aggressive increasing scheme is effective. In wireless channel, the SNR increasing at some time does not guarantee general channel improvement, or it might be a sudden improvement by the fast fading. Thus, if rate increases right after SNR improvement, the next frame might be failed. The reason, why the transmitter increases its rate after ten consecutive successful transmissions in ARF, is the ten consecutive successful transmissions might not be a sudden improvement by the fast fading but high possibility of general channel improvement.

3) Fast retransmission: Since the HPAV standard defines explicit NACK, the transmitter can retransmit the buffered frame after receiving NACK. The transmitter already has the buffered frame, then it can retransmit the frame within Response Interframe Space (RIFS)[4]. While the frame transmission, the transmitter makes another frame which is reduced rate version frame, if the transmitter receives NACK_I or NACK_B it makes a fast retransmission with the buffered frame or reduced rate version frame, respectively. Without receiving NACK, i.e. response timeout occurred, the transmitter does not make a fast retransmission. The fast retransmission is not only useful with throughput enhancement but also appropriate for the CSMA/CA concept which allows one successful transmission opportunity to the transmitter who gets the transmitting chance after contending.

The reason, why IEEE 802.11 transmitter cannot make a fast retransmission, the transmitter notified the transmission failure after ACK timeout[5] which is larger than DIFS. So, the other stations are already contending the channel, that is, the transmitter already releases the use of channel.

Fig. 3 shows the flow chart of our proposed rate adaptation scheme at the transmitter.

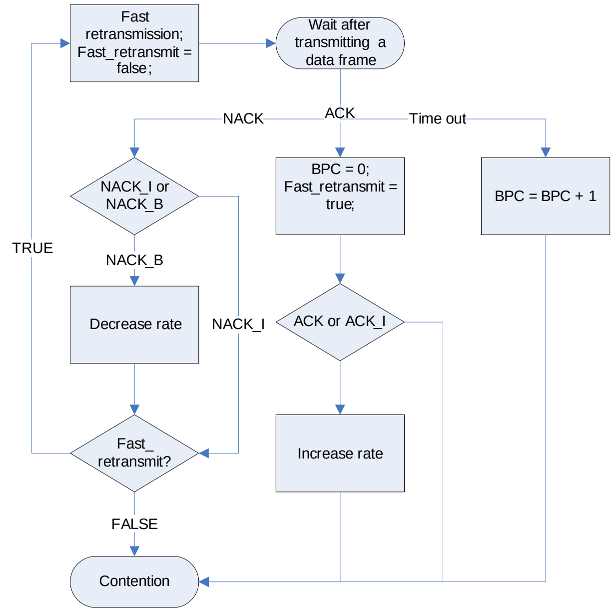

Fig. 3. Flow chart of proposed rate adaptation scheme at the transmitter

V. Simulation Results

In this section, we present the rate adaptation simulation result of the HPAV standard, ARF, and the proposed scheme. We use the event-driven simulator written in C++ language for simulations. The parameters used in simulation are given in Table II. We assume that all flows have the same priority. In the HPAV standard, maximum frame length is not defined by number of bytes but defined by time, named MaxFL. Since we assumed that every station in network always has something to send, that is, all traffic is saturated, so each frame's data transmission time is MaxFL, constantly. The number of MCS level is 14 as the HPAV standard. The maximum and minimum transmission rates are 150.19 Mbps and 9.856 Mbps, respectively.

A. Throughput with ideal channel

Ideal channel means that there is no channel error as past researches assumed. If a transmission error occurred in

[3]default value is 2.

[4]RIFS is the same role of IEEE 802.11's SIFS

[5]SIFS + ACK transmission time + a slot time

TABLE II
THE HPAV SYSTEM PARAMETERS USED IN SIMULATION

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

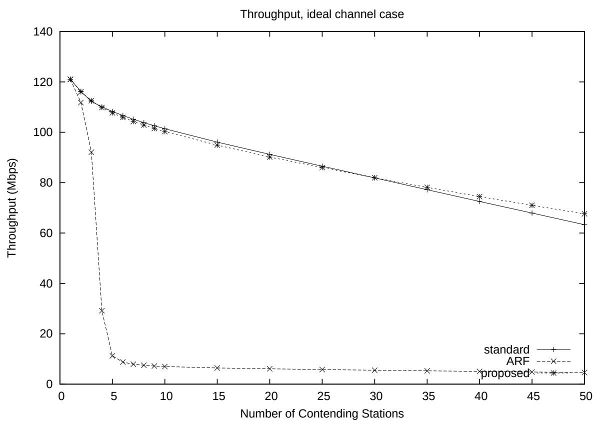

Fig. 4. Throughput with ideal channel

ideal channel, it is always caused by collision. Fig. 4 plots the throughput with ideal channel according to the number of contending stations. Since the ARF cannot distinguish transmission error reason, it gets very low throughput in comparison with the others. In ARF, even the channel is good, the transmitter decreases rate if there is two consecutive transmission failures. The HPAV standard and our proposed scheme performs better since they can distinguish collision and channel error. And the transmitter does not decrease the rate. Our proposed scheme is slightly better than the HPAV standard since the HPAV standard decreases the rate after Max_Collision_Retries consecutive timeout and our proposed scheme will not decrease the rate. The throughput in the HPAV standard and the proposed schemes decrease with the number of contending stations since the more contending station gets the more frame collision.

B. Throughput with impulsive noise

Fig. 5 shows the throughput with hardly distributed impulsive noise scenario according to the number of contending stations. The ARF gets the lowest throughput and our proposed scheme gets the highest throughput. Our proposed scheme performs better than the HPAV standard; since the HPAV standard reduces the rate after Max_NACK_Retries consecutive transmission failures, and our proposed scheme will not reduce the rate because the transmitter knows the reason of NACK. Fast retransmission also reduces throughput loss.

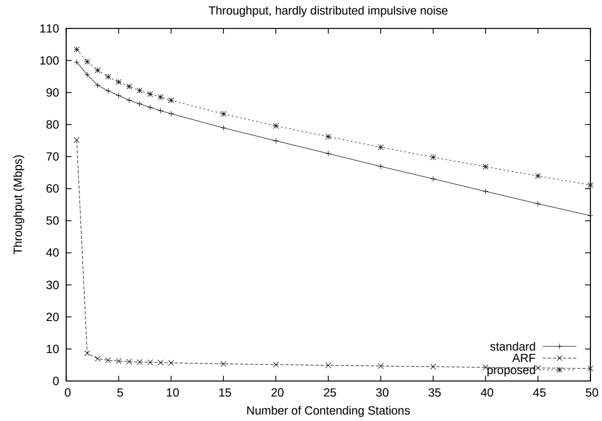

Fig. 5. Throughput with hardly distributed impulsive noise scenario

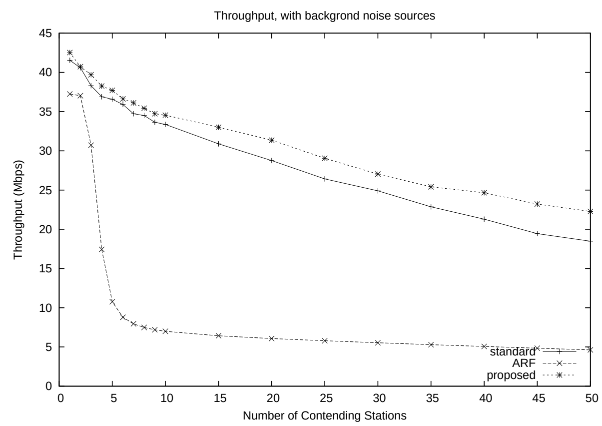

Fig. 6. Throughput with background noise

C. Throughput with background noise

As the background model, we used the M/M/∞//M queueing model proposed in section II-B. The parameter λ and μ set 0.1 and the parameter M sets 14. The throughput with background noise is depicted in Fig. 6. When there is only one transmitter in network, all the three schemes performs similar since every transmission errors are caused by background noise. However the throughput of the ARF drastically decreases with the number of contending stations. Since our proposed scheme decreases the rate with one NACK_B and the HPAV standard decreases the rate with consecutive Max_NACK_Retries NACK, our proposed scheme performs better. Fast retransmission also reduces throughput loss.

D. Throughput with both impulsive and background noise

Fig. 7 shows the throughput with both impulsive and background noises according to the number of contending stations, we uses hardly distributed impulsive noise scenario and the same parameter as section C. Our proposed scheme gets the highest throughput since our proposed scheme can distinguish the transmission failure reason into collision, impulsive noise and background noise.

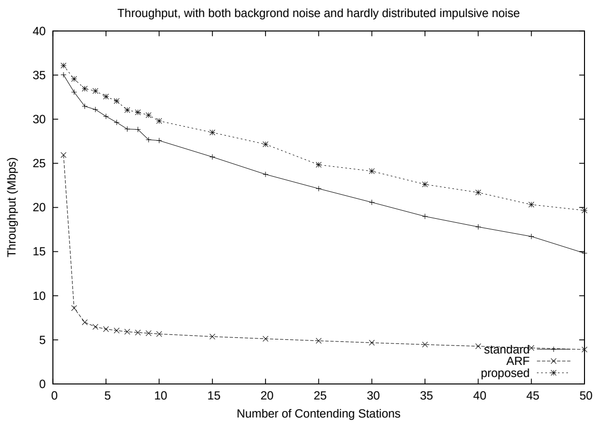

Fig. 7. Throughput with both impulsive and background noise

VI. Conclusion

This paper proposed a novel rate adaptation scheme in power line communication and evaluated our proposed scheme via intensive simulations. Rate adaptation scheme in power line communication is necessary since the power line channel is different from wireless channel, that is, power line channel has no fast fading and impulsive noise. The main idea of our proposed scheme is the classification of transmission error. The transmitter handles the transmission error properly according to the reason in NACK. Also we proposed to use increase ACK which makes the transmitter increase its rate smartly, and fast retransmission. The simulation results show that our proposed scheme reflects the channel variation promptly. Even though our proposed scheme is discussed base on the HPAV standard, it can be easily applied for any other type of power line communication since it is designed for the transmitter to adjust its rate according to the nature of power line channel.

Acknowledgements

This research was supported by the NRL program of MOST/KOSEF, and the ubiquitous Autonomic Computing and Network Project, MIC, in Korea.

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