An Access Control Method for Multipoint Cyclic Data Gathering over a PLC Network

Yuzo OHTOMO*, Takaya YAMAZATO‡ and Masaaki KATAYAMA‡
*Department of Electrical Engineering and Computer Science, Nagoya University. Nagoya, Japan.
Phone: +81-52-789-2729, Fax: +81-52-789-3173, E-mail: ohtomo@katayama.nuee.nagoya-u.ac.jp
‡EcoTopia Science Institute, Nagoya University. Nagoya, Japan.
Phone: +81-52-789-2743, Fax: +81-52-789-3173, E-mail: {yamazato,katayama}@nuee.nagoya-u.ac.jp

***Abstract*—This paper proposes a media access control method for a multipoint cyclic data gathering system, in which each node transmits its data to the base-station periodically. In such condition, by broadcasting ACK/NACK signals from the base-station, the proposed method ensures assignment of a time slot for each node once the node succeeds to transfer its data. It is confirmed that the proposed scheme reduces packet collisions and outperforms conventional slotted-ALOHA scheme in throughput of data even with ACK/NACK errors. Furthermore the proposed scheme realizes adaptive slot assignment under cyclostationary channel environment.**

***Index Terms*—Power-line communication (PLC), access control, data gathering, slotted-ALOHA, cyclostationary noise, smart grid.**

I. INTRODUCTION

The reduction of peaks and total consumption of electric energy is demanded to stop the global warming and to save limited fossil fuels. For effective use of energy, (quasi) real time information of energy consumption is necessary. In addition, information of time varying electric generation by such as photovoltaic or wind is also necessary to introduce the renewable energy in electric power grids [1], [2].

In these applications, multiple nodes report energy consumption or generation periodically to a base-station every few seconds. The amount of data at each node is small as a few bytes, but since there are many nodes in a system, the total required capacity of communication media is not small.

For a communication media of such data gathering systems, radio, conventional cable or power-line communications are possible candidates. The employment of radio communications, however, is not a suitable solution when some nodes may be separated from the base-station by walls. It is not cost-effective to prepare communication cables for low speed data of many nodes. In comparison with these, power-line communication (PLC) connect nodes and the base-station even across walls with low cost because of the legacy infrastructure, power-lines. In addition, there should be already power-lines in the place where electric energy consumption or generation is measured.

In a PLC system, all nodes and the base-station are connected to a power-line network and share the media. Hence, media access control of each node is absolutely imperative.

A traditional method to allocate a channel to many nodes is the demand assignment scheme. The base-station accepts demand from, and assigns a channel to, each node. However, in such systems considered in this paper, since the data of each node is small, the overhead of demand assignment procedure degrades channel efficiency.

Another candidate of multiple access protocol is CSMA, which is often used for sensor network systems [3]. However, in the case of the system discussed in this paper, the performance may degrade because of the hidden terminal problem [4].

The automatic meter reading (AMR) is studied as a data gathering system using PLC [5]. However, in the AMR systems, the interval of data collection is long, which is not applicable for (quasi) real time data gathering.

The remaining protocol for our system is a random access such as ALOHA scheme. In a PLC system, each node shares the same main voltage. And the zero cross of the mains can be used for node-synchronization [6]. Hence, we can employ an access control method, which needs a common clock, such as slotted-ALOHA scheme. The introduction of slotted-ALOHA to the considered system has, however, a problem. Since the generations of packets in each node are periodic, the collisions of the signal also occur periodically.

In the system considered, each node continuously transmit its data for a long period, in which channel condition may vary. Also a new node may be added or a node in the network may be removed. Therefore, an access control method for the considered system is required to adapt these change in the network.

This paper, thus, proposes a new access control method for multipoint data gathering. In the proposed method, by broadcasting ACK/NACK signals, a time slot is exclusively assigned to each node once the node succeeds to transfer its data to the base-station, and reassignment of the slot is executed automatically when the channel condition changes or a node is added/removed.

II. SYSTEM MODEL

Fig. 1 shows the system model discussed in this paper. A base-station (BS) and M nodes are connected to a power-line network, a shared common communication media. At each node, a packet of B[bit] with duration T_p[s] is generated at every T_d[s] and sent to BS. When a packet is not correctly received by BS because of noise or a collision, the packet is simply discarded and no retransmission is requested.

Let us consider that time is divided into frames with length same as a generation period of the packets T_d. Fig. 2 shows examples of relations between the frames and packet generations. In this figure, the arrows express the generations of packets. Since the packets are generated every T_d at each node, in total M packets are generated from M nodes in a single frame. In order to exploit the cyclostationary features of PLC channels, frames are synchronized to mains AC voltage and $2T_d/T_{AC}$ is set to be an integer where T_{AC} is a cycle duration of AC.

Each frame is divided into N slots of the length T_s. In the case of simple slotted-ALOHA, each node transmits its packet to BS as soon as possible, i.e., in the next slot. Since there is no retransmission of a packet, all the time of a frame can be used for uplink. Thus the number of slot in each frame is $N_s = T_d/T_p$.

Not as the simple slotted-ALOHA system, in the proposed system, each time slot is divided into two sub-slots. The first half sub-slot is for transmissions of nodes and the latter sub-slot is for responses from BS. In the system considered in this paper, payload in a packet is relatively small. Thus for fair comparison to slotted-ALOHA, this paper assumes that the response packet from BS has equal duration to data packet from each node. As a result, the length of a slot is $T_s = 2T_p$, and the number of slots in a frame is $N_p = T_d/2T_p$.

In this proposed system, when a packet is generated at a node, it waits for the next frame. The node selects a slot in the next frame and transmits its packet to BS using the sub-slot of the first half of the slot. When BS receives a packet correctly, without a collision or an error caused by noise, it broadcasts an acknowledgment (ACK) to all nodes in the latter sub-slot of the same slot. On the other hand, when BS detects a collision, a parity error in a received packet, or no packet in a sub-slot, it broadcasts a negative acknowledgment (NACK) to all nodes in the latter sub-slot of the same slot.

The ACK/NACK responses are received by all nodes. When a node receives ACK for its packet, the node transmits next packets using the slots of same position of the succeeding frames. On the other hand, if a node receives ACK in a slot in which the node does not send a packet, the node regards the received ACK is for other node and the slot is busy. When a node receives NACK for its packet, the node simply discard the packet, and transmits next packet in the next frame. Then, the slot, in which the node received NACK, is assumed to be free and can be used as a candidate to be selected for next packet transmission.

As noted above, each node expects to receive ACK or NACK for all slots. However, if a node fails to receive ACK/NACK because of noise, the node should judge if the slot is busy or empty. Since there are four possible patterns of judgement as Table I, we compare performance of them in Section IV.

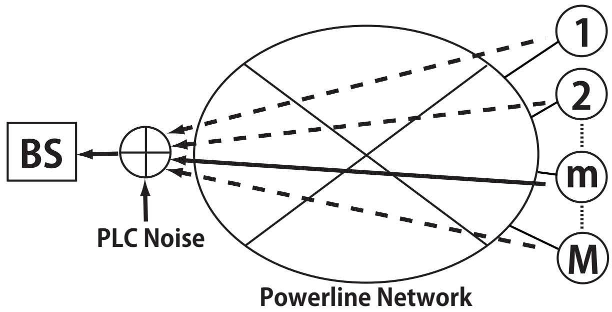

Fig. 1. System model.

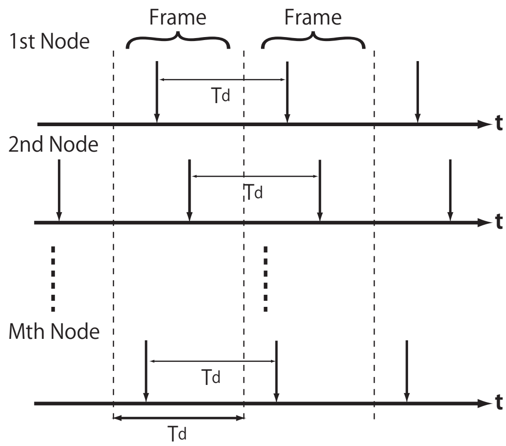

Fig. 2. Relations of the frames and packet generations.

TABLE I
THE JUDGEMENT OF SLOT STATE AT A NODE WHICH FAILED IN ACK/NACK SIGNAL RECEPTION

pattern	node with transmission	node without transmission
1	ACK (success in transmission)	ACK (busy slot)
2	ACK (success in transmission)	NACK (free slot)
3	NACK (failure in transmission)	ACK (busy slot)
4	NACK (failure in transmission)	NACK (free slot)

III. PERFORMANCE ANALYSIS

A. Packet Error Rate of Each Slot

For simplicity, we assume that the channel between BS and each node is flat and time-invariant. The noise at BS and nodes are assumed cyclostationary Gaussian noise whose variance is expressed by a periodic function [7]

$$\sigma^2(t) = \sum_{j=0}^{J-1} A_j |\sin(2\pi t/T_{AC} + \theta_j)|^{n_j}. \qquad (1)$$

In (1), time variation of the variance is denoted as the sum of J functions, where A_j, θ_j, n_j represent the amplitude, peak position in time, and impulsiveness of the noise.

At each node, the data is transmitted using QPSK signals with symbol duration τ. Because the frame length is an integral multiple of the cycle duration of a half main voltage, the variance at the b-th symbol ($b = 0, 1, \cdots, B/2 - 1$) of the i-th slot ($i = 0, 1, \cdots, N - 1$) is the same for all frames and written as $\sigma_{i,b}^2 = \sigma^2(T_s i + \tau n)$. The bit energy of the received signals at BS is denoted as E. Then, the symbol error rate at the b-th symbol of the i-th slot without collision is

$$P_e(i, b) = \text{erfc}\left(\sqrt{\frac{2E}{\sigma_{i,b}^2}}\right), \quad (2)$$

and the packet error rate at the i-th slot without collision is

$$e_i = 1 - \Pi_{b=0}^{B_d/2-1}(1 - P_e(i, b)). \quad (3)$$

In this paper, we assume that a packet is assumed to be error when more than one symbol error occurs.

B. Average SNR

Since the noise power is time-variant, the average SNR is defined as

$$\overline{SNR} = \frac{1}{NB_d/2} \sum_{i=0}^{N-1} \sum_{b=0}^{B_S/2-1} \frac{2E}{\sigma_{i,b}^2}. \quad (4)$$

C. Throughput

In this paper, the throughput of the system is defined as an expected value of the number of packets received at the BS without a collision and an error caused by noise. Then the throughput η is denoted as

$$\eta = \sum_{s_i \in \mathcal{S}} (1 - e_i), \quad (5)$$

where s_i is the i-th slot and $\mathcal{S}$ is a set of slots in which only one node transmits. If the influence of the noise can be ignored, the throughput equals to the number of the nodes ($\eta = M$) when $N > M$. When $N < M$, the throughput is smaller than the number of slots ($\eta \leq N - 1$), because a collision occurs in at least one slot.

D. Channel Capacity per a Frame

The channel capacity per frame C[packet/frame] is written by

$$C = \sum_{i=0}^{N-1} (1 - e_i). \quad (6)$$

This is the maximum throughput when all slots are assigned to the nodes. If the influence of the noise can be ignored, it is clearly that the channel capacity is equal with the number of the slots($C = N$).

TABLE II
PARAMETERS FOR NUMERICAL EXAMPLES

Access Control Method	Proposed	s-ALOHA
Mains Frequency:$1/T_{AC}$	60Hz	
Frame Length:T_d	1s	
Data:B_d	100bit	
Slot Length:T_s	0.5ms	0.25ms
Number of Slots per a Frame:N	2000	4000
Packet Duration	0.25ms	
Carrier Frequency	250kHz	
Band Width	400kHz	

TABLE III
POWER-LINE NOISE PARAMETERS

parameter	A_0	A_1, θ_1, n_1
Noise-A	0.819	0.160,0.150,5.00
Noise-B	0.230	1.68,0.155,2.82

IV. NUMERICAL EXAMPLES

In this section, we evaluate the proposed method by comparing with slotted-ALOHA. In slotted-ALOHA, when a packet is generated, it is transmitted in the next slot immediately. Since each node does not retransmit the packet, the sub-slot of the latter half for the ACK/NACK signals is not necessary. Hence, the number of slots per a frame increases in comparison with the proposed method. In this paper, slotted-ALOHA will have the twice larger number of slots than that of the proposed method. Parameters used for numerical evaluations are shown in Table II.

In Japan, the regulations allow both narrow-band (10-450kHz) and wide-band (2-30MHz) for power-line communication system. Because, a wide-band system is not allowed to use outdoor, we assume a narrow-band system in this paper.

A. Evaluations without noise

Fig. 3 shows the variation of the throughput by the progress of time when all nodes are started up all together. No noise is considered in this figure. The channel capacity of the proposed method by using (6) is also shown in the figure. In this time, the number of nodes is $M = N = 2000$. The throughput of slotted-ALOHA is constant regardless of progress of time. On the other hand, in the proposed method, the throughput becomes larger with progress of time. This confirms that the slots are assigned to the nodes with progress of time, and collisions of the packets decrease. As the result, the throughput of the proposed method is smaller than slotted-ALOHA just after start-up, but it becomes larger than conventional method after several frames. And then, after about 15 frames, the throughput achieves $M = 2000(= N)$. From this, we confirm that the one to one assignment of the all slots to nodes is achieved.

Fig. 4 shows the throughput characteristic for different number of nodes in a steady state. According to Fig. 4,

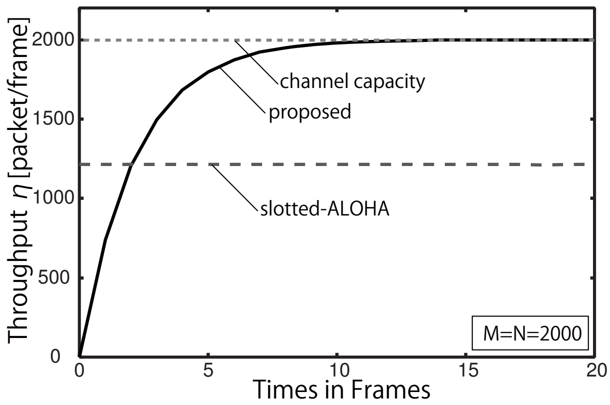

Fig. 3. The variation of throughput by the progress of time without noise.

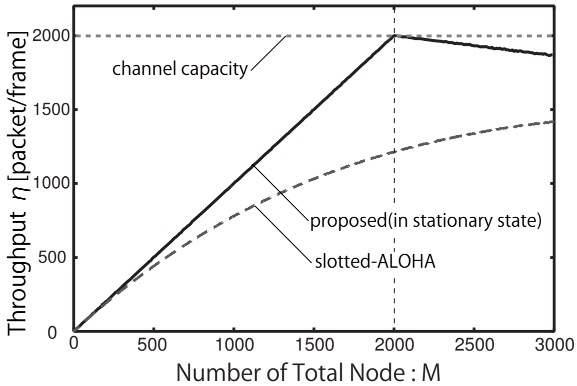

Fig. 4. The throughput characteristic without noise.

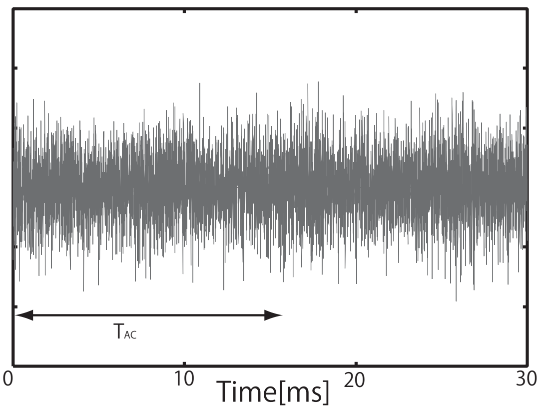

Fig. 5. Noise waveform A.

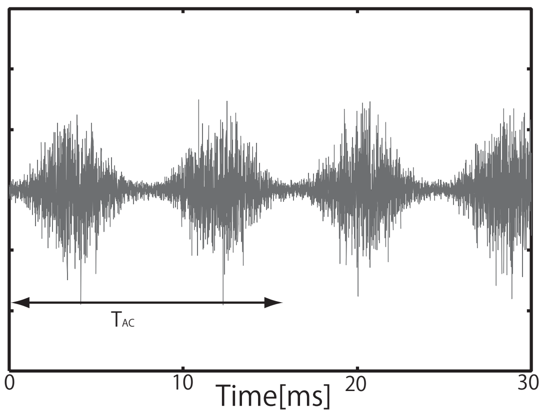

Fig. 6. Noise waveform B.

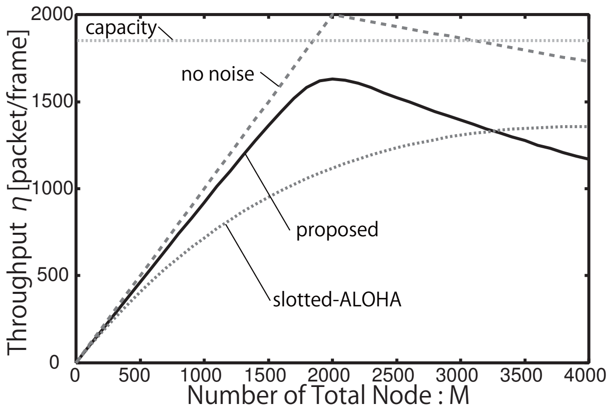

Fig. 7. The throughput characteristic under Noise-A.

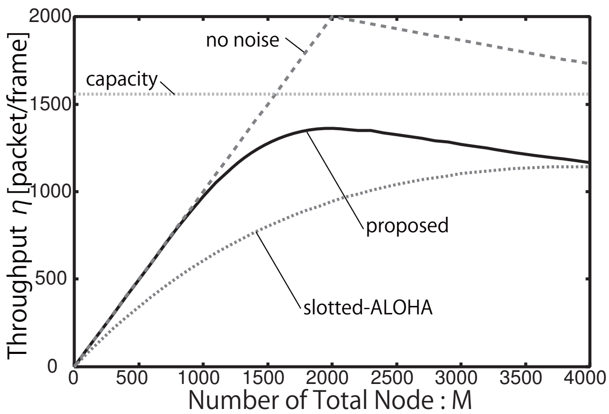

Fig. 8. The throughput characteristic under Noise-B.

the proposed method has a better characteristic than slotted-ALOHA. When $M \leq N$, we observe that the throughput accord with the number of nodes. From this, we confirm that the slots are assigned to each node and a collision does not occur.

B. Evaluations under power-line noise

Parameter of the noise used for evaluations is shown in Table III. Figs. 5 and 6 show examples of the noise waveforms.

Figs. 7 and 8 show the throughput characteristic for different number of nodes under power-line noise A and B. In these figures, only errors at BS are considered and response of BS is assumed to be error free. The throughput without power-

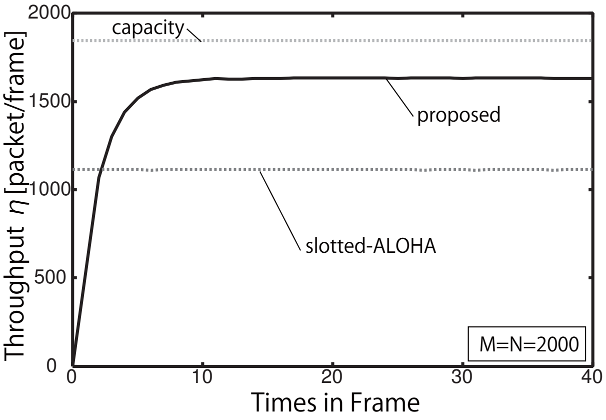

Fig. 9. The variation of throughput by the progress of time under Noise-A.

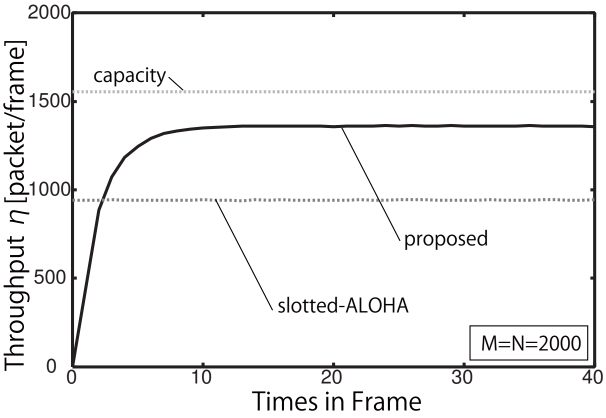

Fig. 10. The variation of throughput by the progress of time under Noise-B.

line noise in Fig. 4 is also shown in these figures. According to Figs. 7 and 8, the proposed method has larger throughput than slotted-ALOHA even with errors by noise at BS.

In the case of Noise-A, the throughput degrades by the influences of the noise for every M. On the other hand, in the case of Noise-B, noise does not degrade the throughput when the number of nodes is small. In the proposed method, each node continues to use the same slot once it gets ACK until a transmitted packet is lost by the noise. Thus, if a node is assigned to a slot with low noise-level, it may continue to use the same slot without error. On the contrary, a slot with high noise-level has high probability to be released by a node assigned to the slot because of error. This means that the proposed method has capability to assign slots with lower noise-level first. This is reason of the good performance of the proposed method under Noise-B. However, when the number of node becomes larger, it is necessary to use slots with high noise-level and the influence of the noise is clearly shown.

When M becomes very large, throughput of the proposed method decreases less than slotted-ALOHA because of collisions. However, by comparing the maximum throughput, the proposed scheme still outperforms slotted-ALOHA.

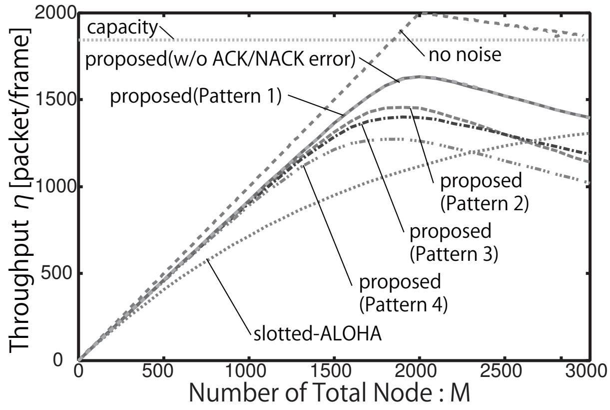

Fig. 11. The throughput characteristic with ACK/NACK errors (under Noise-A).

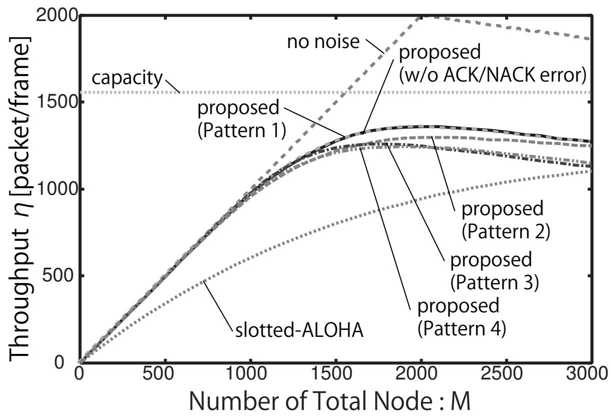

Fig. 12. The throughput characteristic with ACK/NACK errors (under Noise-B).

Figures 9 and 10 show the variation of the throughput by the progress of time when all nodes are started up all together. According to these figures, in the both cases of noise A and B, the proposed method outperform the slotted-ALOHA scheme after several frames, and it arrives the convergence in around 15 frames.

C. Evaluations with ACK/NACK errors

Figures 11 and 12 show the throughput characteristic with ACK/NACK errors for different number of nodes under power-line noise A and B. The same signal to noise ratio and noise statistic are assumed for all node and BS. The four judgement patterns of Table I are considered. It is note worthy that judgement pattern 1 achieves the same throughput as that of no ACK/NACK error shown in Figs. 7 and 8.

Figures 13 and 14 shows the variation of the throughput by the progress of time. It is confirmed that the system with judgement pattern 1 behave same to the system without ACK/NACK error.

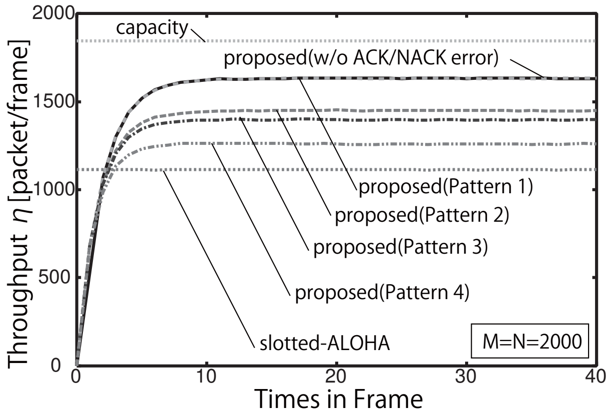

Fig. 13. The variation of throughput by the progress of time with ACK/NACK errors (under Noise-A).

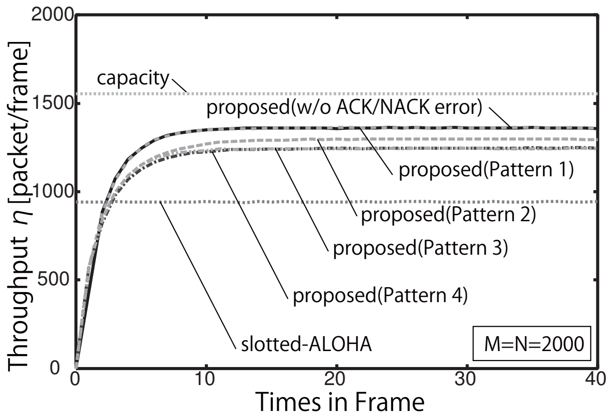

Fig. 14. The variation of throughput by the progress of time with ACK/NACK errors (under Noise-B).

V. CONCLUSION

In this paper, we propose the access control method for multipoint data gathering. By broadcasting ACK/NACK signals, the proposed method ensured assignment of a time slot for each node once the node succeeds to transfer its data to the base-station. The numerical examples show that the proposed scheme achieves larger throughput in comparison with slotted-ALOHA. In addition, we confirm that it is possible to avoid the effect of the ACK/NACK errors.

The feature of the periodic packet transmissions of the proposed method has some similarities to Packet Reservation Multiple Access (PRMA) [8]. However, in the PRMA scheme, the same slot in every frame is allocated to a node until the node finishes its transmission spurt. Thus the throughput degrades if the characteristics of a PLC channel varies before the termination of the spurt. On the other hand, in the proposed method, ACK/NACK broadcasting is used to assign only a slot in the next frame. This makes it possible to realize the autonomous slot assignment adaptive to the change of nose condition. In fact, the numerical example show that the proposed method can finish the allocation procedure in around 15 seconds even if all nodes are started up at the same time. This means that the proposed method can follow abrupt changes of characteristics of PLC channel in a few, say, 15 frames. In this paper, we assume that the transfer functions between BS and all nodes are flat and time-invariant. However, if the channels for every node are different, still the proposed method can realize the adaptive slot assignment.

ACKNOWLEDGMENT

A part of this work is supported by a joint research project of EcoTopia Science Institute of Nagoya University and Chubu Electric Power Company.

REFERENCES

[1] Y. Chen and K. Hwang, "A Reliable Energy Information System for Promoting Voluntary Energy Conservation Benefits" *IEEE Transaction on Power Delivery*, Vol. 21, No. 1, January 2006.

[2] T. F. Garrity, "Getting Smart", *IEEE Power and Energy Magazine*, Vol. 6, Issue 2, pp. 38-45, March-April 2008.

[3] I. Demirkol, C. Ersoy, and F. Alagoz, "MAC Potocols for Wireless Sensor Networks: A survey", *IEEE Communications Magazine*, pp. 115-121, April 2006.

[4] M. Katayama, "Power-Line Communications and their Technical Issues(in Japanese)", *IEICE Fundamentals Review*, Vol. 2, No. 1, pp. 35-47.

[5] A. Zaballos, A. Vallejo, M. Majoral and J. M. Selga, "Survey and Performance Comparison of AMR Over PLC Standards" *IEEE Transaction on Power Delivery*, Vol. 24, No. 2, Aplil 2009.

[6] T. Kistner, M. Bauer, A. Hetzer and K. Dostert, "Analysis of Zero Crossing Synchronization for OFDM-Based AMR System", *IEEE International Symposium on Power Line Communications and its Applications*, pp. 204-208, April 2008.x

[7] M. Katayama, T. Yamazato and H. Okada, "A Mathematical Model of Noise in Narrowband Power Line Communication Systems", *IEEE Journal on Selected Areas in Communications*, Vol. 24, No. 7, pp. 1267-1275, July 2006.

[8] D. J. Goodman, R. A. Valenzuela, K. T. Gayliad and B. Ramamurthi, "Packet Reservation Multiple Access for Local Wireless Communications", *IEEE Transaction on Communication*, Vol. 37, No. 8, pp. 885-890, August 1989.

[9] Y. Ohtomo, T. Yamazato and M. Katayama, "An Access Control Method for Multipoint Data Gathering over Power-Line Communications(in Japanese)", *Technical Report of IEICE*, vol. WBS2009-13, pp. 37-42, July 2009.