A Simulation Study of the PLC-MAC Performance using Network Simulator-2

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Abstract— **Power line communication (PLC) technology can be a viable solution for the future ubiquitous networks because it provides a cheaper alternative to other wired technology currently being used for communication. However, for the better performance of PLC-based networks, their physical layer and medium access control (MAC) protocols need to be a lot more enhanced. Recently, many physical frame encoding technologies have been developed, but the MAC protocols still need more consideration because of the unique characteristics of power line channels. In this paper, we describe an overview of the Korea Standard power line MAC protocol (called "KS-MAC"). We also report the simulation results performed with the well-known simulation tool of network simulator-2 (i.e., NS-2) and compared with the actual field test data.**

***Keywords*— Powerline Communication(PLC), MAC, NS-2**

1. Introduction

In the future, a variety of networking technologies will be used in combination at a same region. Broadband power line communication (BPLC) is one of the competitive options which can provide data communication effectively by utilizing pre-existing power distribution networks. BPLC can provide relatively reliable and high speed data communication, and the extensive coverage in a low cost. However, several limitations are yet to be tackled to raise its standard for its active use in the real scenario. Firstly, the power line is a noisy medium for data communication due to several noise sources such as electrical appliances and radio signal interferences. Secondly, the capacity of power line may decrease with more number of users sharing the medium. Moreover, throughput per user will be severely reduced as a result of probable increase in collision. Thirdly, the signals in power line suffer intense attenuation and distortion due to the topology of power distribution network and load impedance fluctuation over the power line [1].

To achieve reliable, high-speed and extensive coverage power line communication, further research is required especially in the area of physical and medium access control (MAC) layers. In the physical layer of BPLC, robust signal modulation and data coding scheme are needed. Recently, several improved physical modulation techniques were developed such as orthogonal frequency division multiplexing (OFDM)[2] which is adopted by HomePlug[3] and OPERA[4] standards. However, most of the existing MAC protocols for PLC are just based on wireless MAC technologies such as CSMA/CA and TDMA. Thus, it still needs more advanced MAC protocols which are suitable for the power line medium and the topology of power distribution network.

Because of some similarity between the power line medium and the wireless medium, many existing PLC MAC protocols are based on wireless MAC techniques. Generally such protocols classified into three main groups, which are contention-based, contention-free, and hybrid MAC.

The CSMA protocol family such as CSMA/CD[5] and CSMA/CA[6] are the most popular contention-based MAC protocols. The ALOHA[7] protocol family and inhibit sense multiple access (ISMA)[8] protocol are other examples of contention-based MAC. In general, contention-based schemes are inherently distributed and not require central coordination. Such protocols usually show better performance in the large scale networks than the contention-free MAC. Contention-free MAC protocol such as TDMA and token ring protocol guarantees some bounded access delay. Thus, it is more suitable for the traffic that requires QoS. However, the difficulty in accurate time synchronization between stations causes problems in scheduling. With the large network size, long round-trip time is also a disadvantage.

To take advantage of both contention-based and contention-free MAC protocols, hybrid MAC protocols which combine CSMA and TDMA scheme were also suggested. Such protocol provides QoS capabilities in a distributed manner. However, the beacon generation can be an overhead and complexity of MAC protocol design can be a problem. HomePlug[3] standard uses hybrid MAC based on CSMA/CA protocol to guarantee QoS requirements.

In this paper, we introduce the Korea standard PLC MAC protocol, named KS-MAC[9], which was developed for high speed power line data communication in Korea, 2006. We also suggest a simulation technique of MAC protocol by using network simulator-2 (NS-2)[10]. We have made a model of KS-MAC by using NS-2. Based on this, we evaluate the

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performance of KS-MAC protocol in various scenarios, and also we verify the accuracy of our simulator by comparing the results of simulation with the actual field test results.

2. Description of KS-MAC Protocol

In the KS-MAC, the multiple access method is based on the CSMA/CA which is standardized in ISO/IEC 8802-11[6]. It consists of two mechanisms: *carrier sense mechanism* and *back-off mechanism*.

The carrier sense again is performed by two methods that include the physical carrier sensing and the virtual carrier sensing. In the physical carrier sensing, the preamble detection is performed by the physical layer, while the virtual carrier sensing is implemented in the MAC layer, in which the control frames are exchanged to obtain the amount of time when channel is busy. The back-off mechanism is used to reduce the probability of collision. Each station waits within the contention window before attempting to transmit a new frame so that the frame transmission is distributed. Inter Frame Space (IFS) is defined to give a priority among the frames. The length of four different IFS is described below and shown in Fig. 1:

- **SRIFS**: The IFS before transmitting the response frame if the previous received frame was short length frame.
- **SCIFS**: The IFS before starting a new contention if the previous received frame was short length frame.
- **LRIFS**: The IFS before transmitting the response frame if the previous received frame was long length frame.
- **LCIFS**: The IFS before starting a new contention if the previous received frame was long length frame.

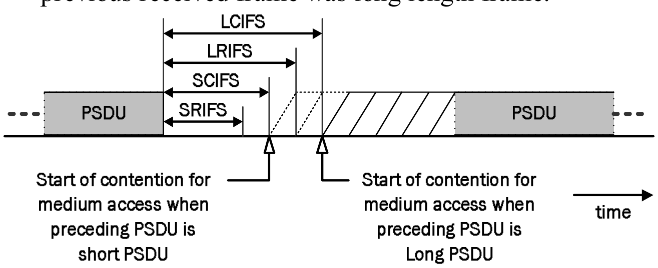

Fig. 1. Four different types of Inter Frame Space

In the back-off procedure, the size of contention window (CWS) is determined after monitoring the network traffic in a given period. The equation for obtaining CWS is defined as follow:

$$\tilde{n}(t) \approx 1 + \frac{E[c(B)](W(t)+1)}{2B} \cdots (1)$$

$$\tilde{n}(t+1) = \alpha \tilde{n}(t) + (1-\alpha)\frac{\sum_{i=1}^{q} \tilde{n}(t-i)}{q} \cdots (2)$$

$$W(t+1) = \tilde{n}(t+1)\sqrt{2T} \cdots (3)$$

$\tilde{n}(t)$: Estimated number of node
B : Periodic time duration for estimating the next CWS
$E[c(B)]$: Number of BUSY slots in B
$W(t)$: Size of the current CWS
α : Weight factor of the current estimated CWS
q : Last estimated number of node
$\sqrt{2T}$: Coefficient factor of contention window
$W(t+1)$: Newly obtained CWS

The adaptive contention window is used to reduce the probability of collision under 10%. Each station generates the back-off value within the individual contention window size. The obtained back-off value is decreased by 1 by time slot as time passes. When the back-off value is 0, the station can start its transmission. If the station detects frame transfer of other station, then the back-off procedure is postponed to next contention. The back-off process is resumed with the suspended back-off value when the next contention starts.

In the KS-MAC, the available data size per frame is changed according to the channel status of the power line. Segmentation occurs when the service block is larger than the available data size. The segmented frames are transmitted by using transaction combo technique. Each communication consists of either single or multiple transactions. The transaction starts with the data frame and ends with the response frame. The transaction combo is a series of transactions. The continuous transaction is ensured by SRIFS which is a shortest inter frame space. Fig. 2 shows the transaction combo to transfer three segmented frames.

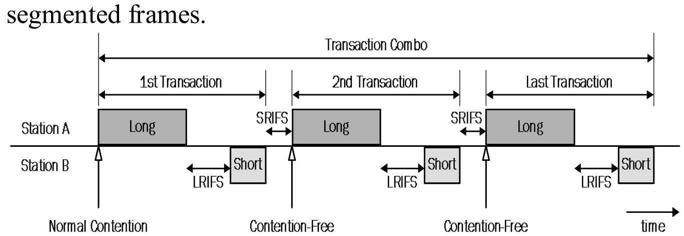

Fig. 2. Transaction Combo Technique

All stations have a group id (GID), used to identify a logical network, called a *cell*. If a station belonging to a particular cell wants to send a frame to another station belonging to some different cell, there should be a special node that can relay the frame. Such a special node is called as “Cell Bridge (CB)” or “Repeater” by the definition in the KS-MAC standard. A slot reservation technique is required when a CB relays a frame between two cells, and it can be used to give higher priority to the CB for relaying the frame. Fig. 3 illustrates the detail of slot reservation technique.

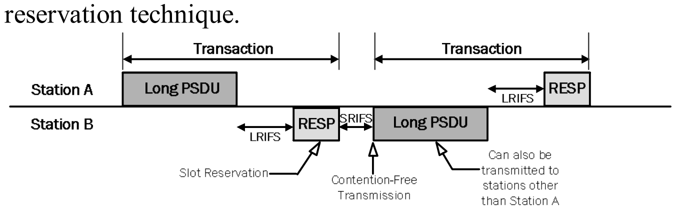

Fig. 3. Slot Reservation Technique

If the station (CB) wants to reserve the next time slot, it set the slot reservation bit in the response frame before sending. Other stations decode the response frame and notice the reservation of next time slot.

3. KS-MAC Modeling with Network Simulator-2

A. Overview of NS-2

The Network Simulator version 2 (NS-2)[10] is a discrete event simulator targeted for the networking research. NS-2 has been heavily used in the data networking research over the past decade, since it was first released by Lawrence Berkeley National Laboratory in 1995.
The core of NS-2 is written in C++, but the C++ simulation objects are also linked to shadow object in Object Tcl (OTcl). Thus, simulation scripts are written in the OTcl language. This structure permits simulations to be written and modified in an interpreted environment without recompiling the simulator at each time a structural change is made. NS-2 has includes an animation object known as the Network Animator (nam), used for visualization of the simulation output and for graphical configuration of the simulation scenarios.

For NS-2 simulation, we have to create a network topology which describes the scenario. Similarly, we have to create nodes, links, and traffic. Defining a node structure is the most essential procedure for the simulation.

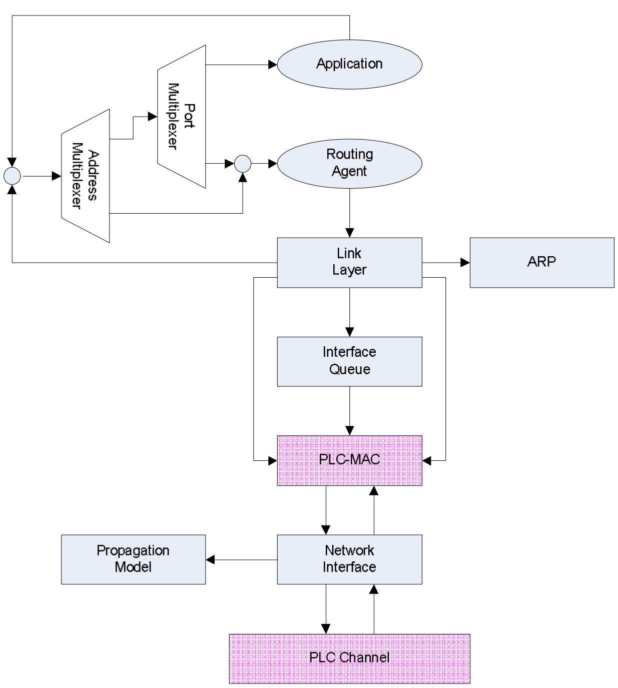

Fig. 4. Architecture of each PLC-Node in NS-2

Fig. 4 shows the architecture of each PLC-node in NS-2 simulator. Each node contains a network stack such as network interface (physical layer), medium access control, interface queue and link layer. The protocol type in each layer can be selected by a user as far as a NS-2 support for that type of protocol is available. This architecture is a built-in model that NS-2 originally supports. Based on this architecture, we implemented the PLC-MAC layer which supports KS-MAC protocol. Using the PLC-MAC layer, each node can control the channel access similar to the KS-MAC protocol. We describe the implementation details of PLC-MAC layer in the next section.

B. NS-2 Implementation Details for KS-MAC

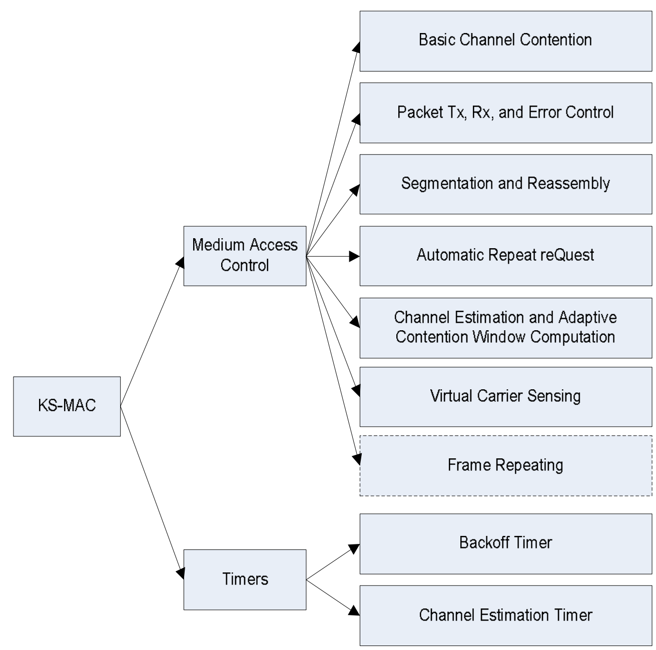

Fig. 5. Modules in KS-MAC Component

Fig. 5 shows the module hierarchy of KS-MAC component. All modules are implemented in the C++ class object. Due to this object-oriented design, the maintenance and modification of KS-MAC component can be done easily. As shown in Fig. 2 KS-MAC component consist of medium access control modules and timers. The medium access control modules include basic channel contention module, packet transmission, receiving and error control modules, segmentation and reassembly modules, automatic repeat request module, channel estimation module, and virtual carrier sensing module. There are two available modes of operation, which are normal and repeater mode. If a node operates in repeater mode, KS-MAC component additively should have the frame repeating module which relays data frame in MAC layer. Each module interacts with each other. The state transition diagram of the basic channel contention, packet transmission and receiving module is shown in Fig. 6. Channel estimation module runs independently and provides the channel state information to the adaptive contention window computation module. The timer modules include back-off timer and channel estimation timer. Whenever each timer is expired, the related timer handler function is called and executes periodic operations.

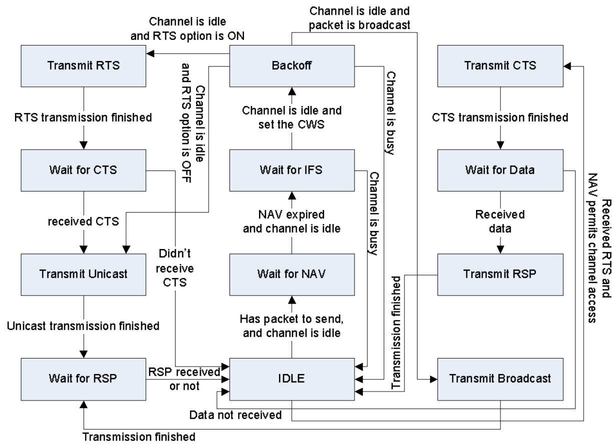

Fig. 6. State Transition Diagram in KS-MAC

4. Performance Evaluation

We have done simulation using NS-2 (version 2.31), aiming to estimate the performance of PLC network and to evaluate the accuracy of the NS-2 simulator. NS-2 parameter settings are summarized in Table 1. We use KS-MAC component as a MAC protocol, and also use static routing protocol to minimize the routing overhead because we want to estimate the performance of MAC layer itself. For the application traffic, we use CBR (Constant Bit Rate) traffic, and data traffic generation rate is varied between 14Mbps and 1Mbps depending on the physical data rate. Physical data rate is also varied between 554BPS and 220BPS, where BPS means bits per symbol. Physical data frame consists of several symbols, and each symbol carries data bits according to the specified BPS rate. For example, when BPS rate is 554, each symbol carries 554 bits of data.

Table 1. NS-2 Simulator Settings

Entry	Value
MAC Protocol	KS-MAC (No RTS-CTS)
Physical Protocol	Abstract Phy
Physical Data Rate (BPS)	554, 460, 320, 220BPS
Routing Protocol	Static Routing
Total amount of simulation time	100 sec
Application Traffic	CBR
Packet Size(Bytes)	1518, 1000, 500, 100, 64
Application Traffic Generation Rate(Mbps)	14

KS-MAC component has several MAC parameters, and these parameters can be set in the OTcl script file while NS-2 simulation is performed. The KS-MAC parameter settings in our simulation are summarized in Table 2. In simple network topology we do not use RTS-CTS control frame, but in more complicated network topology that can suffer from hidden terminal problem, we can change the setting of RTS-CTS usage.

Table 2. Parameter Settings of KS-MAC Component

Entry	Value
Symbol Period	12.48 usec
Time Slot Duration (TSD)	7 symbol
SRIFS	5 symbol
SCIFS (=SRIFS + TSD)	12 symbol
LRIFS	20 symbol
LCIFS (=LRIFS + TSD)	27 symbol
Max Data Frame Length	240 symbol
Max CW Size	512 TSD
Min CW Size	4 TSD
CW Coefficient	8 TSD
Channel Estimation Duration	1000 TSD
Control Frame Duration	12 symbol
RTS-CTS Usage	OFF

A. Simple Scenario

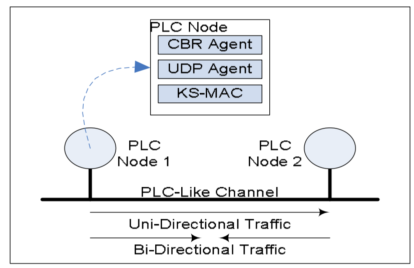

Fig. 7. NS-2 Simulation Topology

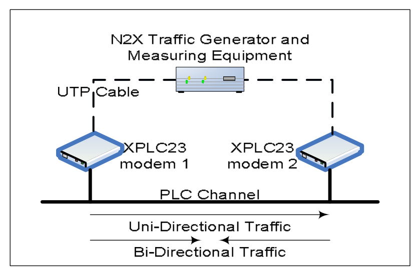

Fig. 8. Testbed Topology

In this set of simulations we use a simple single-hop topology as shown Fig. 7. To verify the accuracy of the result of NS-2 simulation we conducted similar experiment using the real PLC modem (XPLC23[11], which uses KS-MAC protocol). The topology of this testbed experiment is shown in Fig. 8. Traffic flows are either uni-directional or bi-directional. When the traffic flow is bi-directional, two nodes (or XPLC23 modem) send data traffic to each other. In this scenario, varying parameters are physical data rate and packet length. Physical data rates are varied from 554 BPS to 220 BPS, and packet length is varied from 1518 bytes to 64 bytes.

Fig. 9 shows the throughput results of NS-2 simulation and testbed experiment when varying the physical data rate with the fixed packet size of 1518 bytes. NS-2 results show linearly increasing performance with the increasing physical data rate. The testbed results show small fluctuation in some BPS rates, since results are not normalized. In general, NS-2 throughput results are very similar with that of testbed at every BPS rate.

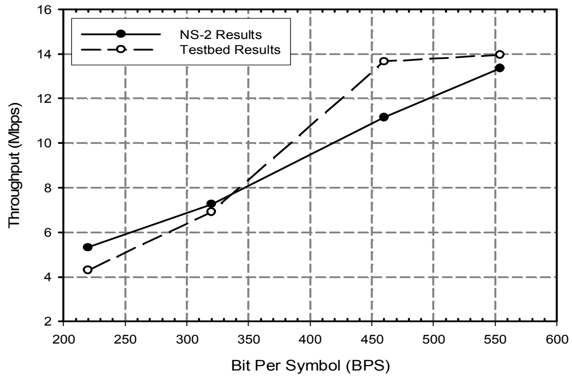

Fig. 9. Comparison of Throughput Depending on the BPS (Uni-directional transmission)

Fig. 10 shows the throughput results when varying the packet size with the fixed physical data rate of 554BPS. The results show that both NS-2 and testbed performance show very similar tendency.

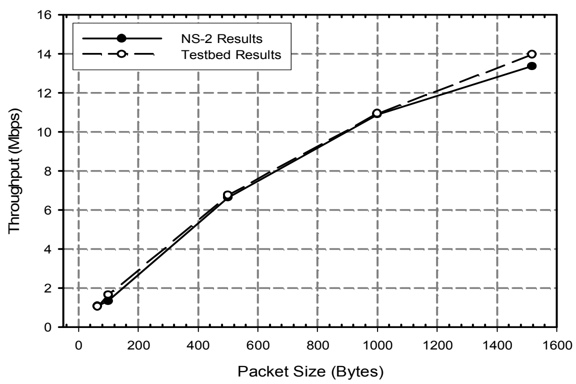

Fig. 10. Comparison of Throughput Depending on the Packet Size (Uni-directional transmission)

From the results of Fig. 9 and Fig. 10, we conclude that the NS-2 simulator reflects the reality of actual PLC testbed.
Table 3 summarizes the throughput results of both NS-2 and testbed when using the bi-directional traffic.

Table 3. Bi-directional Transmission Case (by varying physical data rate)

BPS	Testbed Throughput (Mbps)		NS-2 Throughput (Mbps)	
	Modem 1	Modem 2	Node1	Node2
554	6.26	6.23	7.35	7.25
460	6.21	5.44	5.92	5.88
320	3.15	3.09	3.67	3.74
220	1.93	1.82	2.70	2.72

On Table 3, throughput of each node is divided equally into half of uni-directional throughput. This means that two nodes evenly share the PLC channel, which means that the channel contention module of KS-MAC component ensures the fairness between two nodes.

B. Multi-hop relay scenario

To see the effect of repeater on the performance, we setup the topology as shown in Fig. 11. In total, three nodes are placed in a 2-hop link, with an intermediate node, PLC Node 2, as a repeater. PLC Node 1 and 3 belong to a different cell, while the repeater node belongs to both cells. A node cannot receive frames from the node that belongs to a different cell.

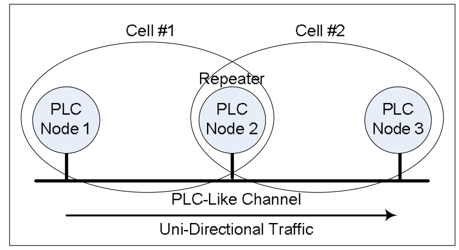

Fig. 11. NS-2 Topology

To compare the NS-2 repeater performance with the actual implementation, we conduct testbed experiment with the similar topology as depicted in Fig. 12.

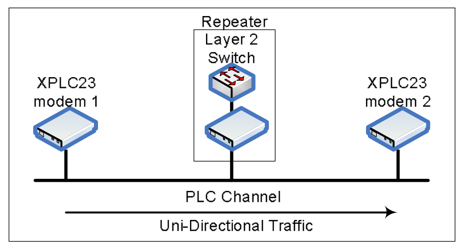

Fig. 12. Testbed Topology

In this scenario Node 1 sends packet to Node 3, but Node 3 cannot receive this packet directly because of the attenuation in the PLC channel. Therefore, the repeater node, Node 2, relays the packet from Node 1 to Node 3.
Packet length is fixed to 1518 bytes, and physical data rates are varied from 554 BPS to 220 BPS. Both results of NS-2 simulation and testbed experiment are shown in Table 4.

Table 4. Comparison of Both Throughput Results

BPS	Testbed Throughput (Mbps)	NS-2 Throughput (Mbps)
554	6.24	6.20
460	5.21	5.28
320	3.08	3.47
220	1.92	2.58

From the results, we can observe that NS-2 repeater simulation also shows a very similar performance in comparison with the testbed experiment. When we compare the NS-2 repeater simulation with a single-hop NS-2 simulation, we can realize that the throughput decreases by half compared to the single-hop throughput. This is quite reasonable because it needs twice more contention and back-off when packet passes through the intermediate node.

C. Realistic scenario

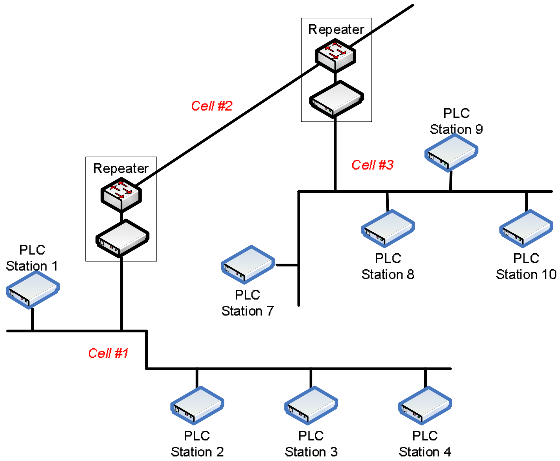

Fig. 13. Realistic PLC Topology

To see how KS-MAC performs in the realistic topology, we construct the topology depicted in Fig. 13 using NS-2 simulator. This network consists of three cells, and repeaters connect one cell with another cell. Each cell is composed of about 4 stations. Overall, entire network forms a kind of tree topology. We set the one CBR traffic from station 1 to 10, and additionally added some background traffics which number is varied from 1 to 6. The source and destination of background traffic are randomly chosen. Packet size is set to 300 bytes, and physical data rate is set to 100BPS.

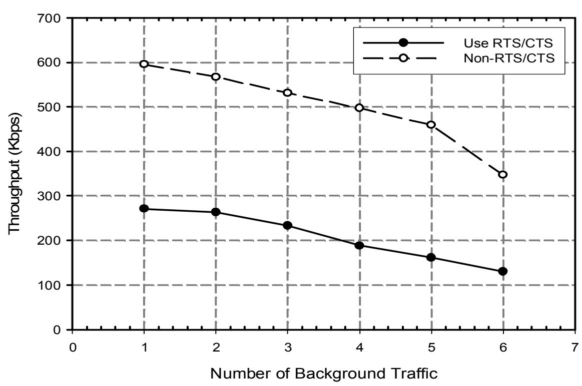

Fig. 14. Throughput of the Main Traffic According to the Number of Background Traffic

According to the results in Fig. 14, as the number of background traffic is increased from 1 to 6, the throughput of main CBR traffic is decreased. When multiple traffics are simultaneously trying to occupy the channel, MAC efficiency is degraded depending on the number of traffic. If the traffic goes through multiple hops, the efficiency will be even worse. When we use the RTS and CTS control packets for channel reservation, the throughput is decreased further because these control packet additionally waste the bandwidth. However, RTS-CTS could be useful in the large scale networks with complicate traffic flows since it prevents the packet collision due to the multiple senders.

5. Conclusion and Future Work

In this paper, we introduced the KS-MAC protocol which is the standard for power line communication in Korea. We made a simulator for KS-MAC using the NS-2 simulator that is widely used in the simulation of wireless and wired networking. To realize the KS-MAC simulator, we implemented the KS-MAC component, and added this component to the architecture of original NS-2 simulator. In order to verify the accuracy of our simulator, we have performed the simulation for two scenarios: single-hop transmission and 2-hop transmission using the repeater. By comparing the results of NS-2 simulation with the actual testbed experiment, we could conclude that our KS-MAC simulator has very good reflection of the real PLC networks. Therefore, we expect that our simulator can be mainly applied to previewing the efficiency of specific PLC network topology before the actual deployment of the network.

Additionally, we have done another simulation for more realistic scenario which reflects actual last-mile PLC access networks. According to the result of this simulation, MAC efficiency is degraded as the number of simultaneous traffic flow increases. This is because KS-MAC protocol is based on distributed contention based MAC mechanism that cannot guarantee bounded medium access delay, especially when multiple traffic are concurrently contending for the channel.
Further research will be focused on improving the KS-MAC protocol, and performance evaluation using the NS-2 simulator.

We are considering two approaches to improve the KS-MAC protocol. First one is, according to the priority of application traffic, to classify the inter frame spaces and back-off ranges to give high probability of winning for higher priority traffic. Another method is a modification of the KS-MAC scheme to hybrid MAC mechanism, which provides both contention based channel access for normal traffics and contention free channel access for QoS required traffic.

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