Host-Based Architecture LON Communication Gateway for Building Air-conditioner Monitoring System

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LONWORKS is a de-facto standard in building management system communication. This paper discusses a LON communication gateway specifically designed for packaged air-conditioners. Compared with other gateways, this gateway manages a maximum of 96 air-conditioners and achieves high-speed communication performance. In addition, this gateway employs the LON dedicated Neuron Chip processor as the communication co-processor and achieves high-speed communication performance which is 1.7 times faster than conventional communication gateways through the use of a high-speed CPU capable of handling a large number of network variables and our proprietary communication protocol interchange software.

1. Introduction

Along with BACnet, LONWORKS is also increasingly accepted as a de-facto standard for building management communication protocol. A few years ago, Mitsubishi Heavy Industries developed these communication gateways for packaged air-conditioners,(1) but the recent market need is increasingly shifting to large capacity and high performance.

In recent building management systems for packaged air-conditioners, each of several hundred air-conditioners has about ten control points. When these air-conditioners are monitored and managed by LONWORKS, several thousand LON network variables must be handled. Because these variables are converted by LON communication gateways, the required number of gateway devices is determined depending on how many air-conditioners one gateway device can manage. Generally, it is said that gateway complexity increases but the total equipment cost and the required network configuration work both decrease when the number of gateway devices is reduced.

Focusing on development technology, this paper discusses the world's premier LON communication gateway for packaged air-conditioners that manages up to 96 air-conditioners and ensures high speed communication performance without bottlenecks even when LON communication concentrates on one gateway.

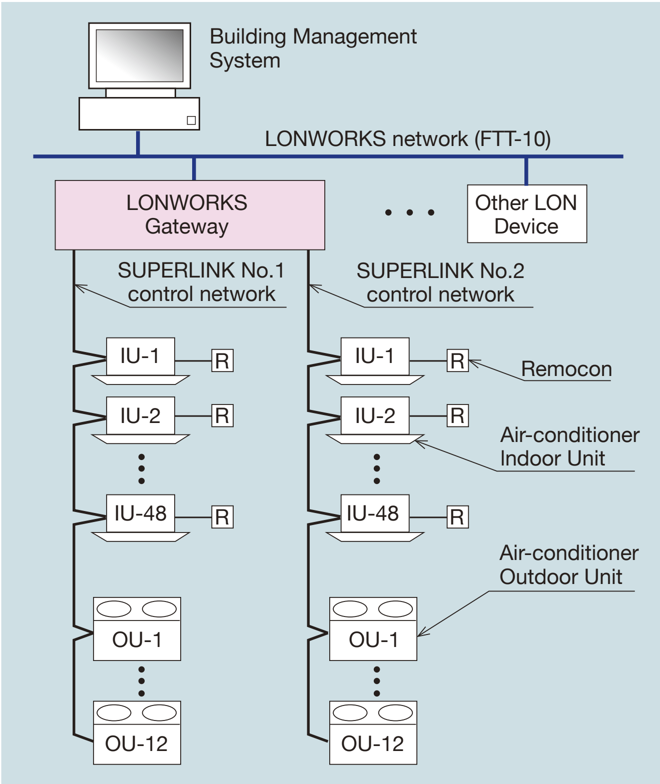

Fig. 1 LON communication gateway system diagram
Two air-conditioner control networks manage 96 air-conditioners in all.

2. LON Communication Gateway

A LON communication gateway means a device for translating LONWORKS protocol to MHI's proprietary air-conditioner communication protocol "Superlink". **Figure 1** shows a LONWORKS building management system diagram for packaged air-conditioners.

LONWORKS provides communication functions such as Media Access Control (MAC) through the LON dedicated Neuron Chip processor so that full communication connectivity can be secured between devices from different vendors. However, the Neuron Chip is an 8-bit processor developed around 1990 and its processing capability is not sufficient nowadays. This processor can internalty handle only 62 network variables. Because dozens of control points are generally required for each air-conditioner, only four or

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five air conditioners can be managed by 62 network variables. For this reason, MHI have employed four LON printed circuit boards (each with a Neuron Chip) in the conventional LON gateway device. In this case, however, there are four LON nodes for each device. Consequently, the network variable binding work becomes difficult as more air-conditioners are installed.

An external view of the new LON communication gateway is shown on the title page and its product specifications are summarized in **Table 1**. As shown in Figure 1, up to 96 packaged air-conditioners are divided into 2 groups of maximum 48 to be connected to our Superlink control network. Because each air-conditioner has 13 kinds of I/O network variable such as the run/stop commands and run mode commands, the LON node is required to handle 1250 network variables in all (1 248 network variables for 96 air-conditioners and 2 network variables for the entire system.) This new LON communication gateway's ability to connect 96 air-conditioners is the best in the world while its nearest rival can only connect 64 as of February 2006. In spite of this large number of control points, it is necessary to devise a new architecture with dramatically improved communication performance, causing no bottlenecks.

Table 1 Product specifications of the new LON communication gateway

ITEM	SPECIFICATION
Dimensions (mm)	260(W) x 200(H) x 79(D)
Max. No. of air-conditioners	96 indoor units
Max. No. of Network Variables	4096 NVs in 1 node
Implemented No. of NVs	1250 NVs
LON datalink protocol	LonTalk EIA-709.1-A
LON physical layer	FTT10A, 78 kbps
Superlink datalink protocol	CSMA/CD
Superlink physical layer	RS485 9.6 kbps
Superlink cabling	Twisted pair, Max. 1 000 m

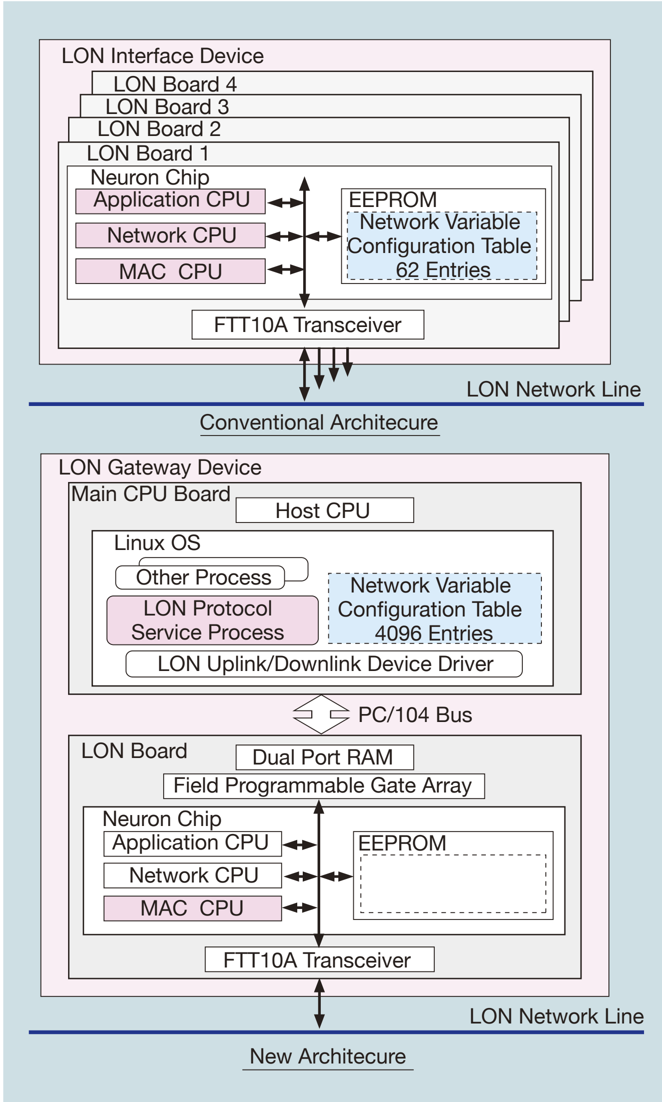

Fig. 2 Host-based architecture
Some neuron chip functions are moved to the high-speed CPU to implement high-speed processing.

3. System Architecture

3.1 LON Host-Based Architecture

Figure 2 shows the architectures of the conventional and new LON communication gateways. The conventional communication gateway employs a neuron-based architecture with four built-in boards. Each Neuron Chip of each board has three CPUs (MAC CPU, Network CPU and Application CPU), and one network variable configuration table having binding information (destination address in network variable, etc.) in the built-in EEPROM.

In contrast, the new LON communication gateway employs host-based architecture. In this architecture, the functions of two CPUs (Network CPU and Application CPU) are moved to the Host CPU and only the Media Access Control function of the MAC CPU is provided by the Neuron Chip. Each Neuron Chip supports functions in layers 1 to 5 in the OSI seven layer model. Concretely, it provides functions such as Media Access Control, packet collision detection, Ack response, and transaction retry. The Host CPU supports layers 6 and 7 in the above OS model. It provides functions such as network variable update, binding information management, and data transfer to/from the application software.

The LON board and the CPU board are connected via a PC/104 bus. This PC/104 bus has a data transfer capability of about 8 Mbps, so that it can fully support LON communication that takes place at a rate of 78kbps. Data transfer from the Neuron Chip to the Host CPU takes place at a high rate via the Dual Port RAM by the FPGA (hardware logic circuit) rather than the microprocessor. The device driver of the operating system (OS) in the main CPU board receives the transfer data, which is a LON-standard message uplink/downlink data structure.

In this way, the high-speed CPU can handle network variables instead of the low-speed 8-bit CPUs in the conventional Neuron Chip. In addition, a maximum of 4096 network variables --- upper limit on the LON standard --- can be defined without memory size restriction because the host-based architecture permits the network variable configuration table to be defined in the Host CPU while the conventional neuron-based architecture does not permit more than 62 network variables to be defined because the Neuron Chip EEPROM memory size has been limited.

3.2 Linux OS and CPU

Conventional communication gateways have employed various embedded operating systems like μITRON. However, technology for using Linux as an embedded operating system has also been studied[2] from the viewpoints of complicated database management, large capacity file handling and IP network connectivity.

As described below, the new LON communication gateway has employed the advanced multitask operating system Linux and a high-performance CPU, considering the concomitant use of WEB communication and BACnet/IP communication functions, but there remains a technical issue in implementing Linux in ROM as a compact embedded operating system. In the new LON communication gateways, a regular Linux distribution has not been stored in the ROM as it is, but its minimum configuration Linux Kernel has been compressed and stored in the limited space of the Compact Flash (CF) ROM. Once BIOS is booted, the Linux disk image file in the CF ROM is decompressed in the main memory and then the boot process is completed. In this case, we have adopted a method for generating a virtual disk drive Ramdisk in the main memory to hold a temporary file because the number of attempts to write to the CF ROM is limited.

We have employed an embedded CPU compatible with the Pentium MMX that can operate at a rate of 300 MHz without a CPU cooling fan, considering that a high-performance x86 CPU is mandatory for implementing advanced Linux OS. The CF ROM and main memory are both 64 MB in size. Employing the ROM Linux and CPU without cooling fans has eliminated the need for mounting rotational components such as the hard disk drives and CPU cooling fans to improve reliability and product-life cycle, implementing a Linux system with an Apache server and TCP/UDP/IP stacks for WEB communication.

4. Software Design

4.1 Protocol Interchange

The new LON communication gateway consists of multitasking software concurrently handling multiple protocols including the LONWORKS. For this software, we have devised a communication protocol interchange architecture for translating message strings asynchronously coming from multiple networks using different protocols into the equivalent Superlink commands and then bundling and transferring them in units of air-conditioner destination addresses. This architecture have taken the steps required for patent filing.[3]

Figure 3 shows the protocol interchange processes, each of which serves as a task unit on Linux OS. Some processes such as Protocol_Service_Process vary with every building management communication protocol,

Protocol_Interchange_Process, and Protocol_Service_Process for every Superlink communication channel run concurrently as independent tasks.

For inter-process data transfer, we have developed a "Connector" class as a proprietary IPC (inter process communication) class library having two kinds of queues Command_Queue and Notify_Queue. In addition, LONWORKS, BACnet/IP and WEB control processes are now available as they depend on communication protocols. Such Protocol_Service_Processes can be dynamically connected or disconnected at any time regardless of the number of processes via the Connector. An IPC message issued to/from Command_Queue or Notify_Queue to be used by the Connector is provided with a Process_Identifier for destination process identification and then passed via the Message Queue API that works as the standard POSIX library of the Linux operating system.

The core Protocol_Interchange_Process has an "Abstract_Cell_Object_Database" generated by abstracting air-

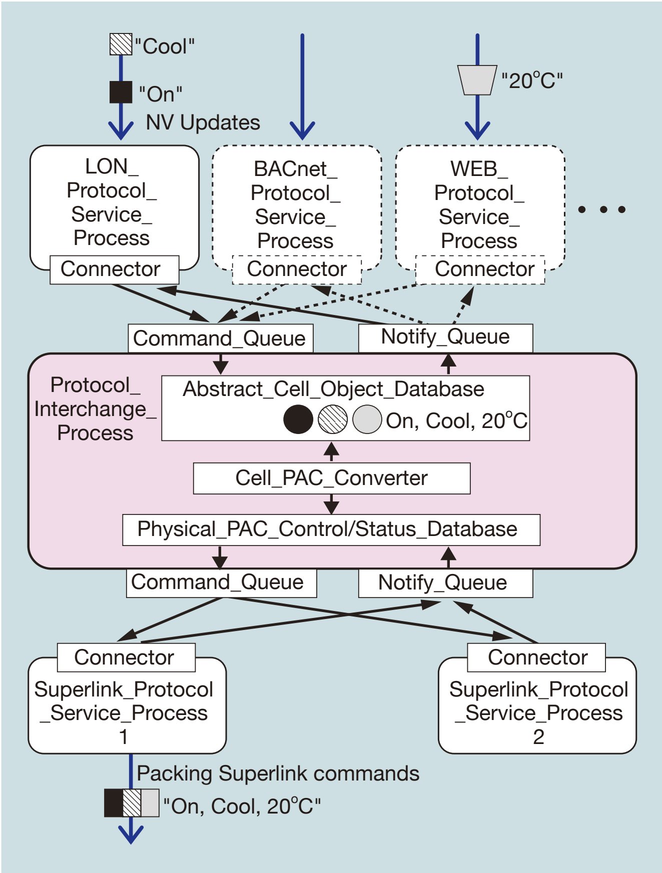

Fig. 3 Communication protocol interchange
Multiple processes with different protocols are run to translate messages into air-conditioner control commands and synthesize them for transmission.

conditioner control and monitor data in a way that does not depend on any communication protocol. This logical unit of air-conditioner management, viewed from the building management system regardless of the actual air-conditioner configuration, is defined as "Abstract_Cell" and each cell instance has properties such as the operating status and operating mode.

On the other hand, Superlink_Protocol_Service_Process for every Superlink channel also accesses Protocol_Interchange_Process. Cell_PAC_Converter is a concurrent processing unit "thread" in the operating system and converts changes in properties of the logical Abstract_Cell to a physical Superlink commands. In addition, multiple air-conditioners can be grouped into Abstract_Cell as an abstract control and monitor unit through this conversion.

The advantage of the communication protocol interchange system devised for the new LON communication gateway is that multiple air-conditioner control commands using different communication protocols can be grouped into consistent operating states in the Abstract_Cell prior to transmission. When messages coming from the respective communication protocol processes are simply transferred to the corresponding air-conditioners sequentially, a problem may arise where a combination of conflicting commands is sent to the same air-conditioner. However, the new protocol interchange system prepares a set of non-conflicting properties in the Abstract_Cell and sends them to the target air-conditioner.

In addition, the Cell_PAC_Converter thread synthesizes the messages sent from multiple building management communication channels to the same air-conditioner in a single Superlink packet, resulting in transmission efficiency improvement.

4.2 Air-Con Cell Functional Block

This gateway provides with a method of structuring a large number of network variables in units of functional blocks because the new LON communication gateway has 1 250 network variables in all. When these network variables are arranged in plain, they are handled as a single virtual functional block with the LON Marker network binding tool and 1 250 network variables are all displayed on the screen. This is an inconvenient way of handling network variables.

Figure 4 shows 96 Air-Con Cell Functional Blocks in this LON communication gateway. Each block corresponds to the control and monitor functions of each air-conditioner. Owing to this functional structuring, only the network variables needed at that point can be displayed in units of functional blocks on the GUI screen of a binding tool like LONMaker.

In addition to these 96 Air-Con Cell Functional Blocks, the LON communication gateway has defined one functional block for all the air-conditioners and has implemented two network variables to stop the entire air-conditioning system urgently and display its status. For example, when an emergency arises, this function stops all air-conditioners immediately and locks all the remote controls. In this way, it eliminates the need for sending two kinds of commands, air-conditioner stop and remote control lock, to air-conditioners 192 times in all (2 commands for each of 96 air-conditioners). In general, emergency messages are intensively generated in related facilities when an emergency like a fire arises. The LON communication gateway has been highly evaluated in that the newly implemented two network variables drastically reduce the emergency communication traffic.

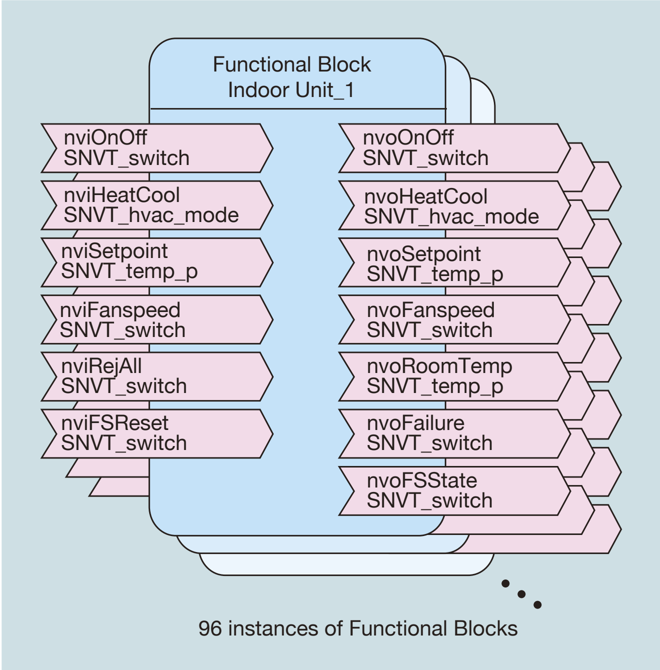

Fig. 4 LON functional block
Network variables are structured in units of indoor air-conditioners for implementation.

In the primitive architecture directly using the Neuron Chip, the LON development tool automatically generates an XIF file as a device definition file. In the host-based architecture, however, the XIF file is not generated automatically. In this LON communication gateway, the Echelon's "NodeUtil" analysis tool has been employed to produce the above functional blocks. To produce this XIF file, we have been required to use the most in-depth knowledge on the LON system.

5. Communication Performance

5.1 Necessity for Communication Performance Evaluation

Our host-based software features high-speed message fetch from the Neuron Chip which does not have enough capability for intensive communication traffic of 78 kbps LONWORKS. LON messages should be fetched quickly from the receiving buffer because the receiving intervals of message cannot be adjusted by the LON gateway, though the transmission intervals can be adjusted by the host computer of the building management system.

When the receiving capability is not enough, an overflow occurs, caused by the receiving buffer full of messages. In addition, even Acked type messages are retransmitted to the LON communication gateway frequently and the LON network channel time is wasted. However, when too many receiving buffers are provided a processing delay occurs or messages not requiring urgent handling are stored resulting in a "Priority Inversion" problem.

To investigate this problem, the effects of the host-based architecture and the protocol interchange were quantitatively measured for comparison with those in conventional communication gateways.

5.2 LON Communication Performance Test

We measured the maximum LON message receiving speed in this gateway. To evaluate pure speed in fetching a message from the Neuron Chip to the main CPU board, only one step receiving buffer was employed. The LON board was connected to the PCI bus of a Pentium 4 machine with a clock rate of 3 GHz for generating test LON messages and sending them to this communication gateway to achieve the fastest processing speed.

The number of successfully received messages was counted with the LOYTEC high-speed LON protocol analyzer with a resolution of 1 μs. In addition, the presence of packet loss was analyzed and assessed with the Echelon analysis tool "NodeUtil". The transaction rate per second was measured by handling a combination of an NV Update message sent from the transmission unit and an Ack returned from this gateway as a single transaction.

As shown in **Figure 5**, the test result of this communication gateway is 70 (transaction/s) per second while that of the conventional gateway is only 42 (transaction/s) per second. In this case, however, additional tests have not been conducted because the transmission unit does not support the faster speed. Because this communication gateway has demonstrated that all Acks were returned without retries. The upper limit of communication performance has been derived from various materials because it could not be measured.

5.3 Examination on Communication Performance Limits

According to the official standard (ANSI/EIA-709.1 Annex C) of LonTalk, the theoretical value of the transport protocol data unit (TPDU) transmission rate can be derived from the following expression;[4]

$$R_{TMAX} = \frac{R_{BPS} \cdot [1-(1/(2 \cdot W_{BASE})+P_E)] \cdot [1-C_{COST} \cdot (1/(2 \cdot W_{BASE})+P_E)]}{[\beta_1 + \beta_2 \cdot (D_{MEAN}+D_{PRI})+L_{AVG}]}$$

where the following values for this test have been used for the respective parameters in this expression. Concretely, the transmission channel bit rate R_{BPS} is 78 (kbps); the number of random slots W_{BASE} is 16; the transmission error rate P_E is 0.01; the coefficient of packet collision loss C_{COST} is 2; the length of inter-frame spacing β_1 is 58 (bits); the unit slot length β_2 is 11 (bits); the average number of transmission delay slots D_{MEAN} is 8 ($W_{BASE}/2$); the number of priority slots D_{PRI} is 0; the average length of physical layer frame L_{AVG} is 120 (bits) including the preamble, that is, the average of NV Update and ACK. Consequently, 268 (TPDUs per second) has been determined as the theoretical limit R_{TMAX}.

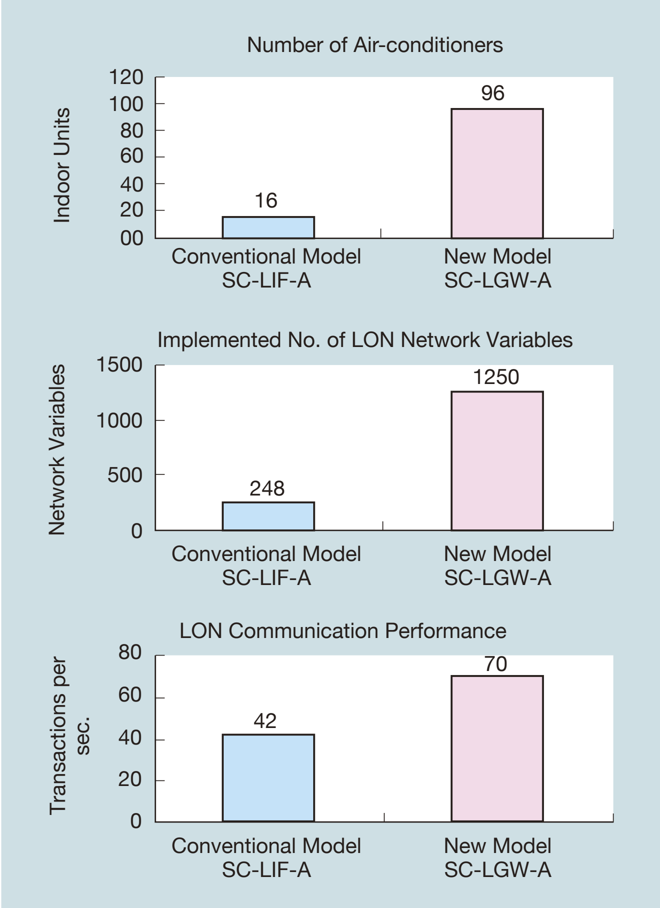

Fig. 5 Performance benchmark
Number of air-conditioners, number of network variables and communication speed that significantly exceed the corresponding values in conventional LON communication gateways

Because roundtrip processing between the network variables Update and Ack is treated as one transaction, the theoretical limit of the transaction rate is determined to be 268/2 = 134 (transaction/s). It seems that this value is lower than the communication channel capacity, and the limit depends on the internal processing time of nodes rather than the communication channel itself.

According to materials from Echelon, the speed of message transmission to the host CPU by the Neuron Chip employed in the host-based architecture is 103 (transaction/s).[5] It is considered that the Uplink/Downlink has not reached its limit yet but there is another overhead or the message transmission speed is about 103 (transaction/s) though the limit could not be demonstrated this time.

In performance comparisons with other manufacturer's LON gateways designed for packaged air-conditioners, it seems that our LON gateways is superior to the others because the best performance found is 50 (transaction/s) according to their catalogs though the comparison conditions are not precise.

6. Conclusion

This paper has described MHI's new LON communication gateway that can manage a maximum of 96 packaged air-conditioners and ensure high-speed processing. The core technologies of this LON communication gateway are a new architecture adopted to handle a large number of network variables with a high-speed host CPU and our proprietary communication protocol interchange software employed to achieve high-speed communication performance (70 transaction/s) 1.7 times faster than (42 transaction/s) our conventional communication gateways.

In the future, MHI will develop communication gateways that can handle three protocols, LONWORKS, BACnet/IP and WEB, in parallel by taking advantage of the communication protocol interchange system for concurrently handling multiple protocols.

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