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Gigabit Ethernet Based Substation

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ABSTRACT

Designing communication architecture for substation automation is a challenging and subtle task for visualizing substations in the digital world under the umbrella of IEC61850. Communication paradigms for substation automation are of critical importance because of two reasons; the communication arena is changing daily and opts for convenience and simple deployment at a lower migration cost and interoperability is one of the core constrains of IEC61850 for substation automation. This paper presents an analysis and outline of the crucial need for the deployment of Gigabit Ethernet in substations and also presents suggestions on how Ethernet technology can help in substation automation. Ethernet is one of the most pervasive communication technologies available and can provide a long term solution in the changing arena of communication. We have performed simulations in NS-2 to prove that our suggested communication paradigm is optimal in various regards with consideration of the constraints imposed by IEC61850.

Keywords: Communication architecture, Gigabit Ethernet, IEC61850, Substation Automation

1. Introduction

This is the digital age. Everyone is talking about the information highway as witnessed by the pervasive use of digital technology in every walk of life. IEC61850 is also playing a vital role in this regard by digitizing traditional substation automation (SA) systems. The significant impact of IEC61850 standards can be observed in the shape of efficient and cost-effective architecture for power systems. By imposing IEC61850 standards, substations will not only boost performance but also provide a universal platform to maintain and upgrade substation assets with cost-effective approaches. The objective of IEC61850 is to track the way for a global standard that would achieve interoperability between different vendors and also would be able to accommodate future technological developments in this regard, i.e., future-proof. In IEC61850, functional and performance requirements are imposed on intelligent electronic devices (IEDs) to achieve interoperability for the automation process as a whole. Functional requirements are supposed to address required capabilities for IEDs and on the other

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hand performance requirements are oriented towards end to end operational or execution response time. To achieve functional requirements for IEDs, a modular approach is addressed by IEC61850 standards which are object-oriented. By contrast, the objectives for achieving performance requirements are changing dramatically as communication technology is getting smarter day by day.

Communication infrastructure obviously has the potential to virtualize the physical world of substations but when it comes to efficient and reliable architecture for SAs then there are many challenges for various economic and standardization reasons. These challenges need to be overcome for the complete realization of SA and also to cope with recent developments in communication technology [1]. Ethernet has been the flavor of choice for SA because of its availability, efficiency, cost-effectiveness, and proven interoperability. The widespread use of Ethernet technology provides a huge base of vendor support. Ethernet is not only used for local communication but it also provides support for long haul communication as a high speed communication backbone. It provides support for transmitting local packets on access technology without incurring the cost of protocol conversion seamlessly. So the goal here is to use Ethernet as a standard networking protocol to achieve the performance requirements as specified by IEC61850 for SA and to build efficient and reliable communication architecture in this regard.

This paper investigates whether Ethernet is a viable solution for addressing the performance requirements of IEC61850 and how sufficient its performance characteristics are to meet the real-time demands of SA. Then the effectiveness of our proposed claim is proved with the help of simulated graphs by taking Gigabit Ethernet and GOOSE (Generic Object Oriented Substation Event) message (UPD/IP packet) into consideration. The rest of this paper is presented as follows. In Section 2, the suggested communication architecture for substation automation is analyzed theoretically. Section 3 presents simulation results obtained for the evaluation of different attributes of a GOOSE message in a Gigabit Ethernet environment. Finally some concluding remarks are presented in Section 4.

2. Gigabit Ethernet in Substation

Efficient and reliable communication architecture is one of the crucial tasks in the automation process of a substation. In order to meet the performance requirements of IEC61850 and to ensure future-proof technological development is adjusted for communication architecture for substations, there are various constraints related to performance, economy, and standardization that need to be addressed. This section presents a suggested communication paradigm for SA, theoretical analysis for the effectiveness of this suggested architecture and critical challenges in this regard.

Before proceeding, it is important to mention that a communication paradigm needs to address various aspects such as capacity, performance, reliability, accuracy, coverage, security, availability, and interoperability for substation automation[1]. By ensuring these communication attributes, robust communication architecture can be designed which will revolutionize power systems for many years as per the specifications of IEC61850.

2.1 Ethernet in Substation

Significant advancements in Ethernet technology evolved from traditional Local Area Networks (LANs) to Wide Area Networks (WANs). So now Ethernet technology is driven by high speed data rate as well as with the dominance of local area communication thereby making Ethernet a feasible communication technology choice for SA[2]. Indeed, Ethernet is the most appropriate communication technology for SA as it can operate at all three levels specified by IEC61850, i.e., station, bay, and at process level seamlessly and can also used to interconnect different substations for long-haul communication.

Ethernet technology supports a very high data rate. 10GB Ethernet switches are now available on the market while landmark 100GB Ethernet switches will soon be available in near future as it is claimed by several computing labs. With such a high speed data rate, Ethernet technology has maintained its performance throughout upgraded generations. The electronics industry is progressing daily, so Ethernet will keep its momentum towards high speed data rate and efficient performance.

Ethernet technology is cost-effective due to the reduced device count and can also carry power as specified by IEEE 802.3af standards thereby offering an economical and safe route to rapid flexible deployment of computing devices. The economical and flexible Ethernet technology can also provide the facility of a fault tolerant Ethernet route thereby minimizing the downtime of substation communication in cases when failures occur in the operational network.

Ethernet technology also provides the support of traffic class prioritization and dynamic multicast filtering as specified by IEEE 802.1p[3]. By making use of this attribute, it is possible to prioritize mission-critical data within the substation over noncritical data and also provide the mechanism for efficient multicasting in an Ethernet environment via layer-2 protocols. It is one of the significant developments towards the realization of deterministic Ethernet[4]. Hence real-time control of a substation can be optimized by making use of deterministic Ethernet.

The wide availability and huge industrial deployment of Ethernet technology assures its interoperability over different access network solutions. Due to Ethernet's pervasive usage, it is the most scalable transmission technology having granularity of bandwidth, reliability, and coverage. Security is one of the main concerns when it comes to Ethernet. However the issue of improving security seems to be compromised at the expense of its technological complexity. So in order to deploy a secure communication network under Ethernet technology, some other corporate network security solutions need to be addressed such as firewalls, VPNs, and use of encryption schemes for mitigating Ethernet security risks.

According to IEC61850, the Ethernet packet is the packet of choice for transmitting substation messages within the substation because of its performance and also most of the proprietary communication solutions are available with Ethernet support[1]. Besides that, when it comes to interconnecting different substations, the same Ethernet packet specified by IEC61850 can be transmitted through long-haul communication to other substations without incurring the cost of protocol conversion unlike ATMs. In this way, Ethernet provides migration to a single and all-encompassing network concept to monitor and configure different substations across the region by making use of EPON which is a communication trend shipped with the two most demanding communication technologies, i.e., Ethernet as a communication protocol and a fiber optical communication system as a communication medium[5]. Hence Ethernet is the most in demand communication trend for substations to build up an efficient communication infrastructure.

In this paper, we are examining the potential of a Gigabit Ethernet switch to meet the communication needs of substations by imposing performance constraints specified by IEC61850. To our knowledge so far not much research has done examining the performance of Gigabit Ethernet within the substation. LAN congestion scenarios for Ethernet based substations are analyzed[6] by Tengdini but it differs from our work in several key aspects such as no consideration for shared process bus, absence of industrial protocols (such as TCP/IP and UDP) specified by Internet Engineering Task Force (IETF) over Ethernet, and also there is no consideration given to background traffic loads for accurate result. Brunner[2] examined the role of Ethernet in SA. However our work differs from [2] as we are deploying Gigabit Ethernet because it is cost-effective and can also be utilized at the access network to take full advantage of inherent local substation messages when different substations are in an inter-network. Additionally we are considering Ethernet packets encrypted using a hybrid encryption scheme[7] as Ethernet security is a crucial concern. Finally, we have divided communication infrastructure at two levels i.e. Bay level and station level.

2.1.1 Suggested Communication Paradigm

In the previous section, theoretical analysis of Ethernet is presented to show the feasibility and preferred choice of Ethernet technology for SA despite the other communication trends available on the market. In this section, models for the suggested communication architecture are presented, i.e., deployment of Gigabit Ethernet within the substation.

According to IEC61850, the functionality of SA has been logically allocated at three distinct levels: station level, process level, and bay level[2]. Station level devices consist of the station computer with a database such as an HMI (Human Machine Interface) device, the operator's workplace, control center, interfaces for remote communication, etc (at this level these devices provide functions to control and protect the entire substation). Bay level devices consist of control, protection, or monitoring units per bay such devices actually relate to the different subparts of a substation. Process level devices are typically remote I/Os, intelligent sensors and actuators. These devices are responsible for providing interface to the primary equipment of a substation[8]. So accordingly, we have built a Gigabit Ethernet model at different logical levels of a substation because of standardization, simplicity, and maintenance purposes.

The Gigabit Ethernet communication model at station level for SA is illustrated in Fig. 1. In this communication model, bays are depicted as another level of communication where Ethernet switch provides interface between the bay level and process level. The Gigabit Ethernet at station level provides interface between bays and station level devices such as HMI, engineering, control center, backup control center and to the access network. Gigabit Ethernet switches are installed at two levels, i.e., at bay level to connect different bays and at substation level to connect all the bays to the station level devices. A fault tolerance switch is also installed to provide connectivity in case the primary operational switch goes down as a result of failure. In order to connect the substation to the outside world for remote monitoring or to connect with other substations as in the case of an SACDA (Supervisory Control and Data Acquisition) system, these switches are further connected to a router which routes the traffic for the substation and then via firewall communication is transferred to the access network. When connectivity to the access network goes down or there is some other problem then wireless communication is used to transmit the substation data to the outside world and also provides connectivity for remote monitoring. Technically, an optical fiber communication system is one of the most attractive communication mediums. Therefore, it is used as a communication medium in substations because of its high capacity, efficiency, coverage, and last but not least security.

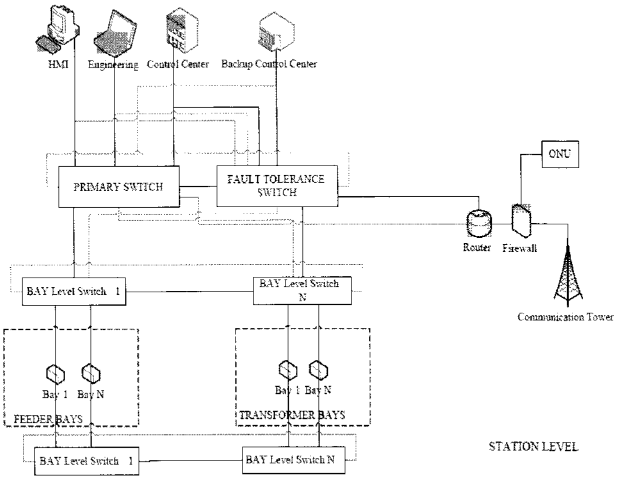

Fig. 1 Gigabit Ethernet based Substation Automation

In Fig. 2, the communication model at bay level for substation automation is shown as the lowest communication level within the substation. In this communication model, an Ethernet switch is deployed between bay level devices such as different IEDs and process level devices such as CT/VTs (Current Transformer/Voltage Transformers), CB (Circuit Breaker), switch gear, and etc. as specified by IEC61850 9-2.

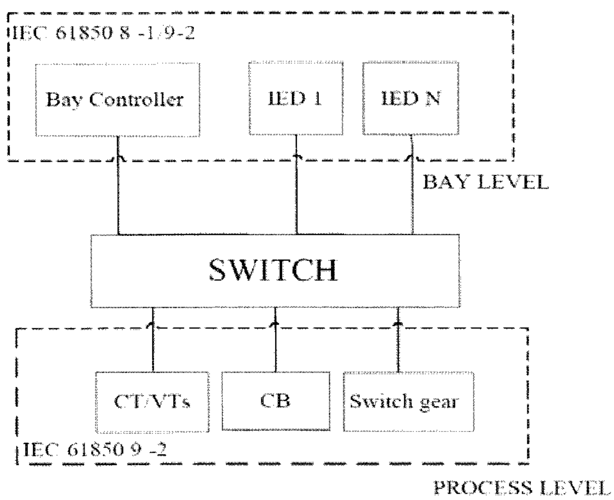

Fig. 2 Ethernet based bay architecture for substation

Indeed Ethernet technology's most pressing need is for the functionality of bay level devices and process level devices since traditionally process level devices were supported by multiple vendors thereby raising concerns related to incompatibility, poor performance, and some other economical reasons. To mitigate all these concerns, Ethernet technology is modeled here between bay level and process level to fulfill the requirements of standardization, performance, and cost effectiveness. On the other hand the proliferation of Ethernet capable IEDs used for SA has increased markedly in the past several years.

The environmental conditions found in the substations can straddle the extremes of the surrounding climatic conditions, so it is one of the challenges for developing Ethernet technology which can operate in such extreme environments. Various kinds of electromagnetic disturbances in a wide frequency range can exist and may be conducted through power supply lines, control lines, or directly radiated by the equipment[8]. Ethernet switches for the substation need to operate in the same temperature range as IEDs and should also fulfill the requirements of general environment and electromagnetic interference (EMI) immunity for network equipment used in substations as specified in the IEC61850-3.

In the next section, performance evaluation related to our suggested communication architecture for SA is presented to show the significant impact of using Ethernet technology within the substation. It is not possible to test Ethernet switches in real substations because of the mission critical and high-voltage substation components, so the alternative is to simulate the whole network with a powerful simulator.

3. Performance Evaluation

In this section, the performance evaluation of a Gigabit Ethernet within a substation is presented with the help of simulation. By keeping into consideration, the real parameters of a substation, network modeling of nodes and background traffic for normal conditions and abnormal conditions, we decided to use NS-2 (Network Simulator 2) for simulation.

3.1 Simulation Framework

According to IEC61850, the transmission of sampled values from the process level to the bay level or to the protection devices should be completed with a maximum delay of about 4*ms* and the same delay is specified for the trip signals which are actually a mission critical data packet. In this respect, two types of messages are specified by IEC61850 draft, i.e., GOOSE and GSSE (Generic Substation State Event). A GOOSE message contains information that allows the receiving device to know that a status has changed and the time of the last status change. A GSSE model is the same a GOOSE except for the kind of information exchanged. GOOSE provides a flexible means to specify which information is to be exchanged whereas GSSE provides a simple list of status information[8]. Therefore, we selected a GOOSE message to simulate in NS-2 for evaluating the performance of the Gigabit Ethernet for the SA. So in order to get the most accurate results, we maintained the size of the GOOSE message so that it could support encryption to cope with malicious attacks. The ability to trade-off reliability for delivering greater determinism is crucial for multicasting GOOSE state change messages. Sending the most recent GOOSE is much more important than resending old updates that were previously dropped by the network, which will probably be out-of-date when they are delivered anyway.

In NS-2, the GOOSE message is modeled as a UDP packet. The UDP as a real-time protocol is able to meet the critical time requirements of a GOOSE message since the normal response requirement for SA is 4ms. Most simulation packages tend to emphasize client-server or publisher-subscriber paradigms. In simulation, we have maintained the model such as to allow different IEDs to subscribe to the multicast group of GOOSE messages or to cancel the subscription for a GOOSE message.

For simulating Gigabit Ethernet at station level within the substation, we have modeled a MAC layer at two levels, i.e., one where different bays are going to interconnect with each other and other at substation level where different bay level switches are interfaced with the station level devices such as HMI, engineering, control center, backup control center, and finally connectivity to the access network for remote communication control via the router and corporate firewall.

Network parameters for simulation setup are derived by keeping into consideration administrative overhead and measured data from IEC61850 specification. The size of the GOOSE packet in simulation is 123 Byte which is evaluated as per GOOSE message requirements specified in IEC61850 with parameters such as Ethernet frame, priority tagging, PDU, dataset, encryption bits and etc[8]. The packet sending rate is 140,000 packets per second which is a gross estimate from real substation requirements[2] thus the data rate is about 137.76 Mbps. By adding a 10% reserve bandwidth, for optimizing the data rate in a real practical scenario the final data rate will be 151.53 Mbps. A strict limit of *4ms* is set for the expiration of a GOOSE message to analyze packet lost ratio. As security in Ethernet is one of the growing concerns, so in order to ensure secure transmission, powerful encryption techniques can be used to encrypt GOOSE messages for the substation thereby adding another 176 Byte in the Ethernet frame for the RSA algorithm. By using these network parameters, the simulation is run for 200 seconds to analyze the different network characteristics shown in the next section.

3.2 Simulation Results

Here we present simulation results obtained from NS-2 related to the simulation of a Gigabit Ethernet based substation at station level. In order to evaluate the performance of the Gigabit Ethernet model for SA, we have selected the following three communication characteristics for the GOOSE message:

- Average packets end to end delay
- Packet drop rate
- Bandwidth consumption

For simulation in NS-2, we have selected four bays from two isolated parts of the substation, and then we examined those four bays over these communication characteristics. In this way, we discovered how much time a GOOSE message takes from process level to all the members of the multicast group during communication, how many GOOSE packets are dropped since a GOOSE message can last for only *4ms* and finally how much bandwidth is consumed by these bays.

Fig. 3 shows the average packets end-to-end delay for the GOOSE message for one bay out of four simulated bays at station level. It is clearly shown in the graph that the GOOSE packets are transmitted with the maximum delay of *7us*. The rest of the simulated bays also show a similar average delay pattern.

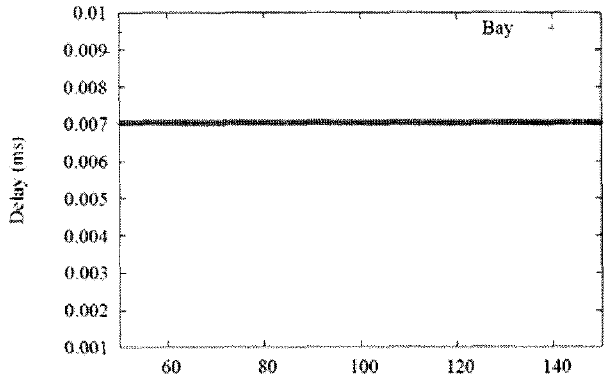

Fig. 3 Average packet end-to-end delay at station level

Fig. 4 shows the packet drop rate for the GOOSE messages. It can be observed clearly from the graph that the packet drop rate for all the bays that we have selected for the simulation is zero. This means during the transmission of the GOOSE messages not a single packet is lost therefore all packets are delivered to the destination.

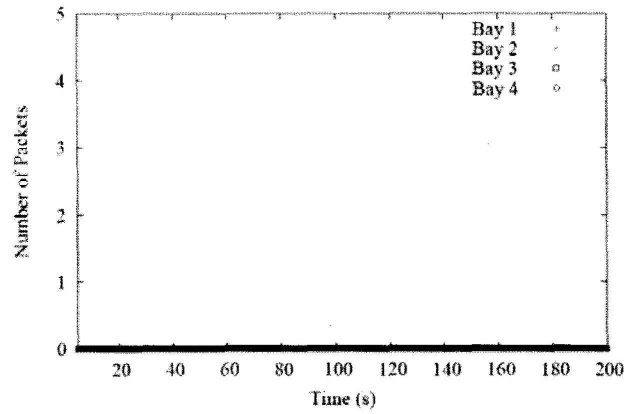

Fig. 4 Packet drop rate

Fig. 5 shows the bandwidth consumption for one bay out of the four simulated bays during the transmission of the GOOSE messages. It can be seen clearly in the graph where the bandwidth is consumed in the range of 139.75-141.75 Mbps for the GOOSE messages.

Fig. 6 shows average delay for the IED at bay level. According to the graph, IED takes 8.45us delay during initiation in the presence of other IEDs which are transmitting GOOSE messages on the network and then an average delay of about 7.1us for the rest of the simulation.

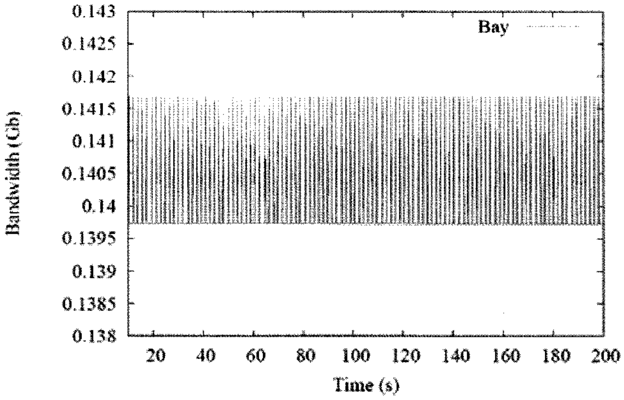

Fig. 5 Bandwidth consumption for bays as stack elements

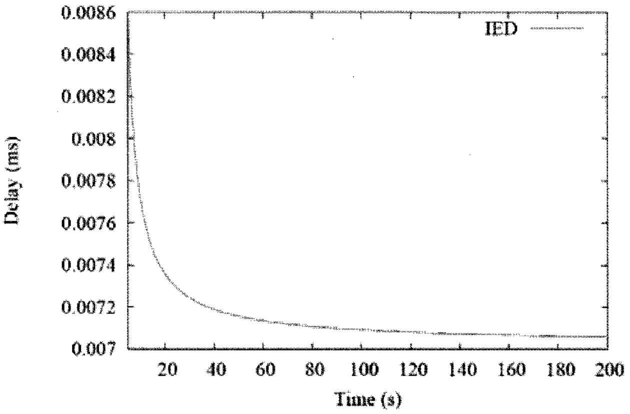

Fig. 6 Average delay at bay level

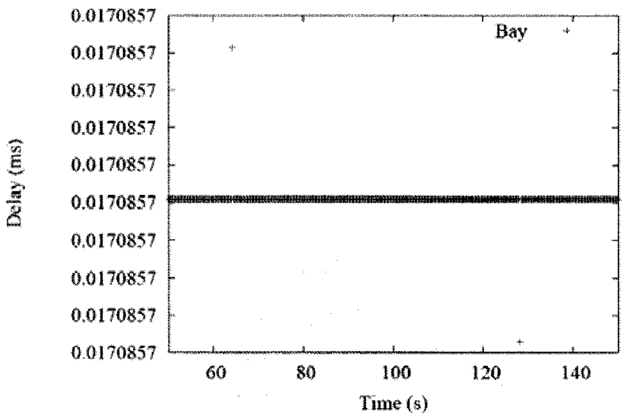

Fig. 7 Average delay at bay level with encryption overhead

Fig. 7 shows the average packets end-to-end delay for an encrypted GOOSE message at bay level. It is evident from the graph that if the encryption technique is employed for a GOOSE message to ensure security initially it takes a 17.1us transmission delay.

3.3 Performance Impact

If a GOOSE message is transmitted for the bay which is located in different regions of the substation then the total round trip delay during initiation phase will be 30.9us and about average 28.2us in steady delay condition. If the GOOSE message is encrypted then the round trip delay during the initiation phase will be 51.1us and about 48.2us in the steady state.

After observing the simulation results we can conclude that a GOOSE message along with an encryption scheme, to combat with security risks, can still manage to transmit under the transmission range limit which is specified by IEC61850, i.e., 4ms when a Gigabit Ethernet is deployed for SA.

4. Conclusions

In this paper, we addressed one of the crucial aspects of substation automation (SA) with respect to communication architecture, i.e., deployment of a Gigabit Ethernet in a substation. Due to cost-effectiveness, high availability and interoperability, Ethernet technology has evolved as one viable solution for substations. The power industry is maturing daily so there is no doubt Ethernet will have widespread use not only for local communication but also for long-haul communication in near future. Additionally, Ethernet networks can migrate seamlessly from 10 to 100 Mbps to 1 Gbps by maintaining the packet format and protocol of most of today's networks thereby saving the cost of protocol conversion. Our proposed communication paradigm is not only optimized for the current IEC61850 constraints but can also easily support future considerations as it is one of the most adaptive and pervasive communication trends available in the communication arena. We used simulated experiments to validate the effectiveness of our proposed communication paradigm and proved the performance impact of Ethernet technology for SA.

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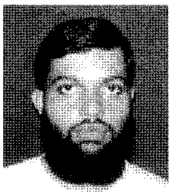

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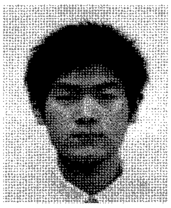

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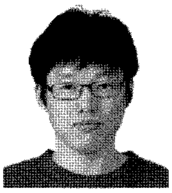

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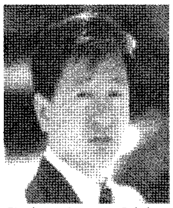

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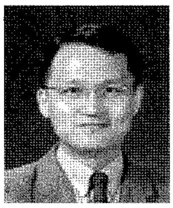

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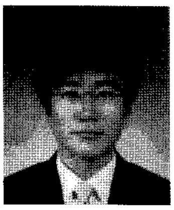

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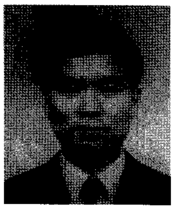

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