Design of Underwater Ad-hoc Communication Protocol for Underwater Acoustic Networks

Changho Yun, A-Ra Cho, Seung-Geun Kim, Jong-Won Park, Youngchol Choi and Yong-Kon Lim, *Member, KIMICS*

Abstract— **In this paper a cross layer protocol, referred to as an underwater ad-hoc communication (UAC) protocol, is proposed for underwater acoustic networks (UANets). An underwater node (UN), which tries to transfer data to another UN or a buoy in ad-hoc manner, can access channel as well as determine routing path by employing the UAC protocol. The channel access, route determination, and reliable data transfer are designed being adaptive to underwater environments. In addition, we propose both UN and packet architectures in order to efficiently implement the UAC protocol for UANets.**

Index Terms—**Ad-hoc, data transfer, channel access, routing, protocol, underwater acoustic network (UANet)**

I. INTRODUCTION

So far underwater acoustic communication technologies have been considerably improved; key underwater acoustic communication elements such as an acoustic sensor and a data modem, as well as a channel equalization technique against underwater multipath fading have been improved [1]. These advances trigger the introduction of diverse underwater applications, including scientific monitoring, probing, surveillance, mining, underwater telephone, submarine communication, and so forth [2].

Apart from fixed underwater sensor networks targeted for consistent underwater monitoring, most applications are on-demand by employing mobile underwater nodes (UNs). Also, the data obtained from a UN can be destined to another UN or a gateway node (GN) which gathers data and sends it to a terrestrial base station using radio frequency (RF) communication or even a satellite counterpart. In practice the data from a UN can be hardly delivered to its destination within single hop due to the intrinsically short transmission distance of a UN [3]. Hence, an ad-hoc based UANet can be attractive to serve aforementioned underwater applications in that an ad-hoc manner can extend communication coverage under infrastructureless network topology [4].

In this paper we narrow our scope to propose an efficient protocol for an ad-hoc based UANet in the network perspective. In particular we focus on designing a cross layer protocol because it may simplify data transfer process layer by layer such that overall processing delay can decrease. [5] and [6] respectively proposed a cross layer protocol which commonly accommodates three layers: modulation technique or forward error correction (FEC) in the physical layer, channel access in the data-link layer, and route determination in the network layer. In [7], another cross layer is proposed for an ad-hoc based UANet, which is responsible for channel access and routing. Although these previous approaches can support a cross layer solution, they are rather theoretical and still lack of feasibility to be implemented; it is necessary to specify a UN architecture and packet format in order to realize a cross layer protocol in practice. Also, compared to previous approaches, it is significantly required to propose a cross layer protocol which puts together several layer algorithms into single protocol.

For this purpose we propose an Underwater Ad-hoc Communication (UAC) protocol for an ad-hoc based UANet, which is responsible for MAC and reliable data transfer in the data-link layer and route determination in the network layer. Especially, we bring together carrier sensing multiple access/ collision avoidance (CAMA/ CA), Acknowledgement (ACK)/Non-acknowledgement (NACK), and ad-hoc on-demand distance vector (AODV) in the UAC protocol assuming that one acoustic frequency is just employed upon simultaneously executing channel access, data transfer, and route determination. We also design a structure of UN as well as two packet types (i.e., a path type packet and a data type packet) and corresponding packet headers so as to implement an ad-hoc based UANet.

The rest of paper is structured as follows. In Section II, an ad-hoc based UANet and corresponding UN architecture are described. In Section III, a UAC protocol is specified in terms of channel access, data transfer, route determination, and packet structure. Finally, we conclude this paper in Section IV.

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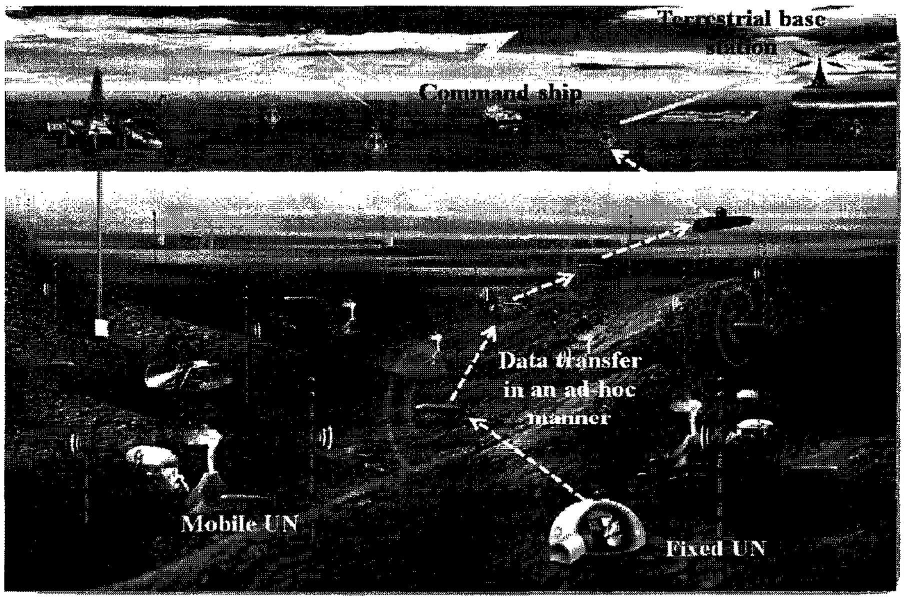


Fig. 1. An illustration of an ad-hoc based UANet.

II. ARCHITECTURE OF UNDERWATER ACOUSTIC NETWORKS

In this section we describe an overall ad-hoc based UANet and architecture of a UN in order to execute the UAC protocol in practice as follows.

A. An Ad-hoc based UANet

As illustrated in Fig. 1, an ad-hoc based UANet consists of several network elements, including several UNs, GNs, and terrestrial base stations. A UN can be fixed or mobile according to applications. A fixed UN can be exemplified as acoustic underwater sensors, optical underwater sensors, fixed underwater stations, or remotely operated underwater vehicles (ROVs). A mobile UN is exemplified as divers, submarines, autonomous underwater vehicles (AUVs), and so forth. A UN is responsible for executing given mission and communicating with another UN or a GN case by case. A GN is an intermediate node which controls UNs and gathers data from UNs and sends it to a terrestrial base station. A GN is also fixed as a buoy or mobile as a command ship with respect to applications. It is equipped to both acoustic and RF communication systems to connect UNs to a terrestrial base station. A terrestrial base station is connected to terrestrial backbone networks. Thus, it is responsible for finally gather information from diverse underwater applications and send it to many Internet subscribers via terrestrial backbone networks.

The data transfer among UNs is executed in an ad-hoc manner, as illustrated in Fig. 1. A UN can be either a source node (SN) which initiates data transfer or a destination node (DN) which finalizes data transfer. Otherwise, a UN can be a relay node (RN) which is located between a SN and a DN such that it forwards data to another UN or a DN according to its position. The details of how to access channel and how to determine a route between a SN and a DN are specified in following Section.

B. An architecture of a UN

Figure 2 shows an architecture of a UN to employ the UAC protocol for an ad-hoc based UANet. A UN is designed to consist of one embedded timer and five sectors, including packet generation sector (PGS), packet reception sector (PRS), communication controlling sector (CCS), packet management sector (PMS), and packet transmission sector (PTS). Before describing each sector, we simply define all packets for data transfer and route determination as a packet. The type of packets will be further specified in following section. First, the function of PGS is changed according to type of UNs (i.e., SN, DN, or RN).

- When a UN is acted as a SN, PGS has responsibility for generating packet and requesting packet transfer and route determination to CCS.

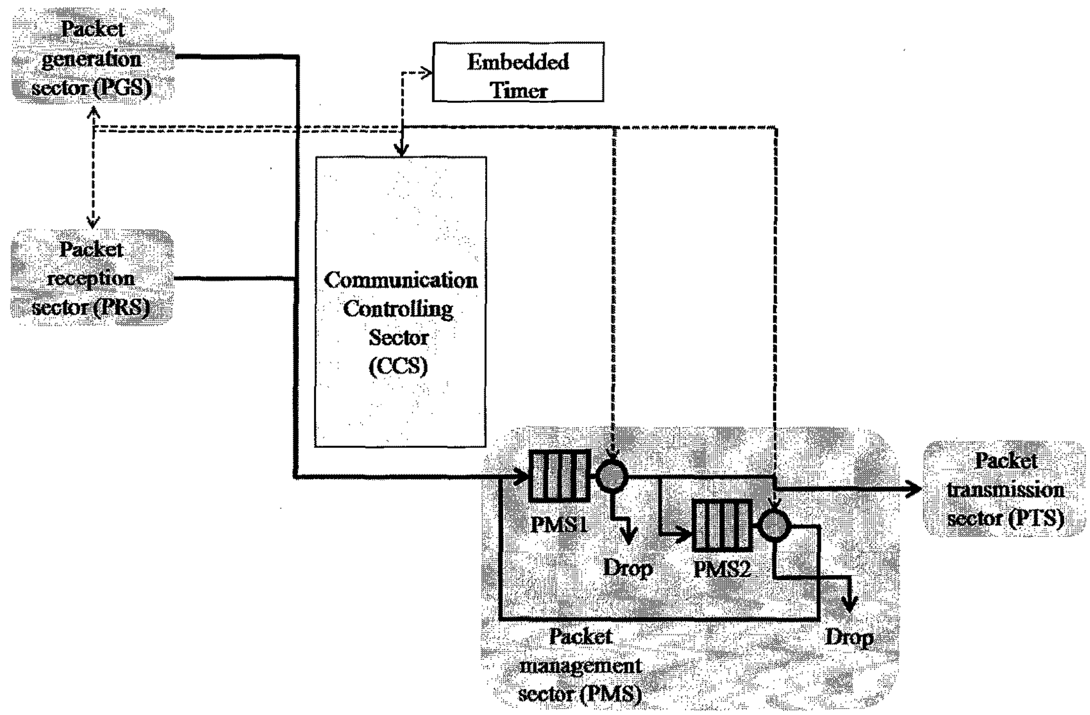


Fig. 2. An illustration of UN architecture.

- When a UN is acted as a DN, PGS generates a packet to confirm route determination.
- It is common for SN, DN, and RN to generate NACK by PGS when they receive a corrupted packet.

Second, PRS is responsible for receiving any packet and forwarding it to PMS. Also, PRS informs CCS of channel status (i.e., busy or idle) once it is requested. Third, PMS deals with arrived packet by asking CCS. PMS sends or throws away arrived packet as CCS indicates. Also, PMS consists of PMS1 and PMS2. PMS1 is the first queue of arrived packet, while PMS2 is the sub-queue which stores already sent packets and sends them back to PMS1 once retransmission is requested. The queuing strategy of PMS1 and PMS2 is determined as first in first out (FIFO). Fourth, CCS is major sector of a UN in that it can control remaining sectors based on programmed UAC protocol. As we mentioned, a packet has several pre-defined headers. CCS makes use of the header information to manage PGS, PRS, PMS, and embedded timer. Finally, embedded timer is responsible for checking whether a packet transfer is expired or not. And it informs the result of CCS if the embedded timer is expired.

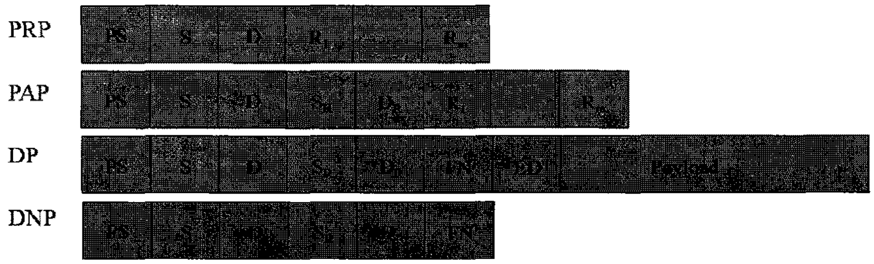
III. UNDERWATER AD-HOC COMMUNICATION PROTOCOL

In this section we describe the UAC protocol, which is programmed in CCS in order to simultaneously execute channel access, data transfer, and route determination. To explain the UAC protocol, we primarily detail packet specification. Then, channel access, data transfer, and route determination of the UAC protocol are explained as follows.

A. Packet specification

A packet for the UAC protocol can be categorized into two types; one is a data type packet, and the other is a path type packet. The former is used to send data which is generated by a SN. The latter is used to determine a route between a SN and a DN. As shown in Fig. 3. (a), each packet consists of several headers, and the type of headers and the number of headers are different according to the type of packets.

First, a path type packet is divided into two types: a path request packet (PRP) and a path ACK packet (PAP). A PRP consists of packet specification (PS), source (S), and destination (D) headers when a SN has data destined to a DN. PS, S, and D headers indicate the type of packets, source address, and destination address, respectively. All packet headers are specified in Fig. 3. (b). As a PRP is forwarded



(a)

Header Type	Description	Length
PS	Packet specification Data specification	1 byte • First 2bits; packet specification (00: PRP, 01: PAP, 10: DP, 11: DP) • Remaining 6bits; data #
S	Source node addr.	1 byte (eg. 00000001: UN No. 1)
D	Destination node addr.	1 byte (eg. 00000100: UN No. 4)
S_R	Sending node addr.	1 byte
D_R	Receiving node addr.	1 byte
R_i	Relay node addr.	1 byte
FN	Fragmentation number	1 byte (max. 500), changeable
ED	Error detection	2bytes (using 16bit CRC), changeable
Payload	Transmittable Data	32bytes (changeable)

(b)

Fig. 3. Packet types and header specification for an ad-hoc based UANet.

by a RN on the way of sending to a DN, the RN attaches its address to the PRP such that the number of R_i headers increases, as shown in Fig. 3. (a). A PAP is sent by a DN when it receives a PRP from a SN. A PAP consists of PS, S, S_R, D_R, R_1,..., R_m headers. R_1,..., R_m are the address headers of RNs which relay a PRP between a SN and a DN. Here R_1 is the first RN, and R_m is the last one. S_R and D_R headers are used to specify corresponding one hop source and destination address along with the determined route. For instance, when a DN sends a PAP, S_R is D, and D_R is the address of R_m.

Second, a data type packet is also divided two types: a data packet and a data NACK packet (DNP). A DP is sent by a SN when a route between a SN and a DN is determined. As illustrated in Fig. 3. (a), a DP consists of PS, S, D, S_R, D_R, fragmentation number (FN), error detection (ED), and payload. FN header is used to number the piece of data of which size is beyond the maximum transferrable data size. The default of maximum fragmentation number is 500 which is determined for our project, but this value can be changeable according to applications. ED header is used to detect packet errors, and the default is 16 bit cyclic redundancy check (CRC) but this is also changeable. Payload contains the transmittable data. The default is 32 bytes but it can be changeable with respect to applications. A DNP is used when a RN or a DN receives corrupted DP, and this packet results in retransmission of the same DP. A DNP consists of PS, S, D, S_R, D_R, and FN headers.

Figure 4 illustrates an overall UAC protocol accommodating channel access, data transfer, and route determination in one protocol. When a UN receives a packet, it checks all headers and handles the packet with respect to the UAC protocol as shown in Fig. 4.

B. Channel Access

Channel access is a prerequisite to send any packet. Aforementioned, the channel access of the UAC protocol is on the basis of CSMA/CA. In the UAC protocol, request-to-send (RTS) and clear-to-send (CTS) are not considered. Instead, a UN just senses channel and sends packet if it detects the channel is idle, as shown in Fig. 5. If not, a UN waits for exponential random backoff time. As the same as 802.11 [8], exponential random backoff time can be defined as multiplying random number (K) by bit time (T_b) where T_b is 1/R, and R is data rate. We specify K by considering the environments of a UANet. In case of n_{th} collision, K is randomly chosen among the values of K = {0 , 1, 2, ..., 2^{s-1}} where s = min(n, s_{MAX}). To determine s_{MAX}, we consider that the maximum transmission distance of a UN is 1.5km and the propagation speed is 1.5km/s as specified in [9]. Also, we assume as follows.

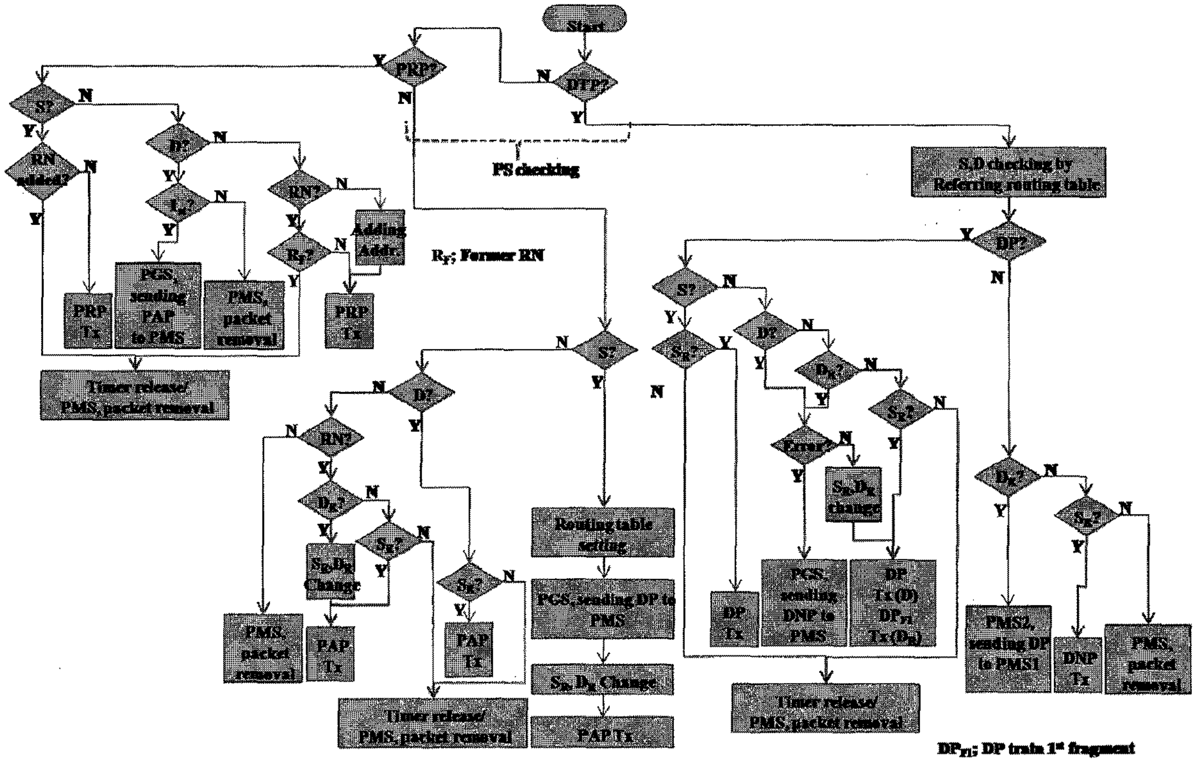


Fig. 4. UAC protocol for an ad-hoc based UANet.

$$2^{s_{MAX}-1} \times \frac{1}{R} \le \frac{1.5km}{1.5km/s} \qquad (1)$$

which implies that maximum random backoff time cannot be greater than the time when a packet is propagated to the maximum transmission distance. Thus, s_{MAX} can be expressed as ($\log_2$ R +1).

C. Route determination

Route determination is a prerequisite of data transfer. Via this procedure, a SN determines a route to which a DN and several RNs belong. A PRP and a PAP are used to determine a route between a SN and a DN. As we mentioned, route determination of the UAC protocol is based on AODV where a PRP is sent to a DN by flooding [10]. When the DN receives the PRP, it sends a PAP to finalize route determination. Compared to a PRP, UNs whose addresses are in a PAP receives and forwards the PAP. Other UNs just discard the PAP.

To avoid forwarding same PRP originated from looping, we propose selective flooding where a UN does not forward any PRP but selectively send a PRP based on the UAC protocol, as illustrated in Fig. 4. If a UN receives a PRP and its address is not in R_m headers, it attaches its address into the PRP and forwards the packet. If a UN receives a PRP and its address is in R_m headers, it should figure out the position of R_m header. Let's define R_F as the former RN of which address belongs to R_m headers but is not attached at the end. If a UN is R_F, it discards the PRP since it is returned to itself due to looping. If not, a UN sends the PRP because the PRP is retransmitted due to timer expiration. For instance, when a UN with address 4 receives a PRP where R_m headers are specified as 2, 3, 4, 5, there are three R_Fs whose addresses are respectively 2, 3, 4. In this case, the UN discards the PRP since it belongs to R_F.

One hop PAP or PRP is used to check whether a PRP or a PAP is reliably received or not, as shown in Fig. 4. It can be checked by receiving another UN's PRP or PAP and checking its headers. When a UN sends a PRP or a PAP, timer starts to work. The timer stops by CCS which is informed that PMS1 receives one hop PRP or PAP. If the timer is expired (i.e., T_R is over) before receiving one hop PRP or PAP, it informs the expiration of CCS. Then, CCS orders PMS2 to send a PRP or PAP to PMS1 again. T_R can be heuristically determined as

$$T_R = 2 \times T_{Pmax} + T_{QPMS} \qquad (2)$$

where T_{Pmax} is the maximum propagation delay and T_{QPMS} is average queuing delay of PMS. As a UN is mobile, determined route between a SN and a DN cannot hold. Thus, a route is determined and updated whenever a UN sends data to another UN.

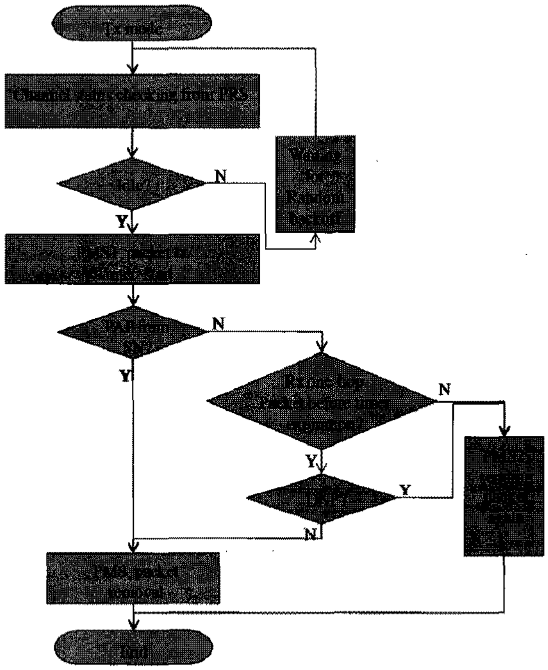


Fig. 5. A transmission mode of the UAC protocol.

D. Data transfer

After determining a route, a SN sends a DP to a DN via RNs specified in the determined route. In order to improve overall delay performance, a UN sends full data using packet train which is a train of DPs [11]. As the data is sent using packet train, first DP contains full headers, including PS, S, D, S_R, D_R, FN, ED headers, and payload, but remaining DPs just contain FN, ED, and payload. RNs forwards received DPs along with determined route.

For reliable data transfer, one hop DP or DNP is also considered as the same as path type packet transfer, as shown in Fig. 4. If a UN receives corrupted DP, it requests to retransmit only corrupted DP by specifying FN in a DNP. After receiving a DNP, a UN sends only corrupted DPs as the same way as sending original DPs. If timer expires before receiving one hop DP or DNP (i.e., timer is over T_D), a UN sends a DP or a DNP again. T_D can be also heuristically determined as

$$T_D = 2 \times T_{Pmax} + T_{QPMS} + T_{PT} \quad (3)$$

where T_{PT} is the packet train processing time.

IV. CONCLUSION

In this paper we proposed a cross layer protocol, referred to as a UAC protocol, which is responsible for channel access, data transfer, and route determination. To execute the UAC protocol, we also designed a UN architecture as well as packet types and headers. In particular, the UAC protocol can be employed in an ad-hoc based UANet where mobile UNs determine a route and send data each other with single acoustic frequency. As this is an ongoing work as a part of our project, it is necessary to analyze the performance of the UAC protocol. Also, the implementation of the UAC protocol on our experimental test bed will be followed in further work.

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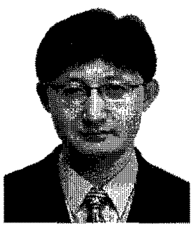

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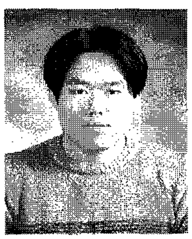

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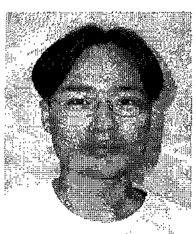

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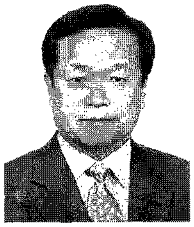

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