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Dual Coalescent Energy-Efficient Algorithm for Wireless Mesh Networks

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ABSTRACT

In this paper, we consider a group mobility model to formulate a clustering mechanism called Dual Coalescent Energy-Efficient Algorithm (DCEE) which is scalable, distributed and energy-efficient for wireless mesh network. The differences of the network nodes will be distinguished to exploit heterogeneity of the network. Furthermore, a topology control, that is, adjusting the transmission range to further reduce power consumption will be integrated with the cluster formation to improve network lifetime and connectivity. Along with network lifetime and power consumption, clusterhead changes will be measured as a performance metric to evaluate the effectiveness and robustness of the algorithm.

Keywords: Wireless Mesh Networks, Topology Control, Group Mobility, Clustering.

1. INTRODUCTION

Wireless mesh network [1] is a dynamic organization of nodes which are differentiated according to types, namely: routers and clients. Figure 1 depicts a hybrid 802.11 wireless mesh network that is comprised of both wireless mesh routers and clients. The dotted lines symbolize wireless links and the solid lines correspond to a wired connection to the Internet. Particularly, mesh routers, can be equipped with multiple channels that can support multi-hop routing. Although with minimal mobility, mesh routers can also be a gateway or bridge which form the wireless backbone of the network. On the other hand, mesh clients that may perform routing within themselves can be stationary or mobile and may only have one wireless interface. Moreover, mesh routers usually do not have strict power consumption constraints compared to mesh clients. Mesh clients may be battery powered while routers are mains-powered. Managing energy consumption is one of the most important components of a reliable network. With knowledge of this contrariness, we can now formally address critical design factors and challenges of a wireless mesh network. Much had been studied in ad hoc and sensor networks regarding energy efficiency, and subsequently the network lifetime. Indeed, it is important to maintain a reliable network that could keep up with network dynamics by reaching objective goals such as extending network lifetime and scalability. It is essential to account for the differences of the nodes, that is, a single treatment for both mesh clients and routers seem inappropriate. To approach these design factors and differences, we adopt some studies based on wireless ad hoc and sensor networks such as clustering and topology control. More often than not, we could view the network nodes especially the network clients to be located on the same zone, performing a related task and moving together as a group. We consider a group mobility concept [2,3] wherein we based our logical clustering of the nodes. By utilizing

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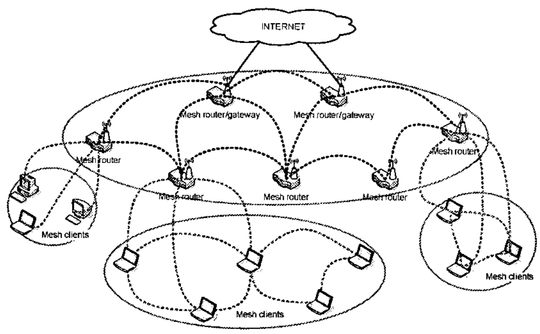

Fig. 1. A hybrid wireless mesh network composed of wireless mesh clients and mesh routers which form the backbone of the network.

node mobility in forming clusters, we essentially increasing the degree of correlation of the nodes within a cluster and thus making it more effective compared to its non-clustered counterpart[4], and also adaptive and self-organizing as what WMN should be. Unlike a topology control that sets minimum transmission range of the nodes to conserve energy, clustering techniques can also be a way to reduce energy consumption [5,6] by superimposing a hierarchy to a flat network. Moreover, node clustering improves scalability [7] so that even if an additional node is added, the network should be able to handle the change and maintain its stability. Furthermore, clustering based on mobility can effectively support scalable routing, efficient radio channel utilization and reduce overhead[8].

Connectivity of the network is the main objective of a typical topology control algorithm [9], along with energy-efficiency, interference awareness, throughput and stability under mobility. Connectivity and energy-efficiency can be achieved by maintaining a graph that would span the entire network while varying the radio range of the nodes. With the incorporation of multi-channel nodes, throughput of a typical wireless mesh networks can be fully realized by proper interference -aware topology control and channel assignment [10].

With these considerations, the problem we would like to address in this paper is to formulate a scalable and adaptive energy-efficient algorithm by utilizing a dual component scheme, namely: clustering and topology control on a wireless mesh network while taking into account both similarities and differences of the entity nodes in the system.

The remainder of this paper is organized as follows: Section 2 briefly surveys related work. Section 3 describes the energy- efficient algorithm which includes cluster formulation and topology control mechanism. Section 4 shows effectiveness of the algorithm. Finally, we draw the conclusion and give directions for future study in Section 5.

2. RELATED WORKS

A number of researches have been performed to seek energy-efficient algorithms and protocols especially on ad hoc and sensor network fields. A wireless mesh network which is a superset of an ad hoc network should not be an exception. Energy efficiency leads to longer network lifetime and thus a more reliable network. Many previous works have been studied regarding energy efficiency in ad hoc and sensor networks but most of them considered a static network. This gives the algorithm susceptibility to node failures and disconnected links. It is good practice to consider mobility patterns to validate the conclusions but a good choice of the mobility model should also be a main concern. A mobility model that is based or very closely related to empirical experiments like reference point group mobility model or random waypoint is an attractive choice [11]. In [12], the mobility patterns discussed in [2] were revisited and mobility metrics were introduced namely: direct mobility and derived mobility metrics. Direct mobility includes relative speed and is defined as the derivative of the difference between positions of two nodes with respect to time. With this particular metric, we could derive several other metrics that could describe the mobility of the nodes. It is also important to consider that mobility has a large-scale impact on the link and route lifetime of the network [11] that makes derived mobility metrics a good measurement to consider as well. Link change rate, average link and path duration are mobility metrics that test the connectivity of the resulting topology that in turn influences protocol or algorithm performance [13].

Clustering is an architecture that can be superimposed on a flat network and there are a lot previous works [6,7,14,15] focused on this area. But for clustering to be energy-efficient, it should consider minimization of post data aggregation, lowering of transmission power, robustness to mobility, link changes and node failures, stability, scalability, heterogeneity and prolonging network lifetime.

A clustered architecture can be effective compared to its non-clustered counterpart if for example, in a monitored environment, a clusterhead is placed in an isocluster [4] wherein all nodes in the isocluster detects similar environment measurement like temperature or humidity, the clusterhead should provide post aggregation of data received especially since the data collected belongs to a similar set. This post aggregation should reduce the volume of intercluster communication by decreasing the number of transmissions. A wireless mesh router is suitable to have this additional functionality given its characteristics.

While clustering can be very effective, limiting of transmission power and thus controlling the effective topology can reduce interference and provide better resource utilization [16]. Usually, if mobility is considered in an algorithm, it is only shown as a metric in performance evaluation. One way to overcome impact of mobility as early as algorithm design is incorporating it as a factor in implementation. Incorporating mobility as one of the component in clustering is discussed in [8] that utilized group mobility metrics similar to [12]. Assigning clusterhead tasks to the least mobile nodes in a cluster reduces reelection of clusterhead instances and increases stability [8]. Although group mobility can be very effective in describing mobility of wireless nodes, it is also important to model individual movements. Consequently, as clusterheads have additional tasks unlike other nodes in the cluster like data aggregation and transfer, they are also source of bottlenecks in the network and it is also substantial to take note the capabilities of the clusterhead. In a heterogeneous network, where there are two types of nodes, powerful and basic nodes, we could choose the powerful nodes to be clusterheads [14]. In a mesh network, the distinction between wireless mesh router and clients that were presented earlier could be the powerful and basic nodes, respectively. An adaptive clustering scheme [15] can be employed to address network changes like mobility. In [8] and [17], mobility based clustering were employed, that is, the most stable node is assigned as a clusterhead within the neighborhood. Specifically, in [8], the nodes were assumed to be mounted with GPS (Global Positioning System) which would be inappropriate since GPS may not be available all the time. On the other hand, in [17], the clusterhead is chosen by combining a distributed scheme to determine relative mobility of the nodes and lowest ID algorithm, the whole heuristic is not implemented on top of a protocol and with a specific objective other than stability. Metrics like link duration and link changes could be good measurement to formulate a feedback mechanism for a more robust algorithm. Our coalescence algorithm is mainly composed of clustering and topology control as we would show and considers all these factors.

3. CLUSTERING AND TOPOLOGY CONTROL ARCHITECTURE

One design factor in a multi-hop environment is allocation of available resources such as power.

Similar to a mobile ad hoc network, wireless mesh networks can be viewed as a multi-hop organization that is composed of multiple groups doing related but independent tasks, such as in disaster recovery teams [3]. Therefore, group mobility is a more realistic movement pattern to consider. In clustering, it is important that the resulting architecture is stable that is, reelection or reassignment of clusterhead among nodes is minimal. A stable node is a node with less mobility and could handle additional functions. A clusterhead with high probability of being mobile should not be elected as clusterhead because this will result to disconnected topology and re-clustering.

The following assumptions are considered in our wireless mesh network cluster framework:

a. A group performing a single task move as a group with dependent movement among themselves but independent among other group

b. An individual node can have individual movement

c. Wireless mesh routers are mains-powered and superior in terms of hardware compared to wireless mesh clients

d. Wireless mesh clients are battery powered

e. Nodes are not equipped with GPS. Therefore, nodes do not know their exact location. Wireless clients can be inside a building and therefore cannot use GPS as a way to know their exact location.

f. The time for the algorithm that is, *Tcluster* << the time of network operation, *Toperation.*

3.1 Cone-Based Topology Control

We define an undirected graph $G = (V, E)$, where V is a set of all nodes and E is a set of all edges. The set of neighbors, the context that is used all throughout this paper, of any node in V is defined as the nodes that belongs to a subgraph $G_{tc} = (V, E')$ and one hop away from a node under consideration after the system executes a cone based topology control. A cone-based topology control [18] is similar to Yao graph wherein for each cone or angle centered to node u chooses another node, v to be its neighbor using minimum transmission power and sending/receiving "hello" messages. We take an angle a, usually $5\pi/6$ wherein a node finds a neighbor within its minimum transmission range and gradually increasing its range until it finds a node within a. It moves to the next cone and finds a neighbor until it completes a revolution. If a node does not find a neighbor within the cone and maximum range, it moves to the next cone using minimum power. This algorithm determines the neighbors of the node by directional information and without GPS. Therefore, at the end of this algorithm, the maximum power a node needed to reach its farthest neighbor would be:

$$\max_{2\pi} \min_{\alpha} \{p_{\alpha}\}, \alpha = 0, \ldots, 2\pi \tag{1}$$

3.2 Relative Mobility Metric

In a non-GPS system, received signal strength can be utilized to approximate the distance of a node and vice versa [19]. Certain assumptions must be considered:

1. Nodes have isotropic antenna or non-isotropic antenna

2. The nodes are deployed in a static channel meaning signal fading and multipath effects are not considered. This is an important assumption since identifying the location of a node could be very difficult since the variations of the signal can either be because of movement or the dynamism of the channel.

XA free space path loss between isotropic antennas is defined as:

$$L_p = \left(\frac{4\pi R}{\lambda} \right)^2 \tag{2}$$

where R is the distance between the receiver and transmitter and λ is the wavelength of transmission. We could determine the received power on every node given by the transmission

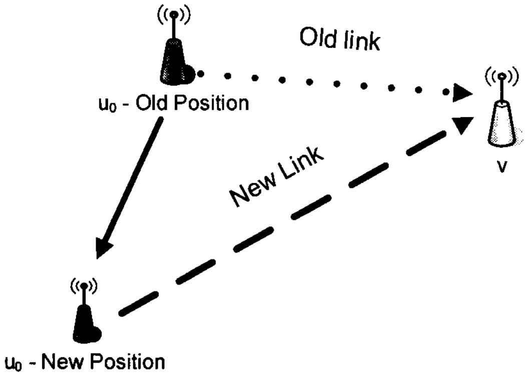

Fig. 2. An illustration for Equation(4).

power of the transmitter using (3):

$$P_R = \frac{P_T}{(4\pi R/\lambda)^2} = \frac{P_T}{L_P} \quad (3)$$

From this, it is easy to see that $P_R / P_T \propto 1/R^2$. Although, it is not reliable to determine the distance using transmit power and with a unity gain, using two successive packet transmissions from a neighboring node, we can approximate the relative mobility between two nodes [17]. We now define the relative mobility of a node v with respect to u_0 by using received power from u_0 as illustrated in Fig. 2:

$$M_v(u_0) = 10\log_{10}\frac{P_{R\_new}^{u_0 \to v}}{P_{R\_old}^{u_0 \to v}} \quad (4)$$

where $P_{R\_new}^{u_0 \to v}$ and $P_{R\_old}^{u_0 \to v}$ are the received power detected in u_0 from old and new position, respectively. From (4), a negative $M_v(u_0)$ means that u_0 and v are moving away to each other, while a positive $M_v(u_0)$ indicates that u_0 and v are moving closer to each other. We combine this to the result with other neighbors of v, say $u_1, u_2, \cdots, u_m$, such that we have:

$$M_v = [E(M_v)^2] = \mathrm{var}_0\{M_v(u_i)\}_{i=1}^{m} \quad (5)$$

A node with a high relative mobility variance is more likely to be more unstable than its opposite and thus should not become a clusterhead.

3.3 Group Mobility Metric

Since movement of the nodes causes reelection of clusterhead and reconfiguration of clusters, it is appropriate to incorporate the mobility pattern in cluster formation. In group mobility, a set of nodes may follow the same pattern of movement depending on their functions, considering the assumptions stated above, we add our fourth assumption:

4. Mobile nodes know their velocity (speed and direction).

The mobility metric to be considered is called degree of spatial dependency, $D_{spatial}$ [13]. Spatial dependency is the measure of correlation in the movements of nodes that are not too far apart or in a neighborhood. Therefore, if the movement of nodes is the same, it is more likely that they moved as a group. Formally, $D_{spatial}$ is defined as:

$$D_{spatial}(u,v,t) = \frac{\vec{u}(t) \bullet \vec{v}(t)}{|\vec{u}(t) * \vec{v}(t)|} * \frac{\min|\vec{u}(t)|,|\vec{v}(t)|}{\max|\vec{u}(t)|,|\vec{v}(t)|} \quad (6)$$

The average degree of spatial dependence is given by [13]:

$$\overline{D}_{spatial} = \frac{\sum_{t=1}^{T}\sum_{i=1}^{M}\sum_{j=i+1}^{M} D_{spatial}(u_i, v_j, t)}{P} \quad (7)$$

where P is the number of combination of *(i, j, t)* and the degree of spatial dependence is not equal to 0. The variable t can be a time interval between two hello messages and not a physical time that needs to be synchronized.

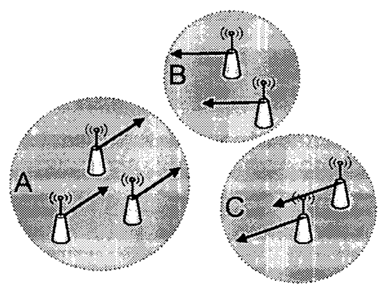

Fig. 3. Mobile nodes within A, B and C have high $\overline{D}_{spatial}$ among nodes within the same area.

3.4 Clustering and Topology Control Algorithm

Since mesh routers do not have power constraints, are less mobile and are therefore stable, they are more probable to become a clusterhead. We outline our algorithm with the following steps:

1. The system will perform a distributed topology control algorithm to form a Subgraph $G_{td}(V, E')$as described in section 3.1

2. All nodes send/receive two "Hello" messages to its neighbors at the start and end of an interval, t_{hello}. Using (4), a neighbor will compute its relative mobility with respect to the sending node and the received power. If a node has k neighbors then the complexity of this step, if the transmission is one unit of time and computation is negligible, is $O(N)$.

3. All nodes will compute its relative mobility M using (5).

4. Then all nodes will broadcast its relative mobility metric M to all its neighbors plus its velocity (speed and direction) and residual energy which is given by:

$$E_{residual} = \frac{E_{current}}{E_{\max}} \tag{8}$$

For a certain period of time t_3, a node will accumulate k values of M. If a node has the smallest relative mobility among its neighbors then it becomes a clusterhead.. The node will also know its degree of spatial dependence among its neighbors after receiving k velocities and by (7). In case of ties or more than 1 contending clusterheads, we consider the node with highest residual energy or a mesh router as a clusterhead.

5. The clusterhead will broadcast its ID and degree of spatial dependence to its neighbors and if a neighbor has the same degree of spatial dependence and relative velocity, then that neighbor will associate itself to that clusterhead via an associate request which in turn be answered by an associate reply. With this, we restrict the number of nodes that will join the clusterhead.

6. There will come a time that a node or group of nodes may move far away from the clusterhead especially if the clusterhead is a mesh router. For this instance, it is necessary to choose another clusterhead. We define an event triggered association and disassociation scheme in the next section.

3.4.1 Association and Disassociation

A clusterhead may poll its cluster members to know if they are still within range or active. But this polling technique may require additional overhead within the cluster and inappropriate if there are no link changes. We designed an event triggered scheme for this network change to avoid this overhead. Fig. 4 shows an association scheme of a node to a clusterhead.

Association

A node will send an associate request to a nearby node, if a node is a clusterhead, the clusterhead will send an associate reply with velocity of the nodes within the cluster. If the recipient is a node that belongs to a cluster it forwards the associate request to the clusterhead.

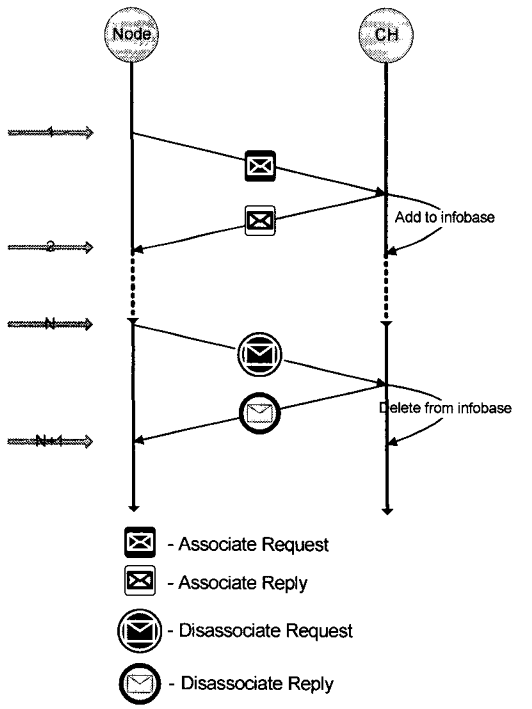

Fig. 4. An event driven association/disassociation scheme to/from a clusterhead by a node.

Disassociation

A node will send a disassociate request to a nearby node, whenever its velocity and direction fall off the mobility of other nodes, if the nearest node is a clusterhead, the clusterhead will send a disassociation reply. If the nearest node is a node in the cluster it forwards the disassociate request to the clusterhead.

4. SIMULATION AND RESULTS

The questions: How stable our algorithm in the presence of mobility and in addition of nodes and how effective it is in extending the network lifetime? will be answered using a simulation. Using ns-2, we modeled our clustering algorithm with topology control. The initial number of nodes is 100. A group mobility is used to model movement of nodes with group velocity between [0, 50m/s], size of the system is 1 x 1 km.^{2} Among n nodes, $0.20n$ are mesh routers. Minimum transmission range is 10m and maximum is 100m. Initial battery for mesh clients is 2J. Two of the results, clusterhead changes and network lifetime which are defined as the time the last mesh client depletes its battery are being shown in Fig. 5 and 6.

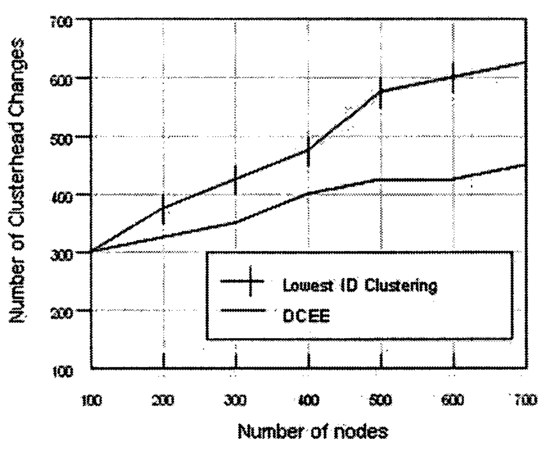

Fig. 5. An increase of the number of nodes does not necessarily increase number of clusterhead changes compared to lowest ID algorithm.

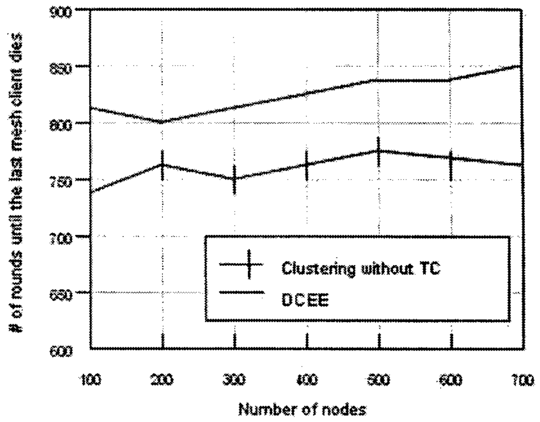

Fig. 6. Although clustering may prolong network lifetime, clustering with topology control is better.

A mobility-based clustering, as discussed in this paper, outperforms lowest ID clustering based from Fig. 5. For an increasing number of nodes, the number of clusterhead changes also increases. This is expected, since increasing number of nodes means increasing number of clusters. However, comparing the two clustering method, although mobility based-clustering increases this is not as much as that of lowest ID method, primarily, because of the inclusion of mobility criterion in cluster formation. It also follows that if there are less clusterhead changes, we have a more stable network.

We know that at some point in time all of the battery-powered nodes will deplete their limited power as shown in Fig. 6. In this figure, clustering coupled with topology control helps prolonging the network lifetime compared to a pure clustering algorithm. It is also important to note that this graph should not follow an increasing or decreasing trend, since the roles of being a clusterhead or a cluster member is distributed among the nodes depending on their capabilities as described in section 3.4. For example, at 200 nodes, however, there is a slight dip on clustering with topology method, as mentioned; this can be attributed to the dynamics of clusterhead selection and role distribution in the network. Overall, our proposed method performs well in terms of stability and prolonging network lifetime.

Furthermore, we compare our algorithm to other clustering algorithms based on time and message complexities. Time complexity is defined as the time for the algorithm to achieve a valid cluster structure. On the other hand, message complexity is defined as how many signaling messages are needed to form clusters. Table 1 shows the comparison between some algorithms and the algorithm presented on this paper, *DCEE* (Dual Coalescent Energy Efficient Algorithm)

The reader is referred to [20] for the details on how to compute the time and message complexity of the other three algorithms. Our analysis shows that since, during cluster change, the association and disassociation of nodes in a cluster is event-triggered and keeps a one-hop distance from clusterhead via topology control, hence, the time complexity can easily be deduced as $(T_{sample}+1)$ and the message complexity as $O(1)$. This is better than the other multi-hop clustering algorithms (MobDHop, Max-Min) as shown in Table 1. On this paper, we have presented an algorithm that stands in the middle ground between achieving stability and network lifetime without sacrificing time and message complexities.

5. CONCLUSION

We have presented an energy-efficient algorithm for a wireless mesh network. The algorithm is composed of a two-tier scheme namely: cluster formation and topology control. The cluster formation makes the network scalable and stable while the topology algorithm makes it more energy efficient and connected. Our scheme shows that the network lifetime is prolonged compared to a clustered topology only without sacrificing time and message complexities.

For our future work, we would like to extend the algorithm by considering a multi-channel implementation of wireless mesh routers which improves their capacity and flexibility. This will be an extension of topology control to reduce interference in the network.

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Table 1. Comparison of Time and Message Complexity.

Algorithm	Time Complexity per Topology change	Message Complexity per Topology change	Total Overhead Per Time Step
DCEE	$(T_{sample}+1)$	O(1)	O(N)
MobDHop	$\leq(T_{sample}+H_{max}) \times H_{max}$	$\leq(H_{max})^2$	O(N)
Max-Min	O(d)	O(d)	O(N)
Lowest-ID	O(1)	O(1)	O(N)

Where:
T_{sample} - the number of time steps taken by a node to collect stability information from neighbors
N - the number of nodes
H_{max} - maximum hop count from clusterheads

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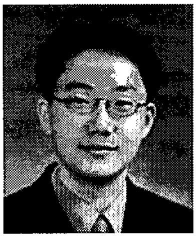

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