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A Truthful and Low-Overhead Routing Protocol for Ad Hoc Networks

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Abstract

Nodes in wireless ad hoc networks depend on others for forwarding packets hop by hop. However, nodes may behave selfishly and do not forward packets for saving their limited resources. Approaches based on Vickrey, Clarke and Groves (VCG) pay to the intermediate nodes a premium over their actual costs to stimulate cooperation for their forwarding services and are truthful routing protocols in which nodes can maximize their utility only when the nodes declare truthful cost for forwarding packets. But the route overhead of the existing routing protocols based on VCG is at least $O(n^2)$ *which is likely to become prohibitively large as the network size grows and leads to serious traffic congestion and packet dropping. In response to the problems, we proposed a truthful and low-overhead routing protocol (TLOR) based on VCG for ad hoc networks with selfish nodes which can achieve cost-efficient routing and truthfulness. TLOR incur the route with overhead of* $O(Ln)$*, where* L *is an upper bound on the hop number of the path and* n *is the number of nodes in network. Analysis and simulation results verify that TLOR is truthful and can significantly reduce the route overhead.*

Keywords: *truthful, low overhead, cooperation enforcement, VCG; ad hoc networks*

1. Introduction

Mobile ad hoc networks (MANET) are autonomous networks that are formed automatically via wireless links by a collection of mobile nodes without the help of a fixed infrastructure or centralized management [1]. Each node in mobile ad hoc networks can communicate with other nodes within its radio communication range. If the destination node is not within the transmission range of the source node, the source node takes help of the intermediate nodes to communicate with the destination node by relaying the messages hop by hop.

However, the mobile nodes of MANET are constrained with limited resources (*e.g.*, CPU, battery power, channel bandwidth). Some nodes in the network might not cooperate for the packet transmission in order to save their resources. Cooperation such as forwarding packets for other nodes cannot be taken for granted in ad hoc networks. Even only a few selfish nodes can significantly damage the network performance [2].

The consumption of limited resources for forwarding data packets can be regarded as the node’s cost. A naive method to stimulate cooperation is to give nodes some incentive/payment for data forwarding. Since different nodes spend different costs on forwarding same amount of data, it is desirable to reimburse the forwarding nodes according to their costs so that those nodes can get incentives. Selfish nodes are rational nodes that to maximize their payment selfish nodes may not reveal their true cost for forwarding. This necessitates the need for truthful mechanisms. A protocol is truthful if it maximizes a node's payoff only when it reveals its true cost.

The VCG mechanism (named after Vickrey [3], Clarke[4] and Grove[5]) is the only truthful routing protocol that can stimulate selfish nodes to expose their true cost for forwarding packets in ad hoc networks [6]. However, the approaches based on VCG need to collect all the path information which incurs at least a route discovery overhead of $O(n^2)$, where n is the number of nodes in ad hoc networks [7, 8]. Such high overhead will lead to severe traffic congestion and packet dropping in ad hoc networks. The maintenance and update of path information are very difficult due to the free mobility and the consistent change of the topology. Furthermore, it is a severe challenge to the nodes' limited resources since the source or the destination need store all the path information and compute the shortest and least cost path.

In this paper, a truthful and low-overhead routing protocol (TLOR) for ad hoc networks with selfish nodes is proposed. TLOR based on VCG mechanism pays to the intermediate nodes a premium over their actual costs for forwarding data packets. To maximize their payoffs, selfish nodes have no incentive to lie about their cost for forwarding packets and will reveal true cost. Every node in TLOR receives route messages from neighbors, selects and broadcast one route message with the least cost in a routing discovery which incurs the route overhead of O(n) where n is the number of nodes in the network. The overhead of TLOR is much lower than that of other approaches based on VCG. The tasks of storing and computing the path information are distributed to every node in ad hoc networks which greatly reduces the pressure of storage and computation on the source node or the destination node.

The remainder of the paper is organized as follows. Section 2 reviews the related work on cooperation enforcement in ad hoc networks. In Section 3 the system model is introduced. In Section 4 the design of TLOR is proposed. Analyses of TLOR are given in Section 5. Simulation results are illustrated to show the validation in Section 6. Finally we conclude the paper.

2. Related work

In order to circumvent the selfishness in ad hoc networks, many approaches have been proposed.

In 2000, Marti, *et al.*, [2] firstly proposed watchdog and pathrater to mitigate selfish behavior in ad hoc networks. Watchdog and pathrater are used to monitor the behavior, change the reputation of the node and select a route to transmit packets with the highest average reputation. CONFIDANT [9] distributes trustworthiness information among the participating nodes, and every node is supposed to keep a reputation list of nodes with which it has previously interacted. STRUDEL [10] is a distributed framework that uses a Bayesian trust model to dynamically select and isolate selfish nodes. SAFE [11] aimed at detecting and avoiding selfish nodes and the computation of the reputation is directly proportional to the percentage of the correctly forwarded packets. ASM [12] is a hierarchical reputation system integrated with a global reputation system and a pricing-based model for effective selfish punishment.

The schemes based on virtual currency introduce the model of services charges. The virtual currency NUGLET [13] is used as micropayment to compensate the resource consumption incurred from the transmission. The virtual currency is maintained by a trusted and tamper resistant hardware module in each node. SPRITE [14] applied the same idea without the requirement of hardware, but with a credit based system and a central clearing banking service.

Mathematical analysis based on game theory was first introduced to stimulate cooperative incentive in packet forwarding phase in [15]. Srinivasan, *et al.*, [15] focused on the energy efficiency aspect, where in their Tit for Tat (TFT)-based solution, the nodes are classified into different energy classes and the behavior of each node depends on the energy classes of participants of each connection. Felegyhazi, *et al.*, [16] defined a game model and identified the conditions under which cooperation strategies can form equilibrium in ad hoc networks. Lu, *et al.*, [17] proposed a repeated-game model of node behavior that takes account of the selfish nodes' future payoff expectation and their long-term desires for profit under which the selfish node will be deterred from cheating by subsequent punishments. Yu, *et al.*, [18, 19] modeled the interactions among nodes as packet forwarding games and proposed a game-theoretic approach to simulate cooperation through playing conditional altruism.

Mechanism based on VCG was firstly introduced to stimulate the cooperative incentive in the routing phase. Anderegg, *et al.*, [20] proposed a reactive routing protocol which achieved truthfulness (it is in the agents' best interest to reveal their true costs for forwarding data) and cost-efficiency (it guaranteed that routing was done along the most cost-efficient path) by paying to the intermediate nodes a premium over their actual costs for forwarding data packets. However, collecting path information in a route discovery incurred a route overhead of $O(n^3)$. Corsac [21] integrates VCG with cryptographic technique in routing protocol and packet forwarding protocol. The message overhead of Corsac is $O(n^3)$. Eidenbenz [22] proposed COMMIT which allows a source to set a reserve price for its data transmission to a destination. By utilizing underlying topology control protocols, COMMIT incurs an overhead of O(n2logn). LOTTO was proposed to find a least cost path for data forwarding with a lower path routing overhead of $O(n^2)$. Such high routing overhead will lead to severe traffic congestion and packet dropping in ad hoc networks. A distributed truthful routing protocol with low overhead is proposed, but it assumes that network is bi-connected and also network density is enough that each two neighbors have a common neighbor which cannot be satisfied in real network [24].

3. System model and preliminaries

We consider ad hoc networks as a directed weighted graph $G=(V,E,C,B)$, where $V=(v_1,...,v_n)$ is the set of nodes, $E \subseteq V \times V$ is the set of links between nodes, $C:E \rightarrow R$ indicates the true cost to forward a packet along the link and $B:E \rightarrow R$ indicates the declared cost responding to $C:E \rightarrow R$.

A protocol is truthful if it maximizes a node's payoff only when it reveals its true cost which means $C(E)=B(E)$. The VCG is the only truthful mechanism that can stimulate selfish nodes to expose their true cost for forwarding packets in ad hoc networks. Selfish nodes will get no more payment or get no payment if they falsely declare the cost for forwarding. The rational node has no incentive to cheat about the cost and TLOR can achieve truthful.

According to VCG, The source node needs to find the least cost path LCP as *<Source, v_1, v_2, ...v_i , ...,Destination>*from the source to the destination. And also need to find the least cost path from the source to the destination excluding node v_i which is called the substitute path of the node v_i, denoted as LCP^{-v_i} .

VCG mechanism pays to the node $v_i \in LCP$ a premium over its truthful costs c_i for forwarding packets. The premium of v_i is the difference between the cost of LCP and that of the substitute path of the node v_i, $|LCP^{-v_i}| - |LCP|$. The payment for v_i is

$$P_{v_i} = |LCP^{-v_i}| - |LCP| + c_i \qquad (1)$$

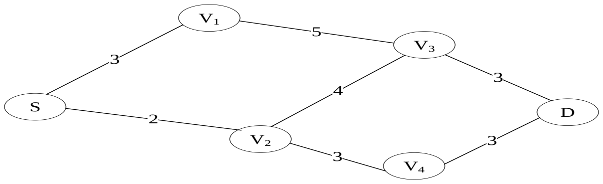

Figure 1. An Example of Payment by VCG

Figure 1 shows an example of how payments are calculated in VCG mechanism. In ad hoc networks that consist of six nodes, the edge-cost is labeled on each edge between two nodes. The least cost path is LCP=(S, v_2, v_4, D) with the cost |LCP|=2+3+4=8. The substitute path of v_2 is LCP^{-v_2} =(S, v_1, v_3, D) with the cost | LCP^{-v_2} | =3+5+3=11. The substitute path of v_4 is LCP^{-v_4} =(S, v_2, v_3, D) with the cost| LCP^{-v_4} |=2+4+3=9. Thus, according to Eq. (1), we have the payment P_{v_2} =11-8+3=6 for v_2 and the payment P_{v_4} =9-8+3=4 for v_4. The additional premium will stimulate the node to participate in the route discovery and packet forwarding.

4. Design of TLOR

VCG mechanism is adapted to stimulate the motivations of the nodes to participate in the routing phase and guarantee the truth telling about the cost. To compute the least cost path and several substitute paths from the source to the destination in the routing discovery phase, the existing methods need every node to broadcast all the path information among nodes and the source or destination has to collect, store and compute all the edge information which are redundant and incur at least the route discovery overhead of $O(n^2)$.

We present TLOR which finds a truthful, least cost path for data transmission with the route overhead of O(Ln) , where L is an upper bound on the hop number of the path and n is the number of nodes in network, and compute the payment to the intermediate nodes. When the source node S initiates the route discovery, every node will broadcast the route request (RREQ) with the least cost from the source node to it. The destination node D will compute and select LCP when it receives RREQs during route request. And D will send at most L-1 route response (RRES) that contains one intermediate node in every one. S will compute and select the substitute path of every intermediate node during route response procedure. Unlike other previous VCG mechanisms, TLOR needs not collect all the topology information and only collect the least cost path and the corresponding substituted paths. The tasks of storage and computation are distributed to every node in ad hoc networks which greatly reduces the pressure on S.

4.1. Route request

When the source S wants to communicate with the destination D and does not know any valid route to D, S will initiate the route discovery by broadcasting RREQ. A route request (RREQ) will be broadcasted. The packet header of RREQ contains several fields: $< S, D, SeqNo >$, where $SeqNo$ is the sequence of number of this request.

The neighbor node of S except D will appends the RREQ by adding its identification and the cost of forwarding a data packet, rebroadcasts the packet.

Without loss of generosity, we can assume that a node v_i receive the RREQ. The path contains the intermediate nodes v_1, v_2, …v_{i-1}. The RREQ packet that v_i receives is as: $< S, D, SeqNo, \{v_1, c_1\}, \{v_2, c_2\}, \ldots \{v_{i-1}, c_{i-1}\} >$, where c_1, c_2, …c_{i-1} is the declared cost of forwarding a data packet by nodes v_1, v_2, …v_{i-1}. The payment to nodes in the path will be paid by the source node S, so the cost of transmitting a data packet by S is not contained in RREQ.

The intermediate node v_i will check if it had received and rebroadcasted the RREQ by searching $< S, D, SeqNo >$ contained RREQ in its REQUEST TABLE. If so, the RREQ will be dropped. Otherwise v_i will put $< S, D, SeqNo >$ into its REQUEST TABLE and set a WAITING TIMER. v_i will receives several RREQ from neighbor nodes with same $< S, D, SeqNo >$. All the RREQ with the same S, D and SeqNo will be put into the same request buffer.

When the WAITING TIMER times out, v_i will compute and select RREQ with the least cost path among all the RREQ in the request buffer with the same $< S, D, SeqNo >$. It will append its identification and cost of forwarding a data packet into RREQ with least cost and broadcast the new RREQ. And it will update the finished flag of REQUEST TABLE for $< S, D, SeqNo >$. After broadcasting, the intermediate node v_i will drop received RREQ with same $< S, D, SeqNo >$ later.

Although the intermediate node v_i will receive several RREQ in one route discovery, it will broadcast RREQ with least cost path from the source to it. Every node will broadcast the RREQ only once which reduce greatly the overhead of routing request message. Algorithm 1 presents the pseudo code for route request.

Algorithm 1 route request procedure

```
v_i receive RREQ
 if RREQ with S, D, SeqNo is in the request table and WAITING TIMER
     times out
   drop RREQ
if RREQ with S, D, SeqNo is not in the request table
   put RREQ into REQUEST TABLE and set WAITING TIMER
if WAITING TIMER not times out
   put RREQ into request buffer
when WAITING TIMER times out
   compute and select RREQ with the least cost path
      append its identification and cost of forwarding a data packet into
          selected RREQ and broadcast
    update the finished flag of REQUEST TABLE
```

RREQ will be broadcasted hop by hop. Upon receiving RREQ packet, the destination D set a waiting timer and receiving RREQ like the intermediate nodes. When the timer times out, D computed the cost of the path from S to D contained in RREQ and selected the path contained in RREQ with the least cost path as the route from S to D.

In one route discovery, the number of RREQ received by the destination in TLOR is equal to the number of its neighbors. It means that the requirement for the resource of storage and computing is much less than that of other previous VCG mechanisms.

4.2. Route response

The path with the least cost from S to D has been gotten in route request. The cost of each intermediate node for forwarding a data packet has been gotten by D. D will send the route response (RRES) to S. The substitute path of the intermediate node v_i (LCP^{-v_i}) will be computed and selected in route response. The premium to the intermediate nodes will be determined by S.

After D select the path with the least cost, it will initiate and broadcast at most L-1 (L is an upper bound on the hop number of the path) route response. The i-th RRES contains not only the information of LCP but also the information of the i-th intermediate node on LCP, v_i. When the intermediate node v_j receives the i-th RRES from its neighbors, it will compute and select the RRES with least cost path and without the node v_i. Similar to the route request phase, v_j will append its identification and cost of forwarding a data packet into i-th RRES and broadcast the new RRES.

Upon receiving the i-th RRES, S will compute the cost of the paths contained in RRES and selected LCP^{v_i} among all the paths without v_i from D to S. And S will compute the payment for each node v_i on LCP according to Eq. (1).

5. Analysis

In this section, we will show that the proposed protocol is truthful and can find the least cost path with the route overhead of O(Ln).

5.1. The least cost path

Lemma 1: LCP given by TLOR in routing discovery is the least cost path.

Proof: We prove by contradiction. Assume that the selected least cost path is LCP^t=(S, v_1,…, v_n, D) , the actual least cost path is LCP=(S, u_1,…, u_n, D) and $|LCP^t| > |LCP|$.

Then we consider whether RREQ along LCP^t and LCP can reach the destination in routing discovery.

1) Suppose that RREQ along LCP^t and LCP are not rejected and both can reach the destination in route discovery.

RREQs along LCP^t and LCP will both reach the destination as shown in Figure 2. If D compute and select LCP^t as the least cost path, we can infer that $|LCP^t| \leq |LCP|$, which is contradictory to the assumption $|LCP^t| > |LCP|$.

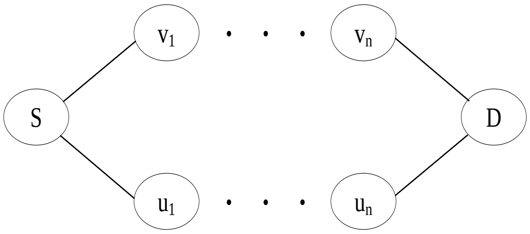

Figure 2. Two Disjoint Paths

2) Suppose that RREQ along LCP^t is rejected and cannot reach destination in routing discovery.

Suppose RREQ along LCP is rejected in the node u_i, and the selected and broadcasted path by u_i is (S, w_1,…, w_{i-1}, u_i) as shown in Figure 3. $|(S, w_1, \ldots, w_{i-1}, u_i| \leq |S, u_1, \ldots, u_{i-1}, u_i|$. So for the new path LCP" =(S, w_1,…, w_{i-1},…,

u_i, u_{i+1},…, u_n, D) , | LCP” |≤| LCP | , which is contradictory to the assumption that LCP is the actual least cost path.

From the above two cases, we conclude that LCP gotten by TLOR in route request is the least cost path.

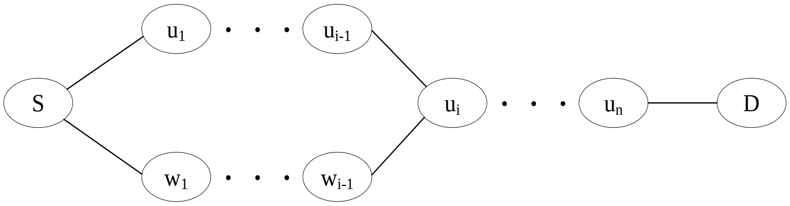

Figure 3. Two joint paths

Lemma 2: LCP^{-v_i} provided by TLOR in routing response is the substitute path of the intermediate node v_i in LCP.

Proof: We can prove by contradiction. The procedure of the proof is similar to Lemma 1.

5.2. Truthfulness

The route protocol based on VCG mechanism is the truthful routing protocol that can stimulate selfish nodes to expose their true cost for forwarding packets in ad hoc networks. TLOR based on VCG can also achieve the truthfulness. When the node falsely declares the cost, it cannot get more payment or get no payment. The rational node has no incentive to cheat about the cost and TLOR can achieve strategy-proof. Telling the truth about the cost is the dominant strategy for every rational node in TLOR.

Lemma 3: Telling the truth about the cost is the dominant strategy for every rational node in TLOR.

Proof: The similar proof can be found in [7].

5.3. Overhead

A route discovery consists of the route request stage and the route response stage. In the route request stage, RREQ is broadcast to all the nodes in ad hoc networks. Each node will receive the same RREQ several times and will rebroadcast only once in TLOR. The overhead is O(n) during route request, where n is the number of nodes in network.

In the route response stage, the destination will initiate one RRES for every intermediate node on LCP that is at most L-1, where L is an upper bound on the hop number of the path in network. Every node will broadcast once for each RRES. The overhead is O((L-1)n) during route response. The number of hops in ad hoc networks is generally limited, because of the disturbance of noise in transmission and the timing of the transmitting service. So TLOR in route discovery will result in a total of O(Ln) route overhead.

6. Simulation Results

We conducted a set of extensive simulations in NS2 to evaluate TLOR in different scenarios. A random network with 50 nodes is generated. The nodes are randomly distributed in the rectangular area of 1000 m x 1000 m. Each node may either be static or moving according to the random waypoint model. Each node starting at a random position randomly chooses a new location and moves toward the new location continuously after a pause time duration which is set to 100 seconds in the simulations. In the random network, the maximum distance between which two nodes can directly communicate with each other is set to be 250m. IEEE 802.11 DCF is adopted as the MAC layer protocol and DSR is used as the route protocol in the simulations. For each simulation, 20 constant bit rate flows are generated randomly with the packet interval time slot, 1s. When the packets are dropped, no retransmission is performed.

We compare TLOR with LOTTO [7] since both protocols stimulate nodes' incentives to forward packets and achieve the truthfulness in route discovery. The simulations were conducted in different moving rate, different number of nodes and different district respectively.

6.1. Impact of node mobility

We evaluate the impact on TLOR in the maximum rate of 4m/s, 8 m/s, 12m/s, 16m/s and 20m/s respectively during 1000s simulation. When LCP is connective, the packets will be transmitted along LCP. When the two nodes move out of the transmission range and LCP is broken, the source will initiate the route discovery for transmitting the following packets.

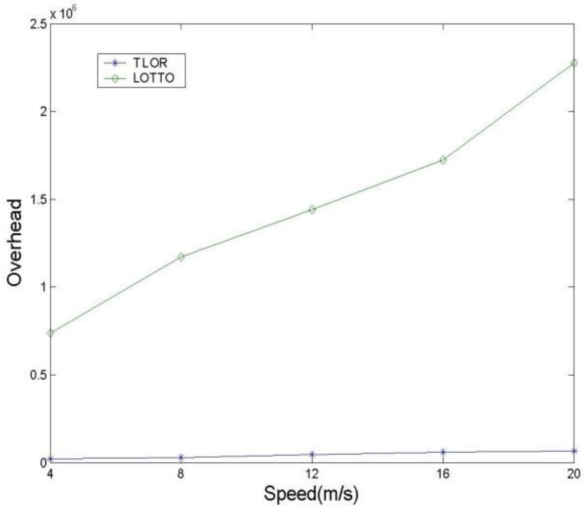

Figure 4. Overhead in Different Moving Rating

In LOTTO, each node's path information about its neighbors will be rebroadcasted by every node. For n nodes in ad hoc networks, LOTTO will incur the route overhead of $O(n^2)$ where n is the number of the node in network. TLOR will incur the route overhead of at most O(Ln) where L is an upper bound on the hop number of the path in network. Figure 4 shows the overhead in different moving rating. When the moving rate increases, the number of route broken and route requests increase and the overhead of TLOR and LOTTO increases as well. In any moving rate the overhead of TLOR is much lower than that of LOTTO. The higher overhead in LOTTO will incur the traffic congestion and packets dropping. The difference of route overhead between LOTTO and TLOR increases when the speed increases.

6.2. Impact of node density

We evaluate the impact on TLOR in different square area of 500m*500m, 600m*600m, 700m*700m, 800m*800m, 900m*900m and 1000m*1000m. The number of nodes is fixed to 50.

LOTTO will incur the route overhead of $O(n^2)$ where n is the number of the node in ad hoc network and TLOR will incur the route overhead of at most O(Ln), where L is an upper bound on the hop number of the path in network. Figure 5 shows the overhead of TLOR and LOTTO respectively in different square area. When the square area increases and the number of nodes is fixed, the transmission distance between the source and the destination increases and the hop number between them increases too. In any node density the overhead of TLOR is much lower than that of LOTTO. The higher overhead in LOTTO will incur the traffic congestion and packets dropping. The difference of route overhead between LOTTO and TLOR increases when the node density decreases.

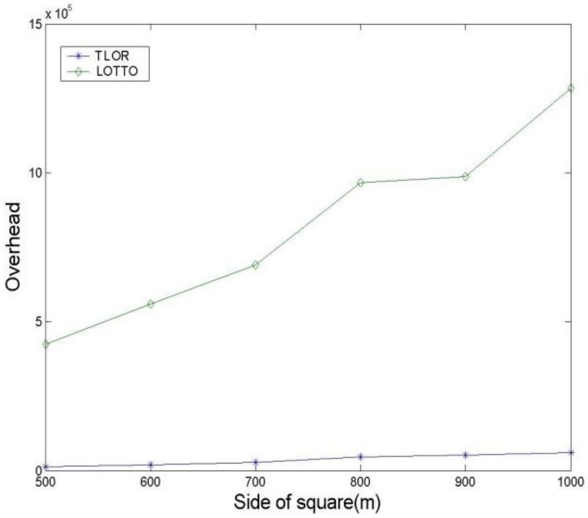

Figure 5. Overhead in Different Square with Fixed Number of Nodes

7. Conclusions

Mechanisms based on VCG are proposed to stimulate the cooperative incentives in routing phase in ad hoc networks. However the topology information in previous approaches will be collected for computing the cost-efficient path and the responding substitute path which incurs the route overhead of at least $O(n^2)$. This paper proposed TLOR which reduces the route overhead to O(Ln). TLOR distributes the mission of computing and storing the path information to every node. The source node collects the least cost path and the substitute path of the intermediate node on the least cost path. TLOR avoids the severe traffic congestion and packet dropping. We analyze and prove that TLOR achieves truthful. Simulation results show that TLOR can significantly reduce the route overhead compared with LOTTO in different scenarios.

Acknowledgments

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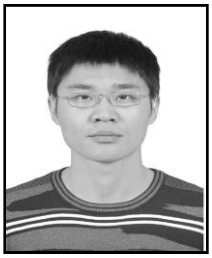

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