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B4SDC: A Blockchain System for Security Data Collection in MANETs

Gao Liu, Huidong Dong, Zheng Yan, *Senior Member, IEEE*, Xiaokang Zhou, Shohei Shimizu

Abstract—Security-related data collection is an essential part for attack detection and security measurement in Mobile Ad Hoc Networks (MANETs). A detection node (i.e., collector) should discover available routes to a collection node for data collection and collect security-related data during route discovery for determining reliable routes. However, few studies provide incentives for security-related data collection in MANETs. In this paper, we propose B4SDC, a blockchain system for security-related data collection in MANETs. Through controlling the scale of Route REQuest (RREQ) forwarding in route discovery, the collector can constrain its payment and simultaneously make each forwarder of control information (namely RREQs and Route REPlies, in short RREPs) obtain rewards as much as possible to ensure fairness. At the same time, B4SDC avoids collusion attacks with cooperative receipt reporting, and spoofing attacks by adopting a secure digital signature. Based on a novel Proof-of-Stake consensus mechanism by accumulating stakes through message forwarding, B4SDC not only provides incentives for all participating nodes, but also avoids forking and ensures high efficiency and real decentralization. We analyze B4SDC in terms of incentives and security, and evaluate its performance through simulations. The thorough analysis and experimental results show the efficacy and effectiveness of B4SDC.

Index Terms—MANETs, security-related data collection, incentive mechanism, blockchain.

1 Introduction

MANET suffers from different attacks due to self-organization [1]. In order to provide a secure and high-quality networking service, security-related data collection becomes essential for network attack detection and security measurement. Security-related data, in short security data, are the data that can be used to discover network threats and measure its security. In data collection, after receiving the request of a collector or detection node, collection nodes send it sensed security data [2]. Since there is no fixed infrastructure in MANETs, nodes cooperate to forward the request and security data. In order to ensure efficient collection, a collector should discover available routes to collection nodes through route discovery, so that the request and security data can be transmitted via these routes. However, the route discovery suffers from various attacks, e.g., wormhole and rushing attacks [1]. Existing detection mechanisms can help a collector to detect these attacks and select reliable routes [13], but the collector should analyze security data provided by forwarders of control information for making decisions, e.g., the timestamps of receiving and sending a packet, the location of forwarders. Unfortunately, few studies provide incentives for security data collection in MANETs. Forwarders might not be willing to sense and provide security data due to extra overload, selfishness, etc., so that the collector could not collect sufficient security data for detection. As a result, the accuracy of threat detection and security measurement cannot be ensured.

Current methods to provide incentives mainly make use of reputation and micropayment systems [3]. However, the present studies in this field are still facing a number of issues to be applied into security data collection in MANETs. First, these mechanisms do not consider spoofing attacks that an attacker launches for maximizing its profits due to no identity management. Second, reputation systems might not resist collusion attacks that selfish nodes raise for improving their reputation, and do not specify the type of incentive (e.g., what profit can be brought by high reputation.) Furthermore, a highly reputable node might suddenly have malicious behaviors. Third, micropayment systems allow a collector to pay to collection nodes and forwarders for their cooperation and contributions, but most of them require a trusted third party to manage debiting and crediting accounts. This kind of design is obviously infeasible for MANETs since such a trusted third party is hard to be deployed. Fourth, in some micropayment systems for route discovery, a source node pays control information forwarders, but cannot constrain its payment, which is caused by an uncontrolled RREQ forwarding scale [3]. In addition, some existing systems allow the source node to only pay the forwarders in discovered routes, which is unfair to the nodes that have participated in route discovery but are not in the routes [5].

In order to solve the above issues, a distributed incentive system for security data collection is highly expected, which should resist spoofing, collusion and excessive forwarding, and feature fairness, and should not rely on a trusted third party. We found that blockchain [6], [7] is a candidate technology to help achieving the above goals due to its advantages, e.g., transparency, immutability, and

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self-organization. In a blockchain system, a miner collects transactions, generates a block and provides it to other miners with a proof of work (e.g., the proof of computing and storage) to gain the majority of acceptance, which is called consensus. In general, the incentive for miners is provided in a form of digital tokens, e.g., bitcoin [8]. At the same time, the transaction can help incenting security data collection.

However, the blockchain itself is still facing many technical challenges, namely forking, low efficiency and a trend of centralization. Based on the current literature review [9], [10], consensus mechanisms mainly include Proof of Work (PoW), Byzantine Faulty Tolerant (BFT), Proof of Sake (PoS), Proof of Useful Work (PoUW) and Trees and Directed Acyclic Graphs (DAGs). PoW and PoUW take the risk of temporary forking due to network latency. PoW wastes a lot of resources since it is a meaningless task. Its transaction confirmation time is long, thus negatively impacting its throughput. PoW and PoUW take the risk of centralization due to the outsourceability of tasks. Because PoS consumes almost no resources, a miner might create two blocks to cause forking. Many BFT based consensus mechanisms focus on scalability, but they provide no incentives for miners. Trees and DAGs can replace the chain structure of blockchain for ensuring a high throughput and avoiding double spending, but some trees and DAGs based consensus mechanisms [11], [12] also employ PoW, thus suffering from the same problems of PoW, namely forking, low efficiency and the risk of centralization.

In this paper, we propose B4SDC, a blockchain system that provides incentives for security data collection in a distributed way in MANETs. Through controlling the scale of RREQ forwarding in route discovery, a collector can constrain its payment and simultaneously make each forwarder of control information obtain rewards as much as possible to ensure fairness. At the same time, B4SDC avoids collusion attacks with cooperative receipt reporting, and spoofing attacks by adopting a secure digital signature. Based on a novel Proof-of-Stake consensus mechanism by accumulating stakes through message forwarding, B4SDC not only provides incentives for all participating nodes, but also avoids forking and ensures high efficiency and real decentralization at the same time. With the above ways, B4SDC successfully avoids collusion and spoofing attacks, allows collectors to control their maximum payments, and ensures fairness for collection participants as much as possible. It also solves current blockchain systems' main problems, namely forking, low efficiency and centralization. Specifically, the contributions of this paper can be summarized as follows.

(1) B4SDC provides incentives for collection participants. It encourages nodes to forward control information that includes security data in route discovery. After routes are discovered, the nodes in selected routes are incented to forward the request of a collector and the security data of collection nodes.

(2) B4SDC removes the need for a trusted third party in many micropayment systems by adopting blockchain. It adopts a secure digital signature for signing sent messages, thus avoiding spoofing attacks. At the same time, B4SDC allows collection participants to cooperatively report their received receipts to miners for gaining rewards, thus resisting collusion attacks and ensuring fairness for all collection participants as much as possible. In addition, a collector can constrain the scale of RREQ forwarding in route discovery, thus it can balance its budget.

(3) B4SDC provides a novel consensus mechanism. Block creation is proposed to ensure the distribution and efficiency of blockchain by avoiding the simultaneous generation of many valid blocks and reducing communication burdens. Single block winner selection is performed to make B4SDC free from forking when multiple valid blocks are created at the same time.

The rest of this paper is organized as follows. Section 2 briefly overviews background and related work. Section 3 and Section 4 present problem statements and the design of B4SDC, respectively, followed by analysis and performance evaluation in Section 5. Section 6 concludes the paper.

2 Background and Related Work

2.1 An Overview of Route Discovery

Mainstream routing protocols adopt route discovery [13] for data transmission, such as DSR and AODV protocols [29], [30]. In the route discovery, a source node floods a RREQ including its and destination node's addresses. When a node receives the RREQ and it is not the destination node and has no routes to the destination node, it adds its address into the RREQ and then forwards this RREQ. If the destination node or an intermediate node having routes to the destination node receives the RREQ, it creates a RREP including a whole route path and sends the RREP to the source node in the reverse of the path.

2.2 Incentive Systems

Current incentive systems mainly include reputation and micropayment systems. Most of them rarely take spoofing attacks [32], [33] into consideration, since no identity management is adopted for nodes.

Reputation Systems: Nodes monitor traffic from their neighbors for determining whether these neighbors forward packets. If a node finds its neighbor does not forward packets, it considers the neighbor uncooperative and broadcasts an uncooperative reputation into the network [3], [4]. However, reputation systems do not specify the type of incentive, especially what profits a node can obtain with a high reputation. In addition, selfish nodes could collude to improve their reputation, and a highly reputable node could suddenly have malicious behaviors [23].

Micropayment Systems: Many micropayment systems allow nodes to forward packets for obtaining receipts. These nodes can send the obtained receipts to a third party for crediting and debiting accounts [3], [34]. However, it is not feasible to deploy this third party in MANETs, since MANETs have no fixed infrastructure and thus have no any management center. In addition, the party might be hacked or compromised. In some micropayment systems [3] for route discovery, a source node encourages the cooperation of control information forwarders for discovering routes to destination nodes, thus it pays these forwarders for incenting them. However, it cannot control the scale of RREQ

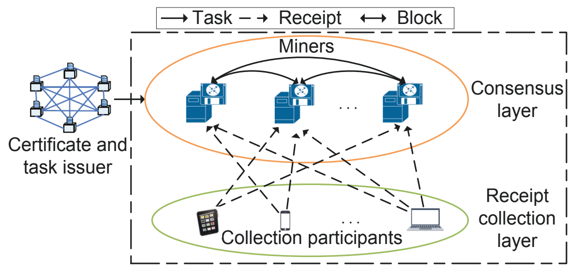


Fig. 1. System model

forwarding, which suggests it cannot limit the amount of payment. In some systems [5], when a route is discovered, the source node only pays control information forwarders in the route, but other nodes that have participated in route discovery but are not located in the route cannot obtain rewards. Thus, the fairness to all participants in route discovery is not guaranteed.

2.3 Blockchain Technology

PoW Based Consensus Mechanisms: Bitcoin employs PoW to make each node agree on some transactions. Due to temporary forking caused by network latency, users wait at least six blocks (i.e., expected 1 hour) for confirming a transaction according to the longest chain principle. It also wastes many resources for solving a puzzle. At the same time, bitcoin also faces the risk of centralization due to the outsourceability of mining tasks. Many consensus mechanisms that adopt PoW have the limitations of bitcoin, such as Permacoin [22] that repurposes the storage of bitcoin.

PoUW Based Consensus Mechanisms: PoUW is usually a non-interactive proof of meaningful computation and storage that can convince any miners. Many PoUW based consensus mechanisms only construct the proof, but fail to show how to achieve the consistency of blockchain. Therefore, they suffer from temporary forking due to network latency [22]. In addition, many PoUW consensus mechanisms allow to split a task into subtasks, which might result in the outsourceability of tasks [26]. As a consequence, they take the risk of centralization.

BFT Based Consensus Mechanisms: BFT agreement protocols allow a set of servers to replicate a service. In much work [24] on BFT, its performance and scalability are emphasized as challenges. However, the set of servers should be chosen and determined in advance, and these servers might become attack targets. If everyone has the right to be a server, Sybil attacks [25] are a potential risk. BFT based consensus mechanisms inherit the limitations of BFT. In addition, BFT based consensus mechanisms face the challenge of lack of incentives for motivating determined servers to be online and perform honestly [9].

PoS Based Consensus Mechanisms: In PoS, each user has its weight, which represents the probability that it is chosen as a leader to create the next block of blockchain. Because creating a block costs almost no resources, a malicious miner might create two blocks, thus causing forking. Meanwhile, adversaries can divide their credits among some users that might be chosen as leaders. Therefore, although a malicious leader is discovered, the penalty that the adversaries take is low. In some PoS based consensus mechanisms, a private key is required for signing the correct branch of blockchain in order to mitigate forking, but occasional forks have appeared [27]. PoS based consensus mechanisms also have the risk of centralization due to the outsourceability of tasks [28].

Trees and DAGs Based Consensus Mechanisms: In order to increase the throughput of bitcoin and solve conflicts (i.e., double spending), some consensus mechanisms [11], [12] were proposed that adopt a tree or DAG structure as the blockchain's underlying ledger instead of chains. However, these consensus mechanisms rely on PoW, thus having its limitations.

3 Problem Statements

3.1 System Model

As shown in Fig. 1, B4SDC involves three types of entities: certificate and task issuer, collection participant and miner.

The certificate and task issuer is responsible for issuing certificates and tasks, which can be a blockchain system for key management, PKI or identity management to ensure decentralization [14], [15], [16]. It does its work honestly for rewards since the published certificates and tasks should obtain the consensus of B4SDC blockchain.

In the receipt collection layer, collection participants involve collectors, forwarders and collection nodes. The collectors discover routes to collection nodes with route discovery, and select some reliable routes to publish requests and receive security data from collection nodes, since the route discovery allows the collectors to collect security data from each forwarder for detecting potential attacks and obtaining reliable routes. The forwarders help forwarding received messages including security data. Each collection node and forwarder can use received messages as receipts and share these receipts to miners. In this layer, each node is not fully trusted since it might forge receipts for rewards.

In the consensus layer, after collecting sufficient receipts and receiving a task, the miners create and publish blocks for consensus. The majority of miners accept one block as the next block of blockchain. It is hard to ensure each miner is trusted since the miner might be hacked or compromised.

3.2 Assumption

Suppose an adversary can control a small number of miners, but its control is limited. It is impossible that all the miners are attacked and functionally down. The remaining miners behave independently and are rational to maximize their gains when investing resources into mining. The time of all the miners is supposed to be synchronized, which can be achieved with the help of public GPS signals [17] or a public time blockchain [18]. Because time synchronization can be achieved in the level of nanoseconds. Although this assumption restricts B4SDC, it is justified compared to secure incentive provisions for security data collection. In addition, miners cannot forge timestamps, since miners in the network are monitored by their neighbors and nodes can employ some lightweight external methods (e.g., wormhole attack detection [17]) to detect this kind of misbehavior.

Each node holds its own unique private/public keys in Elliptic Eurve Cryptosystem (ECC) and uses the private key

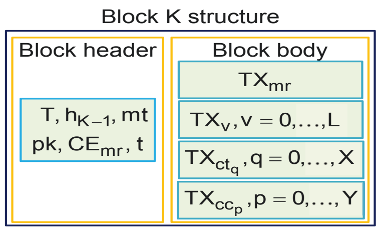


Fig. 2. Block structure

TABLE 1
Notations

Symbols	Descriptions
CE_{mr}	The certificate of block creator issued by the certificate and task issuer.
TX_{mr}	The transaction that a miner uses to consume the age of some tokens for competing for the creator of the next block.
TX_v	The receipt of node N_v collected when it participates in route discovery and security data item collection.
TX_{ct}	The fresh deposit message for route discovery.
TX_{cc}	The fresh deposit message for security data item collection.
sk_i	The private key of node N_i.
pk_i	The public key of node N_i.
CE_i	N_i's certificate issued by the certificate and task issuer.
$sig_{sk}(\cdot)$	The signature with the private key sk.
NL_i	The public key list of N_i's neighbors.
k_h	The number of neighbors that each node at hop h selects as the receivers of RREQ.
PA_{d_j}	A reliable route from the source node N_0 to the destination node N_{d_j}.
n_b	The number of the latest referenced blocks of the blockchain.
n_{bthr}	The threshold of the number of blocks that a miner creates in the latest n_b blocks of the blockchian.
n_{thr}	The threshold of the number of receipts that a miner should insert into its created block.

for signing messages. This can be achieved by allowing each node to register at the certificate and task issuer. Otherwise, potential attacks might disturb security data and receipt provision and detection mechanisms. Suppose that nodes do not attempt to share their private keys to other nodes, since such sharing suggests their tokens are shared.

4 B4SDC DESIGN

In this section, we describe the design of B4SDC, including the block structure and receipt collection. A novel consensus mechanism is introduced for the block creation and block winner selection with an incentive mechanism. We discuss how to balance the budget of collector for route discovery and security data item collection finally. TABLE 1 summarizes the notations used in this paper.

4.1 Block Structure

The block structure of B4SDC is shown in Fig. 2. In the block K's header, T is a task that the certificate and task issuer publishes. h_{K-1} is the hash value of previous block header (i.e., the header of block $K-1$). pk is the ECC public key of creator of block K, and CE_{mr} is the certificate corresponding to pk that is issued by the certificate and task issuer. t represents the time when the block K is created. In the block K's body, TX_{mr} is a transaction that a miner uses to consume the age of some tokens for competing for the block creator. TX_v, $v=0,\ldots,L$ is the receipt of node N_v collected when it participates in route discovery and security data item collection. TX_{ct_q}, $q=0,\ldots,X$ and TX_{cc_p}, $p=0,\ldots,Y$ are fresh deposit messages for route discovery and security data item collection, respectively. In addition, mt in the header represents the root of Merkle tree constructed with TX_{mr}, TX_v, $v=0,\ldots,L$, TX_{ct_q}, $q=0,\ldots,X$ and TX_{cc_p}, $p=0,\ldots,Y$.

4.2 Receipt Collection

Before the consensus, receipt collection should be performed. It consists of *Node Registration*, *Receipt Generation*, and *Receipt Sharing*.

1) Node Registration

Each node provides its public key to and obtain its certificate from the certificate and task issuer.

1. Each node N_i generates a pair of private/public keys (sk_i, pk_i) based on ECC, and uses pk_i to register at the certificate and task issuer N_{TI}.

2. N_{TI} equipped with a pair of public/private keys (sk_{TI}, pk_{TI}) generates the certificate $CE_i = \{pk_{TI}, sig_{sk_{TI}}(pk_i)\}$ with Elliptic Curve Digital Signature Algorithm (ECDSA) [35] and issues it to N_i.

2) Receipt Generation

A collector discovers routes to some collection node with route discovery, which involves security data collection for detection since potential attacks might exist in the route discovery. The collector adopts reliable discovered routes to send a request and collect security data from collection nodes. Each of collection participants (except the collector) considers its received messages as receipts.

Route Discovery

A collector discovers routes to a collection node by broadcasting a RREQ and receiving RREPs. Each participant of route discovery (except the collector) considers its received control messages as receipts.

1. Through neighbor discovery, each node N_i records the public key list NL_i of its neighbors, and periodically publishes $SNL_i = \{CE_i, pk_i, NL_i, t_i, sig_{sk_i}(NL_i, t_i)\}$.

2. Based on collection strategies, the collector N_0 attempts to discover routes to the selected collection node N_d for security data collection. In order to avoid the collector's unreliable payment (e.g., double spending), N_0 should send a blockchain (i.e., B4SDC blockchain, not N_{TI}) the deposit message $TX_{ct} = \{CE_0, pk_0, UID, NU_0\}$ to deposit NU_0 tokens for the unique identity UID of RREQ in advance. If N_0 makes sure that its message TX_{ct} is inserted into blockchain, it can use NU_0 tokens as the budget for route discovery. Then it determines appropriate Time To Live (TTL) and $k = \{k_h : h = 0, \ldots, TTL-1\}$ due to its budget, which is discussed in Section 4.4 later on. k_h is the number of neighbors that each node at hop h selects as the receivers of RREQ.

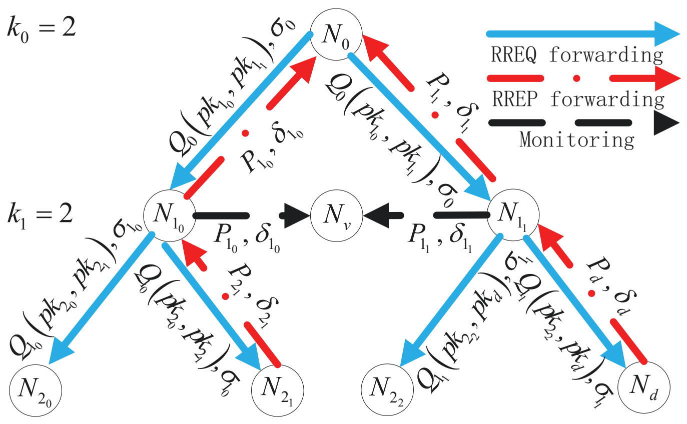


Fig. 3. An example of route discovery

3. N_0 randomly selects its k_0 neighbors $N_{0_1}, \ldots, N_{0_{k_0}}$ as the receivers of its RREQ, whose public keys are $pk_{0_1}, \ldots, pk_{0_{k_0}}$ respectively. Then it computes $BI = \{CE_0$, pk_0, UID, pk_d, TTL, k, $sig_{sk_0}(UID, pk_0, pk_d, TTL, k)\}$, and obtains its RREQ $Q_0 = \{BI$, $h = 0$, RL, pk_{0_1}, $\ldots$, $pk_{0_{k_0}}$, SD, $t_0^{'}\}$ with the signature $\sigma_0 = sig_{sk_0}(Q_0)$, where pk_d is the public key of destination node N_d, RL the route list, SD the security data list including N_0's security data, and $t_0^{'}$ the time of sending Q_0. If $|NL_0| < k_0$, N_0 selects its all neighbors as RREQ receivers.

4. After receiving $Q_i = \{BI, CE_i, pk_i, h, RL, pk_{i_1}, \ldots, pk_{i_{k_i}}, SD, t_i^{'}\}$ and $\sigma_i = sig_{sk_i}(Q_i)$ from N_i for the first time, N_{i+1} can check that the collector does not make an unreliable payment by accessing the blockchain, its public key pk_{i+1} belongs to $\{pk_{i_1}, \ldots, pk_{i_{k_i}}\}$ and $h < TTL$, and then verifies CE_0 in BI, CE_i and σ_i. If all verifications hold, N_{i+1} saves Q_i and σ_i as receipts, then increases h by 1, inserts its public key into RL, selects k_{i+1} neighbors whose public keys are $pk_{i+1_1}, \ldots,$ $pk_{i+1_{k_{i+1}}}$, adds its sensed security data into SD, and generates $Q_{i+1} = \{BI, CE_{i+1}, pk_{i+1}, h, RL, pk_{i+1_1}, \ldots,$ $pk_{i+1_{k_{i+1}}}, SD, t_{i+1}^{'}\}$ and $\sigma_{i+1} = sig_{sk_{i+1}}(Q_{i+1})$. Finally, it broadcasts Q_{i+1} and σ_{i+1}.

In order to prevent N_i from selecting few receivers by deliberately inserting less than k_i public keys in the RREQ for saving resources, each node N_v can serve as an observer for monitoring the behaviors of its neighbor. If N_v finds that the neighbor list NL_i of its neighbor N_i satisfies $|NL_i| \geq k_i$ and N_i forwards Q_i to less than k_i neighbors, it can send the blockchain the report $TX_v = \{CE_v$, pk_v, $RP_v = (SNL_i$, $Q_i, \sigma_i)$, $SIG_v = sig_{sk_v}(RP_v)\}$, thus obtaining rewards by deducting N_i's rewards. Therefore, nodes are incented to provide security data and forward the RREQ.

5. When the destination node N_d or the intermediate node N_w having a route to the destination node receives the RREQ with a signature, it can check that the collector makes a reliable payment by accessing the blockchain, its public key belongs to the public key list in the RREQ and $h < TTL$. If all verifications hold, N_d or N_w saves the received RREQ and corresponding signature as receipts. Then N_d inserts its sensed security data into SD, and generates the RREP $P_d = \{BI, CE_d, pk_d, RL, SD, sig_{sk_d}(BI, RL)\}$ with the signature $\delta_d = sig_{sk_d}(P_d)$. N_w adds its sensed security data into SD, and creates the RREP $P_w = \{BI, CE_w, pk_w, RL, SD, sig_{sk_w}(BI, RL)\}$ with $\delta_w = sig_{sk_w}(P_w)$. Note that RREP's RL is a whole route path from N_0 to N_d, and SD has all security data recorded in the received RREQ. Finally, N_d or N_w forwards its RREP with the signature in the reverse direction of route from N_0 to N_d.

6. When N_i en route (derived from RL) receives a RREP and a signature from N_{i+1}, namely $P_{i+1} = \{BI, CE_w, CE_{i+1}, pk_w, pk_{i+1}, RL, SD, sig_{sk_w}(BI, RL)\}$ or $P_{i+1} = \{BI, CE_d, CE_{i+1}, pk_d, pk_{i+1}, RL, SD, sig_{sk_d}(BI, RL)\}$ with $\delta_{i+1} = sig_{sk_{i+1}}(P_{i+1})$, it verifies the involved signatures. If all verifications hold, N_i saves P_{i+1} and δ_{i+1} as receipts, then inserts its sensed security data into SD, and generates and sends P_i and δ_i to N_{i-1} en route. When N_0 receives valid P_1 and δ_1, the common neighbor N_v of N_0 and N_1 can collect P_1 and δ_1, and share $TX_v = \{CE_v, pk_v, RP_v = (SNL_0, SNL_1, P_1, \delta_1)$, $SIG_v = sig_{sk_v}(RP_v)\}$ to the blockchain for rewards.

An example of route discovery is shown in Fig. 3. The collector N_0 sets $TTL = 2$, $k_0 = k_1 = 2$. N_0 selects two receivers N_{1_0} and N_{1_1}, and broadcasts the RREQ $Q_0(pk_{1_0}, pk_{1_1})$ with its signature σ_0, where pk_{1_0} and pk_{1_1} represent the public key of N_{1_0} and N_{1_1}, respectively. N_{1_0} and N_{1_1} verify $\{Q_0(pk_{1_0}, pk_{1_1}), \sigma_0\}$. If all verifications hold, N_{1_0} and N_{1_1} broadcast $\{Q_{1_0}(pk_{2_0}, pk_{2_1})$, $\sigma_{1_0}\}$ and $\{Q_{1_1}(pk_{2_2}, pk_d)$, $\sigma_{1_1}\}$, respectively. At hop $h = 2$, N_d and N_{2_1} that has a route to N_d receive RREQs, and they verify their received RREQs. If all verifications hold, N_d generates the RREP with its signature, $\{P_d, \delta_d\}$, and N_{2_1} creates $\{P_{2_1}, \delta_{2_1}\}$. N_d and N_{2_1} send their generated RREPs and corresponding signatures to N_0 through the reversed path. N_0 discovers two routes, $N_0 \rightarrow N_{1_0} \rightarrow N_{2_1} \rightarrow \ldots \rightarrow N_d$ and $N_0 \rightarrow N_{1_1} \rightarrow N_d$. Each node (except N_0) stores its received messages as receipts, and shares them to the blockchain for rewards.

Security Data Item Collection

A collector sends a request to collection nodes, and then receives security data items from these nodes. Each participant of security data item collection (except the collector) regards its received messages as receipts.

1. When the collector N_0 has discovered routes to collection nodes, it can determine the reliable route PA_{d_j} to each collection node N_{d_j} for security data collection (e.g., by adopting wormhole attack detection). These collection nodes and corresponding routes are denoted as $\{N_{d_0}, \ldots, N_{d_c}\}$ and $PA = \{PA_{d_0}, \ldots, PA_{d_c}\}$ respectively. The collector also deposits some tokens in advance in order to avoid unreliable payments. In detail, it sends the blockchain the deposit message $TX_{cc} = \{CE_0, pk_0, DI, NU_1\}$ to deposit NU_1 tokens, where DI is the unique identity of request. If the collector knows TX_{cc} has been added into the blockchain, it can start to generate and broadcast the request with the unique identity DI.

2. N_0 generates and broadcasts the request $DT_0 = \{CE_0, pk_0, DI, PA, sig_{sk_0}(DI, PA)\}$ with the signature $\varphi_0 = sig_{sk_0}(DT_0)$.

3. After receiving $DT_i = \{DT_0, CE_i, pk_i\}$ and $\varphi_i = sig_{sk_i}(DT_i)$ from the neighbor N_i, the node N_{i+1} can check that the collector makes a reliable payment by accessing the blockchain, uses DT_i's PA to check it is

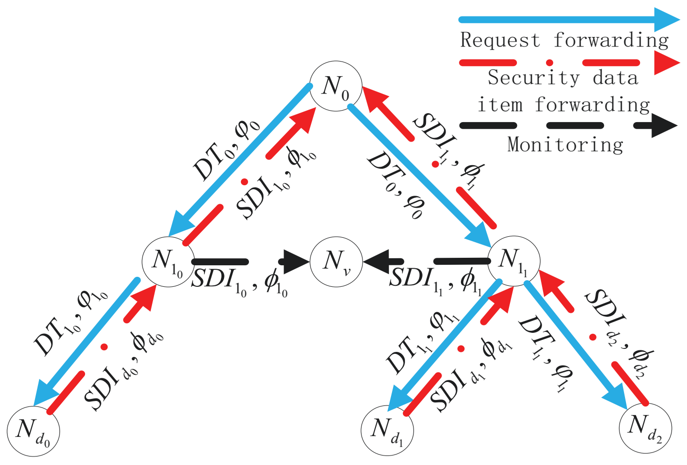


Fig. 4. An example of security data item collection

a legitimate receiver, and verifies involved signatures. If all verifications hold, N_{i+1} considers DT_i and φ_i as receipts, then creates and broadcasts the new request $DT_{i+1} = \{DT_0, CE_{i+1}, pk_{i+1}\}$ with the signature $\varphi_{i+1} = sig_{sk_{i+1}}(DT_{i+1})$.

4. When the destination node N_{d_j} receives the request from N_0, it checks the payment of collector is reliable by accessing blockchain, then checks it is a legitimate receiver and verifies the validity of request through involved signatures. If all verifications hold, N_{d_j} considers the received request and signature as receipts, then creates the security data item $SDI_{d_j} = \{DT_0, CE_{d_j}, pk_{d_j}, SD_{d_j}, sig_{sk_{d_j}}(DT_0, SD_{d_j})\}$ with the signature $\phi_{d_j} = sig_{sk_{d_j}}(SDI_{d_j})$, and then forwards SDI_{d_j} and ϕ_{d_j} to N_0 in the reverse of route from N_0 to N_{d_j}.

5. If N_i receives $SDI_{i+1} = \{SDI_{d_j}, CE_{i+1}, pk_{i+1}\}$ and $\phi_{i+1} = sig_{sk_{i+1}}(SDI_{i+1})$ from N_{i+1}, it verifies the validity of SDI_{i+1} and ϕ_{i+1}. If all verifications hold, N_i saves SDI_{i+1} and ϕ_{i+1} as receipts, then generates and forwards $SDI_i = \{SDI_{d_j}, CE_i, pk_i\}$ with $\phi_i = sig_{sk_i}(SDI_i)$ in the reverse of route from N_0 to N_{d_j}. As a result, N_0 can obtain the security data SD_{d_j} from N_{d_j}. When N_0 receives valid SDI_1 and ϕ_1, the common neighbor N_v of N_0 and N_1 can collect SDI_1 and ϕ_1, and send $TX_v = \{CE_v, pk_v, RP_v = (SNL_0, SNL_1, SDI_1, \phi_1), SIG_v = sig_{sk_v}(RP_v)\}$ to the blockchain for rewards.

We show an example of security data item collection in Fig. 4. N_0 has an idea about routes to N_{d_0}, N_{d_1} and N_{d_2} in advance. After receiving a request that includes the routes and verifying its validity, N_{d_0}, N_{d_1} and N_{d_2} generate security data items with signatures, and send them to N_0 via the reversed path of the route. Each node (except N_0) stores received messages as receipts, and send them to the blockchain for rewards.

Receipt Sharing

1. Each node N_v broadcasts $TX_v = \{CE_v, pk_v, RP_v, SIG_v\}$, where $RP_v = \{Q_{i_v}, \sigma_{i_v}\}$, $\{P_{i_v}, \delta_{i_v}\}$, $\{DT_{i_v}, \varphi_{i_v}\}$, $\{SDI_{i_v}, \phi_{i_v}\}$ or $\{SNL_i, Q_i, \sigma_i\}$, and $SIG_v = sig_{sk_v}(RP_v)$ is N_v's signature on RP_v.

2. Miners collect and verify TX_{ct} with new UID, TX_{cc} with new DI and TX_v, since a miner will obtain rewards in the case that it successfully adds these messages into the blockchain.

```
Input: $T = \{pk_{TI}, TID, n_b, n_{bthr}, n_{thr}, TAG, \theta, sig_{sk_{TI}}$
       $(TID, n_b, n_{bthr}, n_{thr}, TAG, \theta)\}$, the hash value $h_{K-1}$ of the
       header of block $K-1$, $TX_v, v = 0, \ldots, L$, $TX_{ct_q}, q = 0, \ldots,$
       $X$, $TX_{cc_p}, p = 0, \ldots, Y$, the ECC public key and corresponding
       certificate of a miner (i.e., $pk$ and $CE_{mr}$), the timestamp $t$
Output: block $K$
if the miner has created $n_{pk} (n_{pk} < n_{bthr} < n_b)$ blocks within the latest $n_b$
  blocks of blockchain then
    Generate a transaction $TX_{mr} = \{pk, AM\}$;
    Obtain $mt$, i.e., the root of Merkle tree generated with
      $TX_v, v = 0, \ldots, L$, $TX_{ct_q}, q = 0, \ldots, X$ and $TX_{cc_p}$,
      $p = 0, \ldots, Y$, where $L \geq n_{thr}$ ;
    Compute the hash value
      $H_{pk} = h(TID \| h_{K-1} \| mt \| pk \| CE_{mr} \| t)$;
    if $H_{pk} \leq TAG * w(AM)$ then
        Insert $T, h_{K-1}, TX_{mr}, TX_v, v = 0, \cdots, L, TX_{ct_q}, q = 0,$
          $\ldots, X, TX_{cc_p}, p = 0, \ldots, Y, mt, pk, CE_{mr}$ and $t$ into
          block $K$;
    end
end
return block $K$;
```

Algorithm 1: Creation of block K

4.3 Consensus Mechanism

We propose a novel consensus mechanism for B4SDC, which aims to solve three main technical challenges of blockchain, i.e., forking, low efficiency, and centralization. Based on the last block of blockchain, miners in different locations compete to create the next block, and only one of published valid blocks is accepted as the next block. The consensus mechanism consists of block creation, block winner selection and an incentive mechanism.

Block Creation

N_{TI} publishes the task $T = \{pk_{TI}, TID, n_b, n_{bthr}, n_{thr}, TAG, \theta, sig_{sk_{TI}} (TID, n_b, n_{bthr}, n_{thr}, TAG, \theta)\}$ periodically, which triggers the block creation. TID is the unique identity of T. n_b is the number of the latest referenced blocks of the blockchain. n_{bthr} represents the threshold of the number of blocks that a miner creates in the latest n_b blocks of blockchain. n_b and n_{bthr} prevent a powerful miner from generating the majority of blocks of blockchain for controlling the blockchain, thus ensuring the decentralization. n_{thr} is the threshold of the number of receipts that a miner should insert into its created block, which ensures sufficient receipts can be inserted into the blockchain. TAG is a difficulty value, which is set to avoid the simultaneous creation of many valid blocks and thus helps reducing communication burdens. θ represents the time window that a miner waits for more valid blocks after receiving the first valid block.

Algorithm 1 shows the creation of block K. TX_{mr} means that the miner uses the age of AM tokens for making it become the creator of the next block. We denote the age of one token as the blockchain length from the block involving this token to the block K, and the miner uses tokens whose ages are the biggest. If TX_v is inserted into blockchain, this suggests that a collector gives rewards to others and thus the age of related tokens goes to 0. $w(AM)$ represents the weight of age of AM tokens for adjusting the difficulty of the miner to create a valid block. The bigger the age of used AM tokens is, the easier the miner generates a valid block, since it is applied to control the difficulty of block generation. If a miner generates a valid block successfully

```
Input: $B_{ca\_0}$, $B_{ca\_1}$
Output: block winner
1  if $t_{ca\_0} \neq t_{ca\_1}$ then
2      Set the block whose timestamp is earlier as the winner;
3  end
4  else if $t_{ca\_0} = t_{ca\_1}$ then
5      if $n_{pk_{ca\_0}} \neq n_{pk_{ca\_1}}$ then
6          Set the block whose creator has created the fewer blocks within
             the latest $n_b$ blocks of blockchain as the winner;
7      end
8      else if $n_{pk_{ca\_0}} = n_{pk_{ca\_1}}$ then
9          if $L_{ca\_0} \neq L_{ca\_1}$ then
10             Set the block that includes more receipts as the winner;
11         end
12         else if $L_{ca\_0} = L_{ca\_1}$ then
13             Set the block whose related hash value is smaller as the
                 winner;
14         end
15     end
16 end
17 return block winner;
```

Algorithm 2: Block Winner Selection

and has not received valid blocks from others, it publishes its created block. When another miner receives this block, it can verify the validity of block by running **Algorithm 1**.

Block Winner Selection

Multiple valid blocks might be created at the same time. We design how to choose one of them as the block winner (i.e., the next block).

Aiming to summarize selection rules, **Algorithm 2** shows determining the winner from two valid block candidates B_{ca_0} and B_{ca_1}. They have two timestamps t_{ca_0} and t_{ca_1}, and L_{ca_0} and L_{ca_1} receipts, respectively. In addition, both blocks' creators have created $n_{pk_{ca\_0}}$ and $n_{pk_{ca\_1}}$ blocks within the latest n_b blocks of blockchain. If $t_{ca\_0} \neq t_{ca\_1}$, the block whose timestamp is earlier is considered as the winner for ensuring the efficiency of block creation. When $t_{ca\_0} = t_{ca\_1}$ and $n_{pk_{ca\_0}} \neq n_{pk_{ca\_1}}$, the block whose creator has generated fewer blocks within the latest n_b blocks of blockchain is regarded as the winner for preventing a miner from controlling the blockchain by generating the majority of blocks of blockchain. If $t_{ca\_0} = t_{ca\_1}$, $n_{pk_{ca\_0}} = n_{pk_{ca\_1}}$ and $L_{ca\_0} \neq L_{ca\_1}$, the block including more receipts is the winner. When $t_{ca\_0} = t_{ca\_1}$, $n_{pk_{ca\_0}} = n_{pk_{ca\_1}}$ and $L_{ca\_0} = L_{ca\_1}$, the block whose relative hash value H_{pk} is smaller is regarded as the winner.

The valid blocks received by each miner might be different due to network latency. Thus, we show how to mitigate the inconsistency of block reception in order to avoid forking. If a miner receives the first valid block, it stops mining and sets the time window θ for receiving valid blocks from other miners. When a miner succeeds in generating a valid block but has not received valid blocks from other miners, it publishes its created block, waits θ for other valid blocks, and considers its block as the first received valid block. Because creating a valid block successfully before receiving other valid blocks can be considered as receiving the block ahead of the other blocks. θ can be adjusted and published by N_{TI} due to network variations. The miner refuses to receive future blocks once θ expires. Finally, the miner performs block winner selection on all received valid blocks for determining the winner.

Incentive Mechanism

B4SDC should not only provide incentives for security data collection in route discovery and security data item collection, but also encourage the certificate and task issuer to periodically publish a task and miners to insert receipts and deposit messages into the blockchain.

In order to resist the collusion attacks of collector and intermediate nodes (i.e., intermediate nodes do not report their receipts deliberately,) N_v's public key and TX_v's Q_{i_v} recorded in blockchain can be used to construct a virtual tree [3]. Except the tree root, each non-leaf and leaf node obtains α and β ($\alpha > \beta$) tokens from pk_0, respectively. As for each isolated node outside of the tree, the public address pa gets $\alpha - \beta$ tokens, where pa can be recorded in the genesis block. P_{i_v}, DT_{i_v} and SDI_{i_v} can help constructing continuous virtual route paths originating from the first forwarding node in real routes. In the path, each node obtains α tokens from pk_0, but the last one only obtains β tokens. Except all the nodes in the path, if there are l remaining nodes in the real route that have reported involved receipts, pa obtains $l * (\alpha - \beta)$ tokens from pk_0 in order to avoid the collusion of intermediate nodes and collector [3]. In Fig. 3, if all the participants share their receipts and these receipts are inserted into the blockchain, a miner can construct a virtual tree with blue solid arrows based on RREQ forwarding, and two continuous virtual route paths based on RREP forwarding, namely $N_{2_1} \rightarrow N_{1_0} \rightarrow N_0$ and $N_d \rightarrow N_{1_1} \rightarrow N_0$. Therefore, N_{1_0} and N_{1_1} obtain 2α tokens, respectively. N_{2_1} and N_d obtain α tokens respectively. N_v can consider the two received RREPs as receipts, and thus obtains 2β tokens. N_{2_0} and N_{2_2} obtain β tokens respectively. Thus, N_0 should pay $6\alpha + 4\beta$ tokens for route discovery. In Fig. 4, when the receipts of all the participants are inserted into the blockchain, N_{1_0} and N_{1_1} obtain 2α and 3α tokens respectively, since N_{1_1} separately forwards security data items from N_{d_1} and N_{d_2}. N_{d_0}, N_{d_1} and N_{d_2} obtain α tokens respectively. N_v can use received $\{SDI_{1_0}, \phi_{1_0}\}$ and $\{SDI_{1_1}, \phi_{1_1}\}$ as receipts, thus obtaining 3β tokens. As a consequence, N_0 should pay $8\alpha + 3\beta$ tokens for security data item collection.

When the first receipt with UID or DI is inserted in one block of blockchain, miners will not collect and insert receipts with the same UID or DI after lasting n_r blocks from the block, thus redeeming the unexpended tokens of collector. pa might have some tokens, which can be distributed to nodes whose receipts are inserted into blockchain in a specific distribution.

If the new TX_v, TX_{ct} or TX_{cc} is inserted into the next block successfully, the sender of receipt or deposit message gives the relative miner a fixed ratio (ω, $0 < \omega < 1$) of its obtained rewards. The miner gives ξ tokens to N_{TI}.

4.4 Budget Balance of Collector

In this part, we show the collector's budget for route discovery and security data item collection.

Budget for Route Discovery

RREQ forwarding helps constructing a virtual tree. Since a budget is reserved in the whole route discovery, a collector can set the depth of the tree and the out-degree of each node at each hop for discovering a collection node.

N_v's public key and Q_{i_v} received in route discovery can help constructing a virtual tree, and thus the collector can control the maximum depth TTL of tree and the out-degree

k_h of each node at each hop for balancing its budget in the whole route discovery. Conversely, it can determine the depth and out-degree due to a preset budget. Intuitively, the larger the out-degree and depth are, the higher the probability of discovering a collection node is. At the same time, this suggests a bigger budget. A tree with the largest RREQ forwarding scale is generated in route discovery when the receivers of all the nodes at each hop are different. The number of nodes at hop $h+1$ in the tree can be computed as $m_{h+1} = m_h k_h$. Given TTL, k_h, $h = 0, \ldots, TTL-1$, and $m_0 = 1$, the collector can obtain $m_{TTL} = \prod_{h=0}^{TTL-1} k_h$. When all the nodes at hop TTL have routes to a collection node, the payment of collector is the largest. We can compute the maximum payment in the whole route discovery as $CS_0 = m_{TTL}\alpha + \sum_{h=1}^{TTL-1} m_h\alpha + m_{TTL}(TTL-1)\alpha + m_{TTL}\beta = \prod_{h=0}^{TTL-1} k_h(TTL\alpha+\beta) + \sum_{h=1}^{TTL-1}\prod_{i=0}^{h-1} k_i\alpha$. Conversely, the collector can adjust the depth TTL and out-degree k_h for controlling the forwarding scale due to a given budget.

Budget for Security Data Item Collection

A collector can compute its maximum payment based on all discovered routes.

N_v's public key, DT_{i_v} and SDI_{i_v} can be adopted to construct continuous virtual route paths. When the collector succeeds in collecting security data from $N_{d_0}, \ldots, N_{d_c}$ by using the route paths $PA_{d_0}, \ldots, PA_{d_c}$, the virtual route paths are $PA_{d_0}, \ldots, PA_{d_c}$. If these route paths have only one point of intersection (namely the public key of collector), the collector's payment for security data item collection is the largest. The collector can compute the maximum payment as $CS_1 = \sum_{j=0}^{c}[(2h_{d_j}-1)\alpha+\beta]$, where h_{d_j} is the hop count of PA_{d_j}. This budget can help the collector to deposit appropriate tokens for collection.

5 Analysis and Performance Evaluation

In this section, we analyze B4SDC, evaluate its performance, and compare it with mainstream blockchain and incentive systems.

5.1 Analysis

In this part, we discuss that B4SDC provides incentives for all participants, and resists spoofing attacks, collusion attacks, and excessive forwarding and guarantees the fairness to all forwarders in receipt collection. In addition, we analyze B4SDC in terms of the liveness, safety, fault tolerance, and decentralization of blockchain.

1) Incentive: B4SDC not only incents security data collection, but also encourages the certificate and task issuer to publish tasks and miners to insert more receipts or deposit messages into blockchain. In route discovery, each forwarder considers the received control information as receipts, adds sensed security data into the information, and then forwards this information. Each collection node generates and forwards a RREP after receiving a RREQ as a receipt. In security data item collection, each forwarder can also use the received information as receipts. After receiving a request as a receipt, each collection node generates and forwards a security data item. The forwarder and collection node can share received receipts to blockchain, and they obtain rewards if these receipts are inserted into blockchain. Miners are encouraged to insert more receipts and deposit messages into their created blocks, since they obtain more rewards from the reporters of receipt and deposit message when these receipts and deposit messages are added into blockchain successfully. The certificate and task issuer also obtains rewards from the miner of the next block since a block can be created only when a task is issued.

We analyze the acceptance of B4SDC by employing game theoretical analysis. The certificate and task issuer, collector, forwarders, collection nodes and miners are encouraged to cooperatively finish their works. The acceptance of B4SDC is analyzed based on a static game theory model. The players of game are the issuer, collector, forwarders and miners. We do not consider the situation of collection node, since it is the same as the forwarder's. Suppose that these players know the information of each other and treat each other with the same priority. They adopt their own strategies in order to maximize their profits. We denote the strategy S_x of issuer, collector, forwarder and miner as S_{TI}, S_{CO}, S_{FO} and S_M, respectively. $S_x = 1$ suggests that the entity x cooperates with others and finishes its work honestly, and $S_x = 0$ means that x refuses to cooperate.

First, we take into consideration $S_{CO} = 0$. The utility of collector is $ut_{CO} = 0$. If the issuer cooperatively publishes a task, its utility is $ut_{TI} = -c_{TI}$ since blocks cannot be created. c_{TI} is the cost of issuer to generate a task. The utility of forwarder is $ut_{FO} = 0$, since no messages should be forwarded. The utility of miner is $ut_M = 0$, because no receipts and deposit messages are generated for block creation. If the issuer refuses to cooperate, the utility of issuer, forwarder and miner is $ut_{TI} = ut_{FO} = ut_M = 0$.

Second, we consider $S_{CO} = 1$. If $S_{TI} = 0$ and $S_{FO} = 0$, the utility of collector, issuer, forwarder and miner is $ut_{CO} = -c_{CO}$, $ut_{TI} = 0$, $ut_{FO} = 0$ and $ut_M = 0$, respectively, because blocks cannot be created. c_{CO} is the cost of collector to generate a RREQ and a valid deposit message. When $S_{TI} = 0$, $S_{FO} = 1$ and $S_M = 0$ or 1, the utility of collector, issuer, forwarder and miner is $ut_{CO} = b_{CO} - c_{CO}$, $ut_{TI} = 0$, $ut_{FO} = -c_{FO}$, and $ut_M = 0$ or $-n_W c_M$, respectively. b_{CO} is the collector's utility from route discovery or security data item collection, c_{FO} is the cost of forwarder to forward a message and share a receipt. n_W is the number of receipts collected by the collector, and c_M represents the cost of collector to process a receipt. If $S_{TI} = 1$ and $S_{FO} = 0$, the utility of collector, issuer, forwarder and miner is $ut_{CO} = -c_{CO}$, $ut_{TI} = -c_{TI}$, $ut_{FO} = 0$ and $ut_M = 0$. Because the forwarder refuses to forward messages and share receipts, and blocks cannot be generated successfully. When $S_{TI} = 1$, $S_{FO} = 1$ and $S_M = 0$, we can obtain the utility of collector, issuer, forwarder and miner, $ut_{CO} = b_{CO} - c_{CO}$, $ut_{TI} = -c_{TI}$, $ut_{FO} = -c_{FO}$ and $ut_M = 0$, since the miner does not create a block and thus the issuer and forwarder obtain no rewards. If $S_{TI} = 1$, $S_{FO} = 1$ and $S_M = 1$, the utility of collector, issuer, forwarder and miner is $ut_{CO} = b_{CO} - c_{CO} - CS * P_{CO}$, $ut_{TI} = \xi * P_{LI} - c_{TI}$, $ut_{FO} = \beta * (1-\omega) * P_{FO} - c_{FO}$, $ut_M = (\omega * CS - \xi) * P_M - n_W * c_M$. CS is the budget for route discovery or security data item collection, P_{CO} represents the probability that all the receipts of involved nodes en route are inserted into the next block, ξ is the reward of issuer, P_{LI} is the probability of miners to create at least one block, P_{FO} is the probability that the receipt of forwarder is inserted into the next block, and P_M means the probability that the block created by the miner is the next block.

Based on the above analysis, we can obtain an optimal solution. Nash Equilibrium is achieved if those four entities can conduct their work cooperatively (i.e., $S_{CO} = S_{TI} = S_{FO} = S_M = 1$) and their utility exceeds 0. This conclusion can help setting CS, ω and ξ and distributing rewards among issuer, forwarders, collection nodes and the block creator.

2) Resisting Spoofing Attacks: Each node cannot forge the message of other nodes for profits. To be specific, if N_i broadcasts a signed message and a neighbor receives this message, the neighbor attempts to forge another message signed by N_i for profits. However, it cannot forge the message successfully since we adopt the secure ECDSA for signatures and it cannot obtain the private key of N_i by solving a discrete logarithm problem.

3) Resisting Collusion Attacks: We discuss a route path constructed with RREQ forwarding. Due to the literature [3], if the last node colludes with the corresponding collector and does not report its receipt to blockchain, it obtains the behind-the-scene rewards $\beta + \epsilon$ ($\epsilon > 0$) tokens from the collector. Thus, the collector is uncharged by $\alpha - (\beta + \epsilon)$ tokens. In order to resist the collusion attack, the collector is required to transfer $\alpha - \beta$ tokens to the public address pa when one receipt reporter is isolated from the route path. This suggests the collector pays extra ϵ tokens, which refrains the collector from launching the collusion attack. Similarly, if one receipt reporter is isolated from the virtual tree that is constructed with RREQ forwarding and whose root is the collector's public key, the collector pays $\alpha - \beta$ tokens to pa, which eliminates the collusion attack.

We consider a route path generated with RREP, DT_i or SDI_i forwarding. For simplicity, we take the route path constructed with RREP forwarding as an instance. Except receipt reporters in the continuous route path originating from the collection node or an intermediate node having routes to this collection node, if there are l remaining receipt reporters in the real route (i.e., the route list RL in RREP), the collector is required to transfer $l * (\alpha - \beta)$ tokens to the public address. Similarly, this can avoid the collusion attack since the tokens that the collector transfers to pa for the attack are larger than its attack cost.

When the collector N_0 receives a valid RREP or security data item en route, N_0 is not allowed to consider its received messages as receipts. Because it is not willing to share its receipt to the blockchain for saving the cost of reporting a receipt and reducing the payment to N_1 by $\alpha - \beta$ tokens. N_1 can obtain at most β tokens. In order to guarantee the benefit of N_1, a common neighbor of N_0 and N_1 collects the RREP or security data item as a receipt, and shares its receipt to the blockchain. Therefore, N_1 might obtain at most α tokens from N_0, and its profits can be guaranteed.

4) Resisting Excessive Forwarding: Due to a budget (i.e., the maximum payment) in the whole route discovery, a collector can set the maximum depth TTL of virtual tree and the out-degree k_h of each node at each hop for discovering a collection node. In route discovery, a collector constrains the scale of RREQ forwarding by adding TTL and k_h into this RREQ. After receiving the RREQ, each forwarder should select a fixed number of RREQ receivers, otherwise, it obtains no rewards since its neighbor shares a report to blockchain for rewards when discovering its misbehaviors. Even if a node that is not specified as a receiver or whose hop count exceeds TTL can obtain the RREQ, it cannot use the received RREQ as a receipt for getting rewards from the collector since each receipt should be verified and accepted by a majority of all miners. Therefore, B4SDC resists excessive forwarding.

5) Fairness: As long as a node (except collector) participates in receipt generation, it can save its received messages as receipts, and is willing to share these receipts to blockchain for rewards. The issuer is encouraged to publish a task for rewards. Miners are incented to insert more receipts into their created blocks for rewards. Thus, more receipts are inserted into the next block. As a result, as long as a node (except collector) participates in receipt generation, it can obtain rewards with a high probability, which ensures the fairness for each forwarder and collection node.

6) Liveness: The liveness of B4SDC can be ensured, namely the probability of successfully creating a valid block for the next block tends to 1 when a task is published. If the blockchain is comprised of N blocks and the certificate and task issuer publishes the $(N+1)$-th task, we compute the probability that at least one valid is generated for the next block until the reference time TS_{re}.

After the issuer publishes the task, the miner M_i, $i = 1, \ldots, CN$ starts to create valid blocks at the time TS_i until TS_{re}. We suppose $TS_1 \leq \ldots \leq TS_{CN} \leq TS_{re}$ due to the existing network latency. The block creation is a random event, thus the time that M_i spends creating a valid block successfully follows an exponential distribution [20]. The probability of M_i to successfully create a valid block from TS_i to TS_{re} can be computed as $1 - e^{-(TS_{re} - TS_i)/\mu_i}$, where μ_i is the average time that M_i spends creating a valid block successfully. Note that $w(AM)$ is used to adjust the difficulty value TAG, thus μ_i of some miners is short. The probability of these CN miners to succeed in creating at least one valid block is

$$\begin{aligned} P_{LI} &= 1 - \prod_{i=1}^{CN} \{1 - [1 - e^{-(TS_{re} - TS_i)/\mu_i}]\} \\ &= 1 - e^{-\sum_{i=1}^{CN} (TS_{re} - TS_i)/\mu_i}. \end{aligned}$$

If $\sum_{i=1}^{CN} (TS_{re} - TS_i)/\mu_i$ is increased, P_{LI} tends to 1. In order to increase $\sum_{i=1}^{CN} (TS_{re} - TS_i)/\mu_i$, we can grow the number CN of participating miners or $TS_{re} - TS_i$ by growing TS_{re}. As long as a miner with short μ_i participates, P_{LI} tends to 1 rapidly with TS_{re} increasing, thus at least one valid block can be generated within short time.

7) Safety: B4SDC ensures the safety of blockchain, namely the block winner consistency can be achieved among honest miners for avoiding the forks of blockchain. Due to the literature [19], we can compute the probability of a miner in the network to receive the valid block with the earliest timestamp as at least $1 - e^{-\theta/\lambda}$, where λ is the average network latency. Therefore, at least $1 - e^{-\theta/\lambda}$ of all the miners in the network receive the block during their preset time window θ. When θ is large enough, $1 - e^{-\theta/\lambda}$ approximates to 1, which suggests almost all the miners can receive the block with the earliest timestamp. Therefore, the block winner consistency among honest miners can be ensured. The detail process refers to the literature [19].

8) Fault Tolerance: Although an attacker controls $\eta \leq 50\%$ miners, it cannot destroy the consensus that honest miners have reached and ongoing consensus.

Except the miners controlled by the attacker (i.e., malicious miners), other miners are assumed to behave independently and maximize their profits rationally, which are called honest miners.

If the block B_K has got the consensus of honest miners, another block $B_K^{'}$ is stored by the malicious miners. The malicious miners generate a new block based on $B_K^{'}$. It is possible that $B_K^{'}$ is superior to B_K, since the malicious miner might not publish $B_K^{'}$. Suppose B_K and $B_K^{'}$ are generated based on the block B_{K-1} of blockchain. If a new miner participates in the blockchain system, it requests blocks from miners in order to maintain blockchain. The miner could receive B_K and $B_K^{'}$ since the honest and malicious miners exist in the system. Therefore, it should determine which block should be stored as the valid block of blockchain. In order to solve this problem, the miner can request blocks from a number of miners, and get the number of received B_K and $B_K^{'}$ that is denoted as n_{B_K} and $n_{B_K^{'}}$, respectively. If $n_{B_K} \geq n_{B_K^{'}}$, the miner stores B_K. Otherwise, it stores $B_K^{'}$. When $n_{B_K} + n_{B_K^{'}}$ is large enough, $n_{B_K^{'}}/(n_{B_K} + n_{B_K^{'}})$ approximates to η, thus $n_{B_K^{'}}/(n_{B_K} + n_{B_K^{'}}) \leq 50\%$. As long as the miner requests blocks from a large enough number of miners, it stores B_K with the probability $1 - \eta \geq 50\%$. Therefore, the number of honest miners storing B_K is always larger than the number of malicious miners storing $B_K^{'}$, thus the attacker cannot destroy the consensus that the honest miners have reached.

When a malicious miner generates a valid block earlier than honest miners, it could not immediately publish the block, but waits some time and then publishes the block in order to cause the forks of blockchain and perturb the ongoing consensus. However, the malicious miner cannot succeed in perturbing the consensus. It is noted that the time of miners is synchronized, each block includes the timestamp of its creation, and all the miners are monitored by their neighbors. If the malicious miner publishes the malicious block, its neighbors could refuse to forward the block due to its invalid timestamp. Even if the honest miners could receive the block within their time period θ, they can use light weight external methods to detect the invalid timestamp and reject the block. For instance, wormhole attack detection might help estimating the real time of block creation. In order to guarantee the accuracy of estimation, multiple routes that include the different neighbors of malicious miner can be adopted for block propagation, thus solving the low trust problem of estimation of one route. Therefore, the attacker cannot perturb the ongoing consensus when it controls $\eta \leq 50\%$ of all the miners.

In summary, B4SDC resists the misbehaviors of 50% of all the miners.

9) Decentralization: B4SDC prevents a powerful miner from creating the majority of blocks of blockchain for controlling the blockchain, thus ensuring the decentralization. That is, even if the miner creates a valid block more efficiently than others, we can reduce its probability of succeeding in creating the next block to a low degree.

Due to the literature [19], we can model B4SDC including a powerful miner as a state machine, and then define system states. Additionally, we can derive the probability of system state transition and the probability of the system to reach each state. When $n_{bthr} = 1$, the probability of the powerful miner to generate the next block can be computed as $\rho/(1+\rho n_b)$, where ρ represents the probability that the powerful miner creates a valid block earlier than others. When the powerful miner always generates a valid block earlier than others, ρ approximates to 1, and the probability of this miner to succeed in generating the next block is $1/(1 + n_b)$, which decreases with n_b increasing. As a consequence, we can fix n_{bthr}, and then select the appropriate n_b for reducing the probability of the powerful miner to successfully create the next block to a low degree, thus ensuring the decentralization of blockchain. The detail process refers to the literature [19].

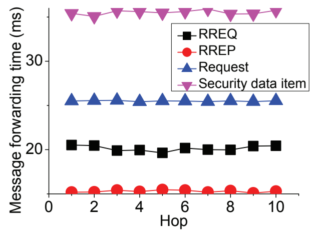
5.2 Performance Evaluation

In this part, we evaluated B4SDC through simulations.

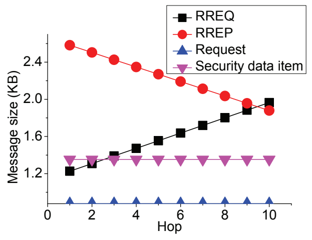
Metrics: (1) Message forwarding time: The average message forwarding time of node at each hop; (2) Message size: The average size of message that a node at each hop forwards; (3) Transaction confirmation time: The average time of B4SDC to confirm a receipt or deposit message; (4) Throughput: The average number of receipts and deposit messages that are successfully recorded in blockchain per second; (5) Block size; (6) Memory usage: The average memory usage of node to forward a message and create and verify a block.

Experimental Settings: With respect to experimental environments, we simulated B4SDC using NS3 and C++ in a laptop that runs ubuntu 18.04 with Intel Core i5-6300HQ CPU @2.3Ghz and 12GB memory. We simulated a node as the certificate and task issuer, 1000 nodes for security data collection, and 4 miners. In terms of network setting, the propagation time of bitcoin block between two miners follows an exponential distribution [20]. Thus, we simulated a real network by introducing the network delay between two miners that follows the exponential distribution with the rate parameter $\lambda = 12.6$s. With respect to receipt generation, we adopted the DSR route discovery and used discovered routes to transmit the request of collector and the security data of collection nodes. In route discovery, a node at each hop adds its local timestamp (i.e., a kind of security data) into received RREQs and RREPs. In security data item collection, each collection node uses a row of feature values in the NSL-KDD database as security data.

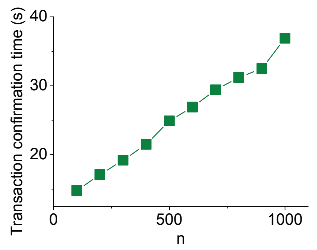
Experimental Results: Message Forwarding Time: As shown in Fig. 5(a), we can observe the average message forwarding time of a node at each hop. The time does not change with the increase of hops. The forwarding time of RREQ, RREP, request, and security data item of the node is approximately 20ms, 15ms, 25m and 35ms, respectively. In receipt sharing, we tested the time token by the node to share a receipt.



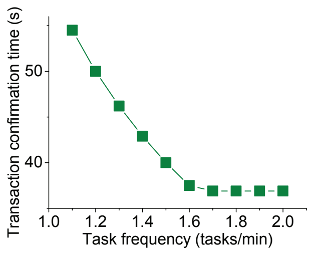
(a) Message forwarding time with different hops



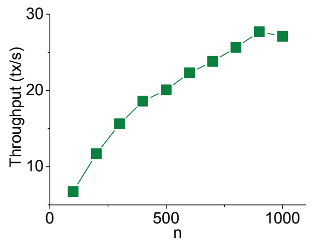
(b) Message size with different hops



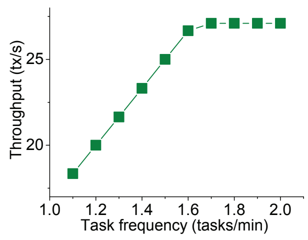
(c) Transaction confirmation time with 4 tasks/min, $n_b = 0$ and different n



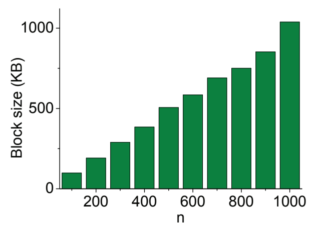
(d) Transaction confirmation time with $n_b = 0$, $n = 1000$ and different task frequencies



(e) Throughput with 4 tasks/min, $n_b = 0$ and different n



(f) Throughput with $n_b = 0$, $n = 1000$ and different task frequencies



(g) Block size with different n

Fig. 5. Experimental results

When the receipt is a RREQ, RREP, request or security data item, the time cost of the node to share the receipt is equal to the time cost of the node to forward it.

Message Size: We show the average size of a message that a node at each hop forwards in Fig. 5(b). When the number of hops increases, the size of RREQ increases but the size of RREP decreases, because the node at hop h adds its sensed security data into the RREQ received from the node at hop $h-1$ and the RREP received from the node at hop $h+1$. The size of request and security data item remains unchanged around 0.8KB and 1.4KB, respectively. When a node considers a received RREQ as a receipt, the size of its shared receipt equals that of received RREQ. If a node regards a received RREP as the receipt, the size of receipt is equal to that of received RREP. When the receipt is a received request and security data item, the size of each node's shared receipt is 0.8KB and 1.4KB, respectively.

TABLE 2
Transaction confirmation time and throughput with 4 tasks/min, $n_{bthr} = 1$, $n = 1000$ and different n_b

n_b	0	1	2	3
TC (s)	36.9	37.2	37.5	38.1
TH (tx/s)	27.1	26.88	26.67	26.25

TC: transaction confirmation time; TH: throughput.

TABLE 3
Memory usage

Operations	**Memory usage**
Forwarding a RREQ or sharing a receipt (i.e., received RREQ)	18.63MB
Forwarding a RREP or sharing a receipt (i.e., received RREP)	18.75MB
Forwarding a request or sharing a receipt (i.e., received request)	18.59MB
Forwarding a security data item or sharing a receipt (i.e., received security data item)	18.71MB
Creating a block	421.98MB
Verifying a block	421.98MB

Transaction Confirmation Time: As shown in Fig. 5(c), we observe the transaction confirmation time when the task frequency is set to 4 tasks per minute, $n_b = 0$, and we change the number $n = L + X + Y$ of receipts and deposit messages that should be inserted into the next block. The time increases linearly with n increasing. The bigger n suggests a miner verifies more receipts and deposit messages of a received block, which takes more time.

If $n_b = 0$ and $n = 1000$, we show the transaction confirmation time by changing the task frequency in Fig. 5(d). When the task frequency is less than 1.7 tasks per minute, the time decreases sharply with the task frequency increasing. Because the task interval is longer than the average consensus time and is regarded as the transaction confirmation time, and the task interval is inversely proportional to the task frequency. If the task frequency exceeds 1.7 tasks per minute, the transaction confirmation time remains invariable since the task interval is shorter than the consensus time.

When we set the task frequency to 4 tasks per minute, $n_{bthr} = 1$ and $n = 1000$, TABLE 2 shows the transaction confirmation time by changing n_b. The time grows with the increase of n_b, since fewer miners participate in mining.

Throughput: When the task frequency is set to 4 tasks per minute and $n_b = 0$, we observe the throughput by changing n. As shown in Fig. 5(e), the throughput increases linearly when n increases. Because more receipts and deposit messages are inserted into the next block.

If $n_b = 0$ and $n = 1000$, we show the throughput by changing the task frequency. As depicted in Fig. 5(f), if the task frequency increases from 1.1 to 1.7 tasks per minute, the throughput grows linearly, since the task interval is longer than the consensus time and thus inversely proportional to the task frequency. If the task frequency exceeds 1.7 tasks per minute, the throughput is almost invariable. Because the task interval is shorter than the consensus time.

When $n_{bthr} = 1$, $n = 1000$ and the task frequency is 4 tasks per minute, we observe the throughput with different n_b. As shown in TABLE 2, when n_b increases, the throughput decreases due to the longer transaction confirmation time.

Block Size: Fig. 5(g) shows the block size with different n. The block size increases linearly with the increasing of n, since the larger n suggests more receipts and deposit messages are added into blockchain.

Memory Usage: We observe the memory usage of node when some operations are performed, as shown in TABLE 3. In route discovery and security data item collection, the memory usage of the node to forward a RREQ and RREP is 18.63MB and 18.75MB, respectively. In receipt sharing, the memory usage of the node to share a receipt (i.e., RREQ, RREP, request and security data item) is also 18.63MB, 18.75MB, 18.59MB and 18.71MB, respectively. The memory size of current routers is 64MB or 128MB, even as large as 518MB. Thus, many smart devices have a sufficient memory space to forward a RREQ, RREP, request and security data item and share a receipt. On the other hand, the memory size of a miner should be at least 421.98MB. Since the memory size of current smart phones reaches 8GB, running B4SDC is not heavy in mobile phone organized MANETs.

Comparison: In TABLE 4, we compare B4SDC with mainstream blockchain and incentive systems in terms of incentive, security and performance.

Some blockchain systems do not consider incentives, e.g., Algorand using BFT. The liveness and safety of PoW, PoUW, BFT, PoS, and trees and DAGs based blockchain systems are analyzed [12], [36]. PoW, PoUW and PoS suffer from the outsourceability of task [37], thus not ensuring the decentralization. However, B4SDC guarantees the decentralization, since it can prevent a powerful miner from creating the majority of blocks of blockchain by setting appropriate n_b and n_{bthr}. In the simulation, if the task frequency is 4 tasks/min and $n_b = 0$, the transaction confirmation time and throughput are $TC = 36.9$s and $TH = 27.1$tx/s. They are rational since a miner consumes almost no computing resources for solving a puzzle. Suppose there exist M miners. In PoW, BFT, PoS, PoUW and trees and DAGs based blockchian systems and B4SDC, a message should be shared to all miners for making them insert this message into blockchain, thus the communication complexity is $O(M)$. In PoW, PoUW, PoS, and trees and DAGs based blockchain systems and B4SDC, the next block should be sent to all the miners. Therefore, their communication complexity is $O(M)$. BFT requires information exchange between any two miners, thus its communication complexity is $O(M^2)$.

The scalability of blockchain is its ability to maintain a high throughput when more miners participate [38]. We assume that there are M miners in blockchain systems. In B4SDC, each miner can collect receipts and deposit messages before the certificate and task issuer publishes a task. Some miner receives the task, and quickly creates the next block with a negligible difficulty based on collected n receipts and deposit messages. The time of task propagation between the issuer and each miner is negligible since the size of task is small. The miner publishes the next block. For simplicity, we consider the network composed of the M miners. The average network delay of a receipt or deposit message between any two miners increases logarithmically with M increasing [39]. Thus, the average time of block propagation between any two miners can be estimated as $nlog_{\tau}M$, where τ is a parameter related to network bandwidth. Signature verifications are the most time-consuming operations in verifying the validity of a block, and the verification time of each signature is denoted as T_{ve}. When the task interval is shorter than the consensus time, we estimate the throughput of B4SDC as $TH_0 = n/(nlog_{\tau}M + nT_{ve}) = 1/(log_{\tau}M + T_{ve})$. When M increases, TH_0 decreases. When the task interval is longer than the consensus time, we can obtain the throughput of B4SDC as $TH_1 = n/TN$, where TN represents the task interval. BFT requires 3-round information exchanges. When there are M miners in a BFT based blockchain system, the average time of 3-round information exchanges is estimated as $(n+2)log_{\tau}M^2$. The throughput of BFT based blockchain system can be estimated as $TH_2 = n/[(n+2)log_{\tau}M^2 + nT_{ve}]$. Therefore, if the task interval is shorter than the consensus time in B4SDC, the throughput of the BFT based blockchain system is lower compared to the B4SDC's throughput. When the task interval is longer than the consensus time in B4SDC and $M > \tau^{(TN-nT_{ve})/2(n+2)}$, the throughput of the BFT based blockchain system is lower than that of B4SDC. When M ($M > \tau^{(TN-nT_{ve})/2(n+2)}$) increases, the throughput of B4SDC decreases more slowly than that of the BFT based blockchain system, which implies the higher ability of B4SDC to ensure a high throughput. Therefore, B4SDC can support better scalability compared to BFT based blockchain systems. In the blockchain systems based on PoW, PoUW, and trees and DAGs, the time of block creation T_{bc} is very long since they aim to prevent an attacker from easily creating blocks in order to avoid forking. Their throughput can be denoted as $TH_3 = n/(T_{bc} + nlog_{\tau}M + nT_{ve})$. Based on the above analysis, we can see that their scalability is worse than the scalability of B4SDC with large enough M since T_{bc} is very large. In a PoS based blockchain system, some miner can quickly create a block with a negligible difficulty. The throughput of the PoS based blockchain systems is $TH_4 = 1/(log_{\tau}M + T_{ve})$. Thus, TH_0 and TH_4 are equal. When the task interval is longer than the consensus time in B4SDC and $M > \tau^{(TN-nT_{ve})/n}$, the throughput of B4SDC is higher than that of the PoS based blockchain system. If M ($M > \tau^{(TN-nT_{ve})/n}$) increases, the ability of B4SDC to maintain a high throughput is higher than the PoS based blockchain systems'. Therefore, the scalability of B4SDC is better than that of the PoS based blockchain system when M is large enough. As a consequence, B4SDC supports better scalability compared to PoW, BFT, PoUW, PoS, and trees and DAGs based blockchain systems.

In summary, B4SDC provides incentives and solves the three challenges (i.e., forking, low efficiency and the trend of centralization) of mainstream blockchain systems, and the security problems of mainstream incentive systems. In addition, B4SDC ensures better scalability compared to the mainstream blockchain systems. Therefore, B4SDC outperforms the mainstream works.

TABLE 4
Comparison of B4SDC with mainstream blockchain and incentive systems

		Blockchain Systems					Incentive Systems			
		PoW	BFT	PoS	PoUW	Trees and DAGs	Reputation	Micropayment		
	Criteria	Bitcoin	Algorand	Ethereum	Permacoin	GHOST [11]	LWT [23]	IMM [5]	Sprite [3]	B4SDC
Incentive	IN	Y	N	Y	Y	Y	-	-	-	Y
Security properties	LI	Y	Y	Y	Y	Y	-	-	-	Y
	SA	Y	Y	N	Y	Y	-	-	-	Y
	FT	25%	33%	50%	25%	25%	-	-	-	50%
	DE	N	Y	N	N	N	-	-	-	Y
	RS	-	-	-	-	-	N	N	Y	Y
	RC	-	-	-	-	-	N	-	Y	Y
	RE	-	-	-	-	-	-	Y	N	Y
	FR	-	-	-	-	-	Y	N	Y	Y
Performance	TC	3600s	40s	72s	3600s	-	-	-	-	36.9s
	TH	7tx/s	875tx/s	30tx/s	-	15.5tx/s	-	-	-	27.1tx/s
	CPB	High	Low	Low	High	High	-	-	-	Low
	CMB	$O(M)$	$O(M^2)$	$O(M)$	$O(M)$	$O(M)$	-	-	-	$O(M)$
	SC	Low	Low	Low	Low	Low	-	-	-	High

IN: incentive; LI: liveness; SA: safety; FT: fault tolerance; DE: decentralization; RS: resisting spoofing attacks; RC: resisting collusion attacks; RE: resisting excessive forwarding; FR: fairness; CPB: computational burden; CMB: communication burden; SC: scalability; Y: supported; N: not supported; -: not given or not suitable for evaluation.

6 Conclusion

In this paper, we proposed B4SDC, a blockchain system for security data collection in MANETs. It not only incented security data collection in route discovery, but also motivated the collection at collection nodes. Analysis and simulation based experiments showed that B4SDC can resist spoofing attacks, collusion attacks, and excessive forwarding, guarantee fairness as much as possible, and also solve the main problems of current blockchain technologies, namely forking, low efficiency, and centralization. In the future, we will explore a feasible scheme to preserve privacy in B4SDC.

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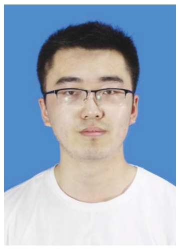

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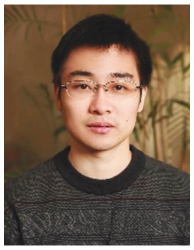

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