FaceChange: Attaining Neighbor Node Anonymity in Mobile Opportunistic Social Networks with Fine-grained Control

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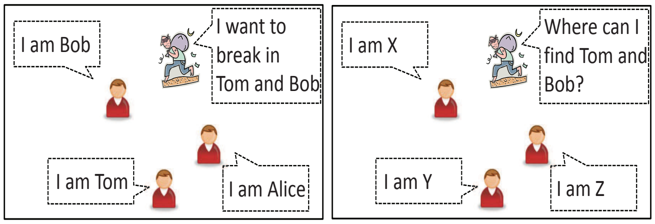
***Abstract*—In mobile opportunistic social networks (MOSNs), mobile devices carried by people communicate with each other directly when they meet for proximity-based MOSN services (e.g., file sharing) without the support of infrastructures. In current methods, when nodes meet, they simply communicate with their real IDs, which leads to privacy and security concerns. Anonymizing real IDs among neighbor nodes solves such concerns. However, this prevents nodes from collecting real ID based encountering information, which is needed to support MOSN services. Therefore, in this paper, we propose FaceChange that can support both anonymizing real IDs among neighbor nodes and collecting real ID based encountering information. For node anonymity, two encountering nodes communicate anonymously. Only when the two nodes disconnect with each other, each node forwards an encrypted encountering evidence to the encountered node to enable encountering information collection. A set of novel schemes are designed to ensure the confidentiality and uniqueness of encountering evidences. FaceChange also supports fine-grained control over what information is shared with the encountered node based on attribute similarity (i.e., trust), which is calculated without disclosing attributes. Advanced extensions for sharing real IDs between mutually trusted nodes and more efficient encountering evidence collection are also proposed. Extensive analysis and experiments show the effectiveness of FaceChange on protecting node privacy and meanwhile supporting the encountering information collection in MOSNs. Implementation on smartphones also demonstrates its energy efficiency.**

***Index Terms*—Mobile opportunistic social networks, Anonymity, Encountering information**

I. Introduction

As a special form of delay tolerant networks (DTNs) [1], mobile opportunistic social networks (MOSNs) [2], [3] have attracted much attention due to the increasing popularity of mobile devices, e.g., smartphones and tablets. In MOSNs, mobile devices carried by people communicate with each other directly without the support of infrastructures when they meet (i.e., within the communication range of each other) opportunistically. Such a communication model can be utilized to support various applications without infrastructures, such as packet routing between mobile nodes [4], encountering based social community/relationship detection [5], [6], and distributed file sharing and Question & Answer (Q&A) [7]–[9] in a community. In each system, a node is uniquely labeled by an unchanging ID (defined real ID), which is obtained from the trust authority (TA), for the corresponding service. Since those services are built upon node encountering, nodes need to collect real ID based encountering information. For example, nodes need to know whom they have met to identify proximity based social community/relationships. In packet routing, nodes need to collect the encountering information to deduce their future meeting probabilities with others. Then, a packet can always be forwarded to the appropriate forwarder.



(a) Possible privacy issue. (b) Solution: neighbor Anonymity.

Fig. 1: Demonstration of a privacy issue and a possible solution in MOSNs.

In current MOSN applications, nodes can collect real ID based encountering information easily since neighbor nodes communicate with real IDs directly. We define two nodes as neighbor nodes when they are within the communication range of each other. However, when using real IDs directly, the disclosure of node ID to neighbor nodes would create privacy and security concerns. For example, a malicious node can first know the IDs of some central nodes or nodes with specific interests. Then, as shown in Figure 1(a), when neighbor nodes communicate with real IDs, a malicious node can easily identify attack targets from neighbors and launch attacks to degrade the system performance or steal important documents. Further, without protection, malicious nodes can easily sense the encountering between nodes for attacks.

Therefore, neighbor node anonymity is critical to prevent the disclosure of real IDs to neighbors. Clearly, a permanent pseudonym cannot achieve such a goal since it can be linked to a node, which can still enable malicious nodes to recognize targets from neighbor nodes. Thus, an intuitive method to realize the neighbor node anonymity is to let each node continuously change its pseudonym used in the communication with neighbors, as shown in Figure 1(b). However, when neighbor node anonymity is enforced, nodes cannot collect the real ID based encountering information (i.e., cannot know whom they have met), which disables aforementioned MOSN services.

Consequently, there is a challenge on anonymizing neighbor nodes for privacy protection and meanwhile still supporting encountering information collection in MOSNs. There are rich investigations on protecting node privacy in MOSNs [10]–[17]. However, most of related works [10]–[16] focus on anonymizing interests and profiles and are not designed for neighbor node anonymity, which is a feature provided in this

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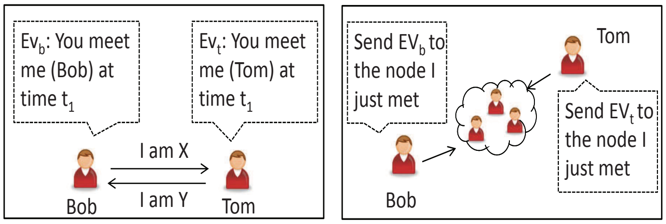

Ev_b: You meet me (Bob) at time t_1
Ev_t: You meet me (Tom) at time t_1
I am X
I am Y
Bob
Tom
Send EV_b to the node I just met
Tom
Send EV_t to the node I just met
Bob

(a) Create the encountering evidence under neighbor node anonymity.

(b) Route the encountering evidence to the other after separation.

Fig. 2: General solution for encountering record collection.

paper. The work in [17] support neighbor node anonymity but fail to provide encountering information collection at the same time.Therefore, we propose FaceChange to realize both aforementioned goals based on a key observation in MOSNs. That is, disconnected nodes cannot communicate with each other directly in MOSNs, which makes attacking disconnected nodes almost impossible. This also means that knowing real IDs after the encountering would not compromise the privacy protection. Thus, the proposed FaceChange keeps nodes anonymous only during the encountering and postpone the real ID based encountering information collection to a moment after two neighbor nodes disconnect with each other.

Figure 2 illustrates the design of FaceChange. When two nodes meet, they communicate anonymously. However, each of them creates an encountering evidence that contains their real IDs. The encountering evidences are sent to the other node only when they separate, thus enabling the encountering information collection while keeping the anonymity during the encountering. For an encountering evidence, we call the node that creates it as the creator and the encountered node that is to receive it as the recipient. FaceChange needs to handle the following challenges for encountering information collection.

- The security of the encountering evidence needs to be ensured. An encountering evidence can only be accessed by its creator and recipient and cannot be forged.
- An encountering evidence needs to be successful delivered to its recipient even when the real ID of the recipient node is unknown due to neighbor node anonymity.
- When creating an encountering evidence, a node can control what contents (e.g., basic encountering information and application information) to be included based on its trust on the encountering node. The calculation of the trust should be privacy-preserving.

FaceChange incorporates the following schemes to handle the three challenges.

Encountering Evidence Encryption and Validation Scheme. For each encountering evidence, FaceChange uses the bilinear pairing technique [18] to generate an encryption key and a pair of uniquely matched token and commitment with efforts from both encountering nodes. The property of the bilinear pairing ensures that nodes other than the creator and recipient, even eavesdroppers, cannot know the key. Further, the token is attached to the evidence and the commitment is stored on the recipient node for validation, thereby ensuring the uniqueness of each encountering evidence.

Encountering Evidence Relaying Scheme. In this scheme, during the encountering, the recipient node specifies a relay node and encrypts its real ID with the public key of the relay node. It then forwards such information to the creator. Later, after the two nodes separate, the creator routes the encountering evidence to the relay node, which decrypts the ID of the recipient node and further routes it to the recipient node, thereby delivering the encountering evidence.

Encountering Evidence Generation Scheme. More similar attributes (e.g., affiliation and reputation) between two nodes often denote higher trust between them [12]. Thus, we realize the control on the contents in an encountering evidence based on the attribute similarity. We use the commutative encryption [19] and the solution for “the millionaire’s problem” [20] to calculate the attribute similarity blindly in this process, which protects node privacy.

With neighbor anonymity, a node may fail to recognize the destinations of its packets even when meeting them, thereby making it hard to deliver packets. We then let nodes pretend to be a better forwarder for packets destined for them to fetch these packets, the details of which are introduced in Section IV-G. As a result, packet routing can be conducted correctly and efficiently in FaceChange. This shows that MOSN services can be supported when FaceChange is adopted.

We further design two advanced extensions to enhance the practicability of FaceChange. The first one enables mutually trusted nodes to disclose real IDs to each other during the encountering, and the second one enhances the routing efficiency of the encountering evidence relaying.

In summary, the major contribution of this paper is to propose a novel design that supports both neighbor node anonymity and real ID based encountering information collection in MOSNs. FaceChange prevents two encountering nodes from disclosing the real IDs during the encountering, so malicious nodes cannot identify targets from neighbors for attack. When nodes move away from each other, they can know the real IDs of nodes they have met to support MOSN services. This is acceptable since in MOSNs, a malicious node cannot communicate with a disconnected node for attacks.

In the following, Section II introduces related work. Section III presents the preliminary background. Sections IV and V introduces the design of FaceChange and three advanced extensions, respectively. Section VI evaluates FaceChange through trace-driven and smartphone-based experiments. Section VII concludes this paper with future work.

II. Related Work

A. Social Network based Applications in MOSNs

There are already many social network based MOSN routing algorithms [6], [21]–[24]. These works utilize various social factors such as frequently met friends, co-location records, centrality, transient contacts, and contact-based community to deduce a node’s future meeting probabilities with other nodes. Then, packets are always forwarded to the node with higher ability to meet their destinations.

There are also some applications in MOSNs. The work in [5] proposes three distributed community detection methods in DTNs. In SMART [6], each node constructs a social map including frequently met nodes to guide packet routing. The works in [7] and [8] realize peer-to-peer (P2P) file sharing and publish/subscribe overlay in DTNs, respectively. In PeopleNet [9], questions are first forwarded to matched geographical community and then propagated within the community via P2P connectivity to seek for answers.

Neighbor nodes in these algorithms communicate directly to collect encountering information for these services. Then, mobile users may be reluctant to participate in the MOSN services due to privacy concerns. Therefore, it is essential to provide neighbor node anonymity for privacy protection.

B. Privacy Protection in MOSNs

Anonymizing node interests or attributes for privacy protection in MOSNs has been studied in [10]–[13], [25]–[28]. The work in [10] uses the solution for "the millionaire's problem" [20] to blindly check whether two nodes have similar interests. PreFiler [11] and the work in [12] adopt attribute-based encryption and/or bilinear pairing technique to blindly check whether a packet matches the destination's interests and whether a node owns the attributes to hold a packet, respectively. In STAP [13], packets for a node are cached in places where it visits frequently. As a result, nodes can fetch packets for them without disclosing their location information. The works in [25]–[28] focus on protecting location privacy of mobile nodes. SLPD [25] hides the location of a node from the server by relaying its location-based requests among its social friends. ALAR [26] encrypts different fragments of a message with different keys and forwards them separately to prevent advisories from deducing its location from the captured fragments. The work in [27] uses additive homomorphic encryption to obtain the statistics of reported data in sensing systems without deteriorating individual users' privacy. In STAMP [28], nodes generate location proofs for co-location nodes anonymously to protect their location privacy.

The works in [14]–[16] provide anonymous profile matching between nodes in MOSNs. FindU [14] leverages the secure multi-party communication techniques to enable a user to find the best match user with limited information exchange. The work in [15] designs a fine grained profile matching algorithm based on Paillier Cyptosystem. Liang *et al* [16] further propose a serial of profile matching algorithms with full anonymity. The work in [17] lets each node continually change its pseudonym to protect its privacy in MOSNs.

There are also researches on secure and privacy-preserving communication between neighboring mobile devices [29]–[32]. However, most of these systems [29]–[31] rely on infrastructures to set up trust, which does not apply to the pure MOSN scenario without infrastructures. SDDR [32] enables neighboring nodes to communicate securely with flexible control over the linkability in an energy efficient and distributed manner. However, it cannot directly support the feature of letting nodes collect real ID based encountering information when nodes are anonymized during the encountering. With SDDR, two encountered nodes will either fail to collect the encountering information (when they are not allowed to recognize each other or one party) or disclose their real IDs (when they are allowed to recognize each other).

Though effective on protecting node privacy, those methods fail to investigate how to safely collecting real ID based encountering information under neighbor node anonymity, which is the design goal of FaceChange.

III. Preliminaries

A. Network Model

We focus on a mobile opportunistic social network with m human-carried mobile devices, denoted by N_i ($i \in [1, m]$). We assume that the network is large. Otherwise, a node can easily guess the identities of its neighbors. Mobile devices/nodes move in the network following the mobility of people carrying them. Each node (i.e., device) has a limited communication range, and two nodes can communicate only when they are within the communication range of each other. Efficient neighbor discovery method [33] that dynamically adjusts the neighbor scanning interval can be adopted to save energy.

We assume a Trust Authority (TA) in the system responsible for some system management functions such as system parameters and certificates distribution and attribute validation (e.g., reputation, affiliation, and ID), both of which can be conducted off-line. This is because without a TA, no trust can be built upon the network to support applications. The TA is a fixed server with both wireless capability and Internet access. Its real ID is always visible for easy access. Nodes can access the TA through two ways: 1) when moving close to the TA and 2) when having access to the Internet through WiFi or LTE. When a node connects to the TA, it can get the updated system information such as the set of legal node IDs.

Each node has a unique real ID in the network, denoted by NID_i. The real ID of each node is assigned by the TA with a signature generated by the TA's private key, through which nodes can verify the authenticity of received real IDs. DTN incentive schemes [34], [35] can be adopted to encourage nodes to be cooperative. Thus, we assume that nodes are cooperative in FaceChange in this paper, i.e., would follow the proposed FaceChange protocol in the network.

B. Adversary Model

In this paper, we assume malicious nodes can attack target nodes only when they find targets from neighbor nodes. This is reasonable since 1) an attacker in MOSNs cannot communicate with the target directly if they are not neighbors, and 2) it is costly to attack every encountered node. This means that malicious nodes can steal privacies or launch attacks only after identifying target nodes from neighbor nodes. Thus, in this paper, we focus on preventing real ID leakage during the communication between neighbor nodes, while still supporting encountering information collection.

C. Cryptographic Techniques

1) Bilinear Pairing: Let $\mathbb{G}_1$, $\mathbb{G}_2$ and $\mathbb{G}_\mathbb{T}$ be three cyclic groups with the same prime order q, and $P \in \mathbb{G}_1$ and

$Q \in \mathbb{G}_2$ be generators of $\mathbb{G}_1$ and $\mathbb{G}_2$, respectively. A bilinear pairing is a map e: $\mathbb{G}_1 \times \mathbb{G}_2 \rightarrow \mathbb{G}_{\mathbb{T}}$ satisfying the following properties [18]:

- Bilinearity: $\forall\ a, b \in \mathbb{Z}_q^*$: $e(aP, bQ) = e(P, Q)^{ab}$
- Non-degeneracy: $e(P, Q) \neq 1$
- Computability: e can be computed efficiently

We utilize symmetric pairing in this paper, in which $\mathbb{G}_1 = \mathbb{G}_2 = \mathbb{G}$ and they have the same generator P. As mentioned in Section IV-A, upon the start of the system, the TA first generates parameters for adopted bilinear pairing, i.e., $BiParas$. In this step, TA randomly selects a security parameter ς and runs the bilinear pairing generation function $\mathcal{F}(\varsigma)$ to generate these parameters ($BiParas$): $(e, q, P, \mathbb{G}, \mathbb{G}_T)$.

2) Commutative Encryption: A commutative encryption algorithm $\mathbb{E}(\cdot)$ [19], [36] satisfies the commutative property. That is, for any encryption keys k_i and k_j, message M, rational number t and $\gamma < 1/2^t$, it holds

- $\mathbb{E}_{k_i}(\mathbb{E}_{k_j}(M)) = \mathbb{E}_{k_j}(\mathbb{E}_{k_i}(M))$,
- $\forall\ M_1 \neq M_2$, $Pr(\mathbb{E}_{k_i}(\mathbb{E}_{k_j}(M_1)) = \mathbb{E}_{k_j}(\mathbb{E}_{k_i}(M_2))) < \gamma$.

where $\mathbb{E}_{k_i}(M)$ is the result of encrypting M with key k_i.

Many commutative encryption algorithms exist, such as RSA [36] and one-time pad [37]. These algorithms have different complexity and security levels. Nodes can select a commutative encryption algorithm based on their specific requirements. The work in [19] adopts Pohlig-Hellman encryption to realize a commutative encryption algorithm with acceptable security and complexity.

IV. System Design of FaceChange

A. System Setup

Upon the bootstrap of the system, the TA first generates parameters for the adopted bilinear pairing, i.e., $BiParas$, the detail of which is introduced in Section III-C1. TA also selects a secure commutative encryption algorithm $\mathbb{E}()$ [19] and a collision-resistant hashing function $\mathcal{H}()$ [38], which are used for encountering evidence encryption. Additionally, TA generates a pair of public key and private key (PK_T, SK_T) through the public-key cryptography, e.g., RSA [36]. Finally, TA generates the system parameter $SysPara = (BiParas, \mathbb{E}(), \mathcal{H}(), PK_T)$, where $BiParas$ represents the bilinear pairing parameters

When a node N_i joins in the system, it registers to the TA through the following steps:

- N_i creates a pair of public/private key (PK_i, SK_i) by the same method used by TA and reports PK_i to TA.
- N_i fetches the system parameter $SysPara$ and its unique real ID NID_i from TA.

B. Neighbor Node Anonymity in FaceChange

Neighbor node anonymity means that each node does not know the real IDs of its neighbor nodes. To realize this goal, FaceChange lets each node communicate anonymously with neighbor nodes. Specifically, whenever a node disconnects with a neighbor node, it randomly changes its pseudonyms in all communication layers (e.g., MAC address, IP address and pseudonym) and communication parameters (e.g., signal strength), which will be used for the communication with the next encountered node. Note that both MAC and IP addresses can be easily modified through software [39].

Therefore, the pseudonyms and parameters used by a node are non-linkable. We further carefully design the encountering evidence generation and collection in FaceChange to ensure that neighbor node anonymity is maintained in these processes. Section IV-H1 gives out the final analysis to prove the neighbor node anonymity. For easy description, we use PID_i to uniformly represent node N_i's pseudonyms and NID_i to represent its unique real ID.

C. Challenges on Encountering Information Collection

In FaceChange, neighbor nodes communicate anonymously to protect their privacy. However, MOSN services require the real ID based encountering information. To solve such a problem, each node creates an encountering evidence for the other to learn the encountering information (e.g., whom it has met), as shown in Figure 2(a). To ensure neighbor anonymity, the encountering evidence is routed to the other node only after they separate from each other, as shown in Figure 2(b).

However, there are several challenges in this solution. First, the security of encountering evidences needs to be ensured against privacy leakage and fabrication during the routing. Second, the encountering evidence needs to be successfully and uniquely collected. Third, when creating an encountering evidence, a node may want to control the content in the evidence based on its trust on the encountering node. Sections IV-D, IV-E, and IV-F present the detail of proposed schemes that can solve the three challenges, respectively.

In the following, we use the case in which N_i creates an encountering evidence for N_j to illustrate the three schemes. The major notations are illustrated in Table I.

TABLE I: Notations.

Notation	**Meaning**
N_i	The i-th node in the MOSN
NID_i	The real ID of node N_i
$PID_i(t)$	The pseudonym of node N_i at time t
$\mathcal{EV}_{ij}(t)$	The encountering evidence generated by N_i for N_j at time t
$\mathcal{EV}'_{ij}(t)$	The encountering evidence $\mathcal{EV}_{ij}(t)$ after encryption
$\mathcal{Y}_i$	The encountering evidence generation policy of N_i
$\mathcal{S}_i$	The attribute set of N_i
$\mathcal{S}_{ti}$ & $\mathcal{S}_{vi}$	The type-based & value-based attribute subset of N_i
t_{ik}	The k-th type-based attribute of N_i
v_{ik}	The k-th value-based attribute of N_i
a_k & val_k	The name and value of v_{ik}
$\mathbb{E}(\cdot)$	The adopted commutative encryption algorithm
$Enc(\cdot)$	The adopted public-key encryption algorithm
$\mathcal{H}(\cdot)$	The adopted collision-resistant hashing function

D. Encountering Evidence Encryption and Validation

When N_i meets N_j, it creates an encountering evidence for N_j, denoted by $\mathcal{EV}_{ij}(t)$, to record their encountering. We introduce the encountering evidence creation process later in Section IV-F. N_i then routes $\mathcal{EV}_{ij}(t)$ to N_j after it disconnects with N_j. Since the evidence is routed by nodes in the network, its security and confidentiality needs to be ensured. In the following, we first introduce the detail of the proposed scheme and then present the security and cost analysis.

1) Ensuring the Security of Encountering Evidences: To protect the security of encountering evidences, FaceChange uses the bilinear pairing to generate the encryption key, token, and commitment. Generally, each of the two encountering nodes, i.e., N_i and N_j, first generates a random number, i.e., r and s. They then use $e(rP, sP)$ as the encryption key. They further reutilize s and r to generate the token and commitment as rP and $(s+\mathcal{H}(PID_j(t)))$, respectively, where $\mathcal{H}(PID_j(t))$ is the hashing value of the pseudonym of the recipient of the encountering evidence (i.e., N_j). The security analysis of this scheme is provided in Section IV-D2.

Specifically, N_i and N_j first select a random number $r \in \mathbb{Z}_q^*$ and $s \in \mathbb{Z}_q^*$, respectively. N_j selects a s that is not used by any commitments in its commitment list. N_j then sends sP and $(s + \mathcal{H}(PID_j(t)))P$ to N_i for the encryption key and token generation, where $\mathcal{H}(PID_j(t))$ is the hash of its pseudonym at the encountering time t.

$$N_j \rightarrow N_i : sP \quad and \quad (s + \mathcal{H}(PID_j(t)))P$$

N_i also randomly generates a key k_r. Then, N_i computes the encrypted encountering evidence as $\mathcal{EV}'_{ij}(t) = (Z_1, Z_2, Z_3, Z_4)$, where

$$\begin{cases} Z_1 = e(rP, P) = e(P, P)^r \\ Z_2 = e(rP, (s + \mathcal{H}(PID_j(t))P) \\ Z_3 = \mathbb{E}_{k_s}(\mathcal{EV}_{ij}(t)), \ k_s = e(rP, sP) \\ Z_4 = \mathbb{E}_{SK_i}(k_r) \end{cases} \tag{1}$$

In $\mathcal{EV}'_{ij}(t)$, Z_1 is the token, Z_2 is the verification number for the commitment, Z_3 is the encountering evidence encrypted by key k_s, and Z_4 is key k_r encrypted by private key SK_i.

N_i further sends its real ID encrypted by key k_r, i.e., $\mathbb{E}_{k_r}(NID_i)$, to N_j

$$N_i \rightarrow N_j : \mathbb{E}_{k_r}(NID_i)$$

Then, N_j computes the commitment as the following and inserts it into its commitment list.

$$CT_{js} : \quad < s + \mathcal{H}(PID_j(t)), \mathbb{E}_{k_r}(NID_i), s > \tag{2}$$

We can see that in this commitment, NID_i represents the ID of the node that N_j actually meets during the encountering corresponding to this commitment. It is stored in the commitment to prevent encountering evidence fabrication under eavesdropping, as introduced in the next subsection.

When N_j receives an encrypted encountering evidence $\mathcal{EV}'_{xj}(t_k) = (Z_1, Z_2, Z_3, Z_4)$, it checks whether Z_1 matches with any commitment in its commitment list. Suppose there is a commitment $CT_{ju} :< s + \mathcal{H}(PID_j(t_k)), \mathbb{E}_{k_r}(NID_x), u >$ satisfying $Z_1^{(s+\mathcal{H}(PID_j(t_k)))} = e(P, P)^{r(s+\mathcal{H}(PID_j(t_k)))} = Z_2$, this means that the received $\mathcal{EV}'_{xj}(t_k)$ matches the commitment based on the properties of bilinear pairing and the fact that the s in each commitment in the commitment list is unique. Then, Z_3 is decrypted with key $k_s = Z_1^u = e(P, P)^{ru} = e(rP, uP)$ to obtain the encountering evidence, and Z_4 is decrypted with the public key of N_x (learned from the evidence) to get k_r. After the verification, the commitment is removed from the commitment list.

2) Security Analysis for Evidence Encryption and Validation: The above scheme can ensure the confidentiality and uniqueness of each encountering evidence.

First, the privacy in the encountering evidence can be protected. Recall that in the encryption key generation process, N_j only sends $(s+\mathcal{H}(PID_j(t)))P$ and sP to N_i, and N_i only attaches $e(rP, P)$ to the encountering evidence. This means that a malicious node can at most know $(s+\mathcal{H}(PID_j(t)))P$, sP, and $e(rP, P)$, which are not sufficient to deduce the encryption key ($e(rP, sP)$). Therefore, an encountering evidence's contents are protected against nodes other than its creator and recipient.

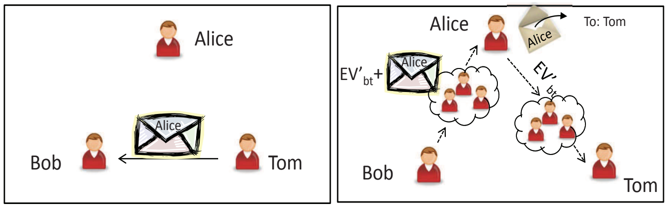
Second, the encountering evidence forgery can be prevented. Based on the discussion in Section III-C1, the token $e(rP, P)$ is uniquely matched with the commitment $s + \mathcal{H}(PID_j(t))$ with the specified verification item Z_2. Therefore, malicious nodes cannot create a valid token for fabricated encountering evidences that can pass the check on the recipient node without knowing $(s+\mathcal{H}(PID_j(t)))P$. However, a malicious node, say N_m, can eavesdrop the communication between N_i and N_j and know $(s+\mathcal{H}(PID_j(t)))P$. Then, it can generate a random number r^* and a key k_r^* to forge an encrypted encountering evidence $\mathcal{EV}'_{mj}(t)$ as the following.

$$\begin{cases} Z_1^* = e(r^*P, P) \\ Z_2^* = e(r^*P, (s + \mathcal{H}(PID_j(t)))P) \\ Z_3^* = \mathbb{E}_{k_s}(\mathcal{EV}_{mj}(t)), \ k_s = e(r^*P, sP) \\ Z_4^* = \mathbb{E}_{SK_m}(k_r^*) \end{cases} \tag{3}$$

We can see that ${Z_1^*}^{s+\mathcal{H}(PID_j(t))} = e(r^*P, (s + \mathcal{H}(PID_j(t)))P) = Z_2^*$, which means that the faked encountering evidence matches the commitment created for the encountering between N_i and N_j. Then, N_m can make N_j believe a non-existing encountering. However, the design of $\mathbb{E}_{k_r}(NID_i)$ in the commitment can prevent this attack. This is because the decryption of $\mathbb{E}_{k_r}(NID_i)$ with k_r^* would lead to an ID that is different with the one claimed in the faked evidence $\mathcal{EV}_{mj}(t)$. This decrypted ID can be regarded as some sort of random since it is encrypted by one key and decrypted by another key. Then, N_j can know that it is not a valid ID based on the list of legal user IDs in the system and drop the faked encountering evidence shown in Formula (3). As a result, FaceChange ensures the uniqueness of each encountering evidence.

Furthermore, as shown in [40], the k-CAA (collusion attack algorithm with k traitors) can hardly work in above commitment scheme. That is, given $(P, Q = sP, h_1, h_2, \cdots, h_k \in \mathbb{Z}_q^* \ and \ (h_1 + s)P, (h_2 + s)P, \cdots, (h_k + s)P)$, there is no polynomial-time algorithm that can compute $(h^* + s)P$ for some $h^* \notin \{h_1, h_2, \cdots, h_k\}$ with non-negligible probability. This means that a commitment $((s + \mathcal{H}(PID_j(t)))P)$ can hardly be forged by nodes other than its creator (N_j). Therefore, even when a malicious node can intrude another node, it cannot purposely create commitments on the node that can match the tokens in fabricated encountering evidences.

Third, impersonating another node without knowing its private key is thwarted due to the design of Z_4. For example, suppose node N_m pretends to be node N_i in the meeting with node N_j. In this case, when N_j receives the encountering



(a) Select the relay node.

(b) Relay to the recipient.

Fig. 3: Relaying encountering evidence to the recipient.

evidence, it would decrypt Z_4 with the public key of N_i, leading to a wrong k_r (because Z_4 is encrypted with the private key of N_m). Consequently, the decryption of $\mathbb{E}_{k_r}(NID_i)$ in the commitment would lead to an ID that is different with what claimed in the encountering evidence (i.e. N_i).

Forth, the encryption and commitment generation process does not break the neighbor node anonymity. Specifically, since s is randomly generated and $PID_j(t)$ is a non-linkable pseudonym, the sP and $(s + \mathcal{H}(PID_j(t)))P$ transmitted by N_j are different at the encountering with different nodes and thus are not linkable. Similarly, the $\mathbb{E}_{k_r}(NID_i)$ transmitted by N_j is not linkable because k_r is randomly selected. Other than this, no other information is exchanged among the two nodes for encryption and commitment generation. As a result, the neighbor node anonymity is kept in this process.

3) Cost Analysis: In the commitment generation process, bilinear pairing accounts for major computing. As introduced in [11], we can use Tate pairing, in which each element in $\mathbb{G}$ is 512-bit and q is a 160-bit prime. The computation cost for a pairing then is around 8.5 ms in a Pentium III 1GHz machine [11]. Therefore, considering modern devices (e.g., smartphones) usually have similar or higher capacity than such a machine, the cost of the bilinear pairing is acceptable.

E. Encountering Evidence Relaying Scheme

After disconnecting with N_j, N_i routes the created encountering evidence to N_j. However, due to node anonymity, N_i cannot know the real ID of N_j, which is the recipient of the evidence. We propose an encountering evidence relay scheme to solve this problem. In this scheme, during the encountering, the recipient node N_j specifies a relay node and encrypts its real ID with the public key of the relay node. Such data is forwarded to the evidence creator N_i. Then, after the two nodes disconnect, the creator routes the encountering evidence to the relay node, which first decrypts the recipient node's real ID and then routes the evidence to the recipient node.

Figure 3 demonstrates this scheme. When Bob and Tom meets, Tom informs Bob that the encountering evidence should be relayed by Alice and inserts its real ID inside the envelope. His real ID can only be seen by Alice and cannot be seen by Bob. Then, when Alice receives it, as shown in Figure 3(b), it finds that the recipient is Tom and routes the encountering evidence to Tom. The two clouds in Figure 3(b) mean that the message is routed by nodes in the system.

In the following, we first introduce the details of the relay scheme and then present the security and cost analysis.

1) Relay Node Selection: In this process, to prevent privacy leakage, we do not allow the two nodes (i.e., N_j and N_i) to communicate to select the relay node. Instead, the recipient node of an encountering evidence, say N_j, randomly selects a relay node from the set of nodes it trusts. A trusted node refers to the node that is believed to keep its private key secure (i.e., does not share it with any other nodes). Otherwise, neighbor anonymity may be broken during the encountering. This is because, when two nodes meet, each node encrypts its real ID with the public key of the relay node and sends that to the encountered node (detail in Section IV-E2). Then, if the relay node's private key is disclosed, the real ID is no longer safe.

Inappropriately selected relay node may make N_j easily trackable. For example, suppose the selected relay node is N_r, and it can be possibly selected by only a few nodes, say m nodes. Then, when a malicious node finds that a neighbor node specifies N_r as the relay node, it has a probability of $1/m$ to deduce that the neighbor node is N_j. It can further combine such information with the location information to enhance the success rate. Such a problem can be alleviated in a network when the following conditions are satisfied 1) the system includes a large number of nodes, 2) each node has a large number of trusted relay nodes, and 3) relay nodes are shared across a large number of nodes in the system. This means that a relay node may be used by many nodes, and a node may have many potential relay nodes.

However, such requirements may not always be satisfied. We then further propose an advanced relay node selection algorithm that can enhance the anonymity protection in this process. In this scheme, we let the TA selects a set of trusted nodes for all nodes. The TA itself can also be a trusted relay node. Each node then just randomly selects one relay node from the set of trusted nodes obtained from the TA for encountering evidence relay. As a result, since all nodes share the same set of trusted nodes, it would be hard to deduce the real ID of a node from the relay node it selects.

Both schemes have advantages and disadvantages. By letting each node select the relay node, the relaying load is distributed in the network, and the encountering evidences can reach the recipient nodes quickly. However, the anonymity may suffer attacks in this case. By selecting relaying nodes from the set of nodes provided by the TA, node anonymity can be better protected. However, with this method, the encountering evidence relaying load is concentrated on those relay nodes, and the relaying delay cannot be controlled. The system administrator can select a suitable relaying scheme based on application requirements.

2) Relaying the Encountering Evidence: We use RN to denote the selected relay node. The recipient node, i.e., N_j, generates a random key k_y to encrypt its real ID, i.e., $\mathbb{E}_{k_y}(NID_j)$, and then encrypts k_y with the public key of the relay node: $Enc_{PK_r}(k_y)$. $\mathbb{E}$ and Enc refer to the commutative encryption algorithm and the public-key encryption algorithm, respectively. Then, N_j sends both encrypted items to N_i when they are still neighbors of each other. The design of k_y is to prevent disclosing N_j's real ID. That is, if N_j forwards $Enc_{PK_r}(NID_j)$ directly to N_i, N_i can deduce N_j since it knows PK_r and all real IDs in the system. Finally, N_i

generates the encountering message as below.

$$(RN, Enc_{PK_r}(k_y), \mathbb{E}_{k_y}(NID_j), \mathcal{EV}'_{ij}(t)), Sign_{SK_i}(\mathcal{EV}'_{ij}(t))) \quad (4)$$

where RN denotes the relay node, $\mathcal{EV}'_{ij}(t)$ is the encrypted encountering evidence (Formula (1)), and $Sign_{SK_i}(\mathcal{EV}'_{ij}(t))$ is a signature generated by N_i that can ensure the integrity and authenticity of the encrypted evidence.

After the two nodes separate, N_i routes the message to RN. Upon receiving the message, RN decrypts $Enc_{PK_r}(k_y)$ with its private key SK_r and knows that the recipient of the message is NID_j. Then, it routes below to N_j:

$$(NID_j, \mathcal{EV}'_{ij}(t), Sign_{SK_i}(\mathcal{EV}'_{ij}(t))) \quad (5)$$

After receiving the above message, N_j can obtain the encountering evidence from $\mathcal{EV}'_{ij}(t)$ by following the decryption procedure mentioned in Section IV-D1.

We adopt MOSN routing algorithms, e.g., RAPID [1] and PROPHET [41], to route an encountering evidence to the relay node or N_j. The delay of such routing usually is large, and some packets may fail to reach the destination, as shown in Section VI-B, since they use the hop-by-hop relay to forward packets and assume no network infrastructure. However, we can import network infrastructures to reduce the routing delay and ensure evidence delivery (i.e., allow packets with a large delay to be forwarded through infrastructures).

3) Security Analysis for Evidence Relaying: The designed scheme can provide secure encountering evidence relay.

First, the confidentiality of the encountering evidence is maintained. The content of $\mathcal{EV}'_{ij}(t)$ cannot be seen by any intermediate nodes. This is because the encryption key k_s is only known by N_i and N_j, as proven in Section IV-D2. Further, the signature of the encrypted encountering evidence $\mathcal{EV}'_{ij}(t)$ in the relayed message, as shown in Formulas (4) and (5), ensures its integrity and authenticity.

Second, by requiring N_j to select relay node only from nodes it trusts, the possibility that N_i and the selected relay node RN collude can be greatly limited in FaceChange. Otherwise, by colluding with RN, N_i can know the private key of RN (PK_r) and know N_j's real ID during the encountering.

Third, since the relay node is selected by N_j, it may collude with the relay node or even use itself as the relay node. However, even in such an attack, N_j still cannot know the real ID of N_i during the encountering. This is because N_i forwards the encountering message to other nodes only after it separates with N_j. Then, when N_j receives the message from another node, say N_x, it cannot determine that N_x is N_i since N_x may be a node that just relays the message.

Fourth, the neighbor node anonymity is maintained in the relay node selection process. The real IDs of N_i and N_j are not disclosed in the encountering message generation process. Only N_j tells N_i its encrypted real ID. Also, since N_j randomly generates the k_y, the $Enc_{PK_r}(k_y)$ and $\mathbb{E}_{k_y}(NID_j)$ transmitted by N_j are different in each encountering and thus are not linkable. Further, as mentioned in Section IV-E, N_i and N_j are not allowed to communicate to decide the relay node. The advanced relay node selection algorithm introduced in Section IV-E1 can prevent a node from being tracked by the relay node it selects. As a result, no linkable information is leaked in this process.

4) Cost Analysis: The extra costs in this step are mainly from the encountering evidence relaying. In MOSNs, nodes usually are sparsely distributed and meet opportunistically, which means that the number of encountering evidences in a unit time is limited. Further, an encountering evidence only contains simple information with a limited size. It can be attached to the packet routing with no additional processing. Therefore, the cost on relaying encountering evidences is constrained and will not drain the network resources.

F. Encountering Evidence Generation Scheme

We introduce how to create encountering evidence when two nodes meet in a privacy-preserving manner in this section. The basic idea is to create the encountering evidence based on the trust. In FaceChange, each node, say N_i, maintains a policy, $\mathcal{Y}_i$, to decide what information can be included in the encountering evidence for each trust level. Below, we first define attributes and evidence creation policy and then present the encountering evidence generation process. We also present the security and cost analysis of this scheme in the end.

1) Attribute Definition: Both type-based and value-based attributes are supported in FaceChange. The type-based attributes, e.g., organization and interests, refer to those that represent certain properties with no numerical meaning. The value-based attributes, e.g., reputation and age, refer to those that can be represented by numeric values. How a node's attributes are obtained is not the focus of this paper. We do not index the type-based attributes with numeric values, i.e., using 1 to represent the university name, to make a uniform attribute expression. This is because 1) such a value is still a symbol with no numeric meaning and cannot be compared, and 2) this needs pre-definition and limits the attribute scalability.

Then, the attribute set of a node, say N_i, can be expressed as $\mathcal{S}_i : \{y_{i1}, y_{i2}, y_{i3}, \cdots, v_{i1}, v_{i2}, v_{i3}, \cdots\}$, where y_{im} and v_{in} represent a type-based attribute and a value-based attribute, respectively. v_{in} is represented as a $[name : value]$ pair. For example, the attribute set of a student can be expressed as $\mathcal{S}_i : \{ABCUniv., Student, [reputation : 0.8], [age : 20]\}$.

2) Evidence Creation Policy: when creating the encountering evidence, a mobile node may wish to control what information to disclose to an encountered node to ensure both security and application needs. For example, in a packet routing, a node may wish to disclose nothing to a non-trustable node, as the node may be an attacker. It may want to disclose basic encountering information (i.e., ID, location and time) to a node that is moderately trustworthy, thus supporting packet routing while protecting some privacy. It may disclose basic encountering information plus social status to a trustable node, which can be used to realize more efficient packet routing.

Therefore, the general rule of the evidence creation policy is the more trustable an encountered node is, the more information can be disclosed. In MOSNs, as nodes are anonymized during the encountering, traditional trust system cannot offer trust information to encountered nodes. We thus follow the concept in [12], [42] to decide a node's trust on an encountering node based on the similarity between attributes.

Generally, the evidence creation policy on a node determines the amount of information in the encountering evidence by comparing the match value on attributes with a set of thresholds i.e., $\{T_1, T_2, \cdots, T_n\}$. As different nodes have different sensitivity or rationales on privacy protection, we allow nodes to determine the values of those thresholds and the information corresponding to each threshold by themselves.

We give an example of the evidence generation policy on node N_i in the following.

- If $MatchV \leq T_1$, this means that N_j is not trustable. Then, N_i does not create the encountering evidence.
- If $T_1 < MatchV \leq T_2$, N_i creates an evidence with basic encountering information, such as the real ID of N_i (NID_i) and the encountering time and location.
- If $T_2 < MatchV$, N_i creates an evidence with full information, including basic encountering information and additional information that can facilitate packet routing (e.g., network centrality, social status, etc.).

Note that basic encountering information should be included as a whole and cannot be split for finer granularity. This is because a node's own encounter records can help infer certain encountering information. For example, when N_i receives the encountering evidence from node N_j saying that they have met at time T_1. Then, node N_i can search its encounter records and find the encountering location, even though it is not included in the encountering evidence.

3) Blind Attribute Checking: FaceChange utilizes the commutative encryption and the solution for "the millionaire's problem" [20] to calculate the match value blindly.

The attribute set of N_i, denoted $\mathcal{S}_i$, can be split into two subsets consisting of the two types of attributes: $\mathcal{S}_i = \{\mathcal{S}_{yi} \cup \mathcal{S}_{vi}\}$, where $\mathcal{S}_{yi}$ and $\mathcal{S}_{vi}$ represent the type-based attribute subset and the value-based attribute subset, respectively. We introduce how to calculate their match value separately.

Calculating the Match Value between Type-based Attribute Subsets ($|\mathcal{S}_{yi} \cap \mathcal{S}_{yj}|$): $|\mathcal{S}_{yi} \cap \mathcal{S}_{yj}|$ is calculated as the number of shared attributes in the two subsets. This process is conducted without disclosing each node's attributes by using a commutative encryption algorithm.

Specifically, N_i and N_j first select a random encryption key, say k_i and k_j, respectively. Then, each node encrypts the attributes in its type-based attribute subset with its encryption key. As a result, N_i has $\mathcal{S}'_{yi} = \{\mathbb{E}_{k_i}(y_{i1}), \mathbb{E}_{k_i}(_{i2}), \mathbb{E}_{k_i}(y_{i3}), \cdots\}$ and N_j has $\mathcal{S}'_{yj} = \{\mathbb{E}_{k_j}(y_{j1}), \mathbb{E}_{k_j}(y_{j2}), \mathbb{E}_{k_j}(y_{j3}), \cdots\}$. Then, each node sends the encrypted attributes to the other node.

$$N_i \rightarrow N_j : \mathcal{S}'_{yi} \quad and \quad N_j \rightarrow N_i : \mathcal{S}'_{yj}$$

Upon receiving $\mathcal{S}'_{yi}$ and $\mathcal{S}'_{yj}$, each node again encrypts each encrypted attribute with its key. Then, N_i has $\mathcal{S}''_{yj} = \{\mathbb{E}_{k_i}(\mathbb{E}_{k_j}(y_{j1})), \mathbb{E}_{k_i}(\mathbb{E}_{k_j}(y_{j2})), \mathbb{E}_{k_i}(\mathbb{E}_{k_j}(y_{j3})), \cdots\}$, and N_j has $\mathcal{S}''_{yi} = \{\mathbb{E}_{k_j}(\mathbb{E}_{k_i}(y_{i1})), \mathbb{E}_{k_j}(\mathbb{E}_{k_i}(y_{i2})), \mathbb{E}_{k_j}(\mathbb{E}_{k_i}(y_{i3})), \cdots\}$. After the second round of encryption, each node further sends the encrypted attributes to the other node.

$$N_i \rightarrow N_j : \mathcal{S}''_{yj} \quad and \quad N_j \rightarrow N_i : \mathcal{S}''_{yi}$$

Then, the two nodes have both $\mathcal{S}''_{yi}$ and $\mathcal{S}''_{yj}$. They can check the number of the same attributes in $\mathcal{S}''_{yi}$ and $\mathcal{S}''_{yj}$ based on the aforementioned property of the commutative encryption: if $\mathbb{E}_{k_j}(\mathbb{E}_{k_i}(y_{ia})) = \mathbb{E}_{k_i}(\mathbb{E}_{k_j}(y_{jb}))$, then $y_{ia} = y_{jb}$.

Calculating the Match Value between Value-based Attribute Subsets ($|\mathcal{S}_{vi} \cap \mathcal{S}_{vj}|$): In this paper, we define $|\mathcal{S}_{vi} \cap \mathcal{S}_{vj}|$ as the number of N_j's value-based attributes that satisfy N_i's requirement on their values. In FaceChange, a node's requirement on a value-based attribute is represented by a threshold and an indication on the comparison direction, i.e., larger or smaller than the threshold. Specifically, suppose N_i's requirement on attribute a_n is $(VT_{ia_n}, \geq)$. Then, N_j's attribute $v_{jn} = [a_n, val_n]$ satisfies N_i's requirement if $val_n \geq VT_{ia_n}$.

The rationale for such a design is that the value of a value-based attribute often has a certain meaning. For example, the reputation of a node represents how trustable it is in a certain application. Then, a node can determine whether a value-based attribute is trustable based on its value and use the number of trustable attributes to calculate the match value. Therefore, each node is required to determine a set of requirements for value-based attributes, i.e., $\{(VT_{ia_1}, \geq), (VT_{ia_2}, <), \cdots\}$, for encountering evidence generation, which is regarded as a part of its encountering evidence generation policy.

In detail, $|\mathcal{S}_{vi} \cap \mathcal{S}_{vj}|$ is calculated by the following steps:

- N_i and N_j first decide the list of names of value-based attributes to compare, e.g., $\{a_1, a_2, a_3, \cdots\}$, and handle those names one by one.
- For each attribute name, say a_x, N_i picks its requirement for it: $(VT_{ia_x}, \geq)$, and N_j picks its value: v_{jx}.
- N_i and N_j compare VT_{ia_x} and v_{jx} by the solution for "the millionaire's problem" [20] without disclosing the values of VT_{ia_x} and v_{jx} to the other node.
- N_i checks whether the result satisfies the comparison direction (i.e., whether $v_{jx} \geq VT_{ia_x}$). If yes, $|\mathcal{S}_{vi} \cap \mathcal{S}_{vj}|$ increases by one. Otherwise, it remains unchanged.

The solution for "the millionaire's problem" enables two people ($Alice$ and Bob), each of whom has one number, to compare their numbers without disclosing their values. Please refer to [20] for the detail of this algorithm. We assume equal weight for each attribute in this paper. We can easily expand current design to the case with different attribute weights.

Calculating the Total Match Value The total match value $MatchV$ is calculated as the weighted sum of the two types of match value: $MatchV = \alpha * |\mathcal{S}_{yi} \cap \mathcal{S}_{yj}| + (1-\alpha) * |\mathcal{S}_{vi} \cap \mathcal{S}_{vj}|$, where $\alpha \in [0, 1]$. The value of α can be changed node by node to reflect its preference. We set it to 0.5 by default to show equal importance of the two types of match value.

4) Fine-grained Evidence Generation: In summary, when N_i meets N_j at t, N_i first calculates the match value of its attribute set with that of N_j blindly (i.e., $MatchV = |\mathcal{S}_i \cap \mathcal{S}_j|$), as in Section IV-F3. Then, $MatchV$ is applied to its encountering evidence creation policy $\mathcal{Y}_i$ to decide what information can be included in the encountering evidence, as in Section IV-F2. Finally, N_i creates the evidence $\mathcal{EV}_{ij}(t)$ accordingly.

5) Security Analysis on Evidence Generation: First, with the commutative encryption, N_i cannot know the type-based attributes of N_j from $\mathcal{S}'_{yj}$ since it is encrypted by k_j, which is not known by N_i. Similarly, N_j cannot know the type-based attributes of N_i either. This means that $|\mathcal{S}_{yi} \cap \mathcal{S}_{yj}|$ is calculated blindly. Second, with the solution to "the millionaire's problem", N_i obtains $|\mathcal{S}_{vi} \cap \mathcal{S}_{vj}|$ blindly, i.e., without disclosing its thresholds or knowing the values of N_j's value-based attributes. In summary, attributes are compared blindly in FaceChange, thereby protecting node privacy.

6) Cost Analysis: The extra costs in blind policy checking are incurred by the commutative encryption and the solution for "the millionaire's problem". For the commutative encryption algorithm, we can choose a suitable one to control the complexity. Note that a good property of our scheme is that the key used by a node can change after each policy checking. Then, simple commutative encryption algorithm, e.g., XOR, can provide reliable encryption at a low cost.

The complexity of the solution for "the millionaire's problem" is $O(d^2)$ [20], where d is the length of the binary representation of the compared value. While d can be controlled to be 8, i.e. char, the extra cost for this step is acceptable.

G. Realizing General Packet Routing in FaceChange

In this section, we take packet routing as a case to show how a MOSN service is realized under FaceChage.

1) Routing Utility Update: The received encountering evidences on each node are utilized to update the routing utility used for packet routing. One common routing utility is the future meeting probability with a node.

However, encountering evidences may not arrive in the same order in which they are created due to the opportunistic packet routing in MOSNs. Therefore, FaceChange adopts a cache period, denoted T_c, to maximally solve this problem. When a node receives an encountering evidence, it stores it in its memory. At the end of the N-th cache period ($N > 2$), i.e, at $N * T_c$, the received encountering evidences that are created before $(N-1) * T_c$ are handled in the order of their creation times to update related routing utilities.

2) Packet Routing Process: In traditional MOSN packet routing, two encountering nodes first delivers packets destined for the other node. They then compare routing utilities and forward the other node packets that the other node has a higher routing utility for their destinations.

In FaceChange, neighbor node anonymity blocks the first step by preventing nodes from recognizing the destinations of their packets even when meeting them. To solve this problem, we let each node claim to have higher routing utility for itself to fetch packets for it. In detail, N_i only tells N_j that it is more suitable to carry packets for N_i (i.e., has higher routing utility for N_i). Then N_j would send packets destined for N_i to N_i even under neighbor node anonymity. We use the case that N_j needs to decide which packets should be forwarded to a newly met node, say N_i, to show such a solution.

- N_j sends N_i the destinations of its packets along with its routing utilities for these destinations: $\{des_1 : u_{j1}, des_2 : u_{j2}, des_3 : u_{j3}, \cdots\}$, where u_{j1} denotes N_j's routing utility for destination des_1.
- For each received destination, say des_x, N_i compares its routing utility for des_x, denoted u_{ix}, with that of N_j (u_{jx}). If $u_{ix} > u_{jx}$, N_i inserts des_x into a forward list.
- If the list of destinations received from N_j contains N_i, N_i inserts its ID into the forward list directly.
- Finally, N_i sends the forward list to N_j, which then forwards packets destined for nodes in the list to N_i.

In above process, N_i tells N_j that it is more suitable to carry packets for itself (N_i) to capture packets destined for it under neighbor node anonymity. Following the above scheme, nodes can correctly compare utilities to forward packets and deliver packets to their destinations, thereby ensuring general MOSN packet routing in FaceChange.

H. Security Analysis of FaceChange

We further analyze how FaceChange ensures node anonymity and the security of the encountering evidence collection from the perspective of the system.

1) Ensuring Neighbor Node Anonymity: First, neighbor nodes are anonymized in FaceChange by constantly changing their pseudonyms (Section IV-B). The encountering evidence relaying scheme (Section IV-E) allows two nodes to collect the encountering information without disclosing their real IDs during the encountering, as proven in Section IV-E3.

Second, nodes cannot be linked in FaceChange. As previously explained, two neighbor nodes do not transmit any linkable information in encountering evidence encryption/commitment (Section IV-D2), encountering evidence collection (Section IV-E3), and encountering evidence generation (Section IV-F5). To receive packets destined for it, a node just claims to be a better forwarder for these packets. As a result, a node cannot be linked by tracking packets for it. In summary, no linkable information of a node is disclosed.

The two features ensure that node anonymity is maintained. Since neighbor nodes are anonymized and none linkable information of a node is disclosed, creating many sybils cannot help deduce the real ID of a neighbor node.

2) Ensuring Encountering Information Collection: The encountering information can be confidentially and correctly collected by nodes in FaceChange. As introduced in Section IV-D2 and Section IV-E3, the encryption key k_y and the signature ensure the confidentiality, integrity, and authenticity of each encountering evidence.

3) Preventing Fabricating Encountering: With the commitment scheme introduced in Section IV-D, nodes cannot claim non-existing encountering with others. As introduced in Section IV-D2, the generated token and commitment are uniquely matched, which prevents attackers from arbitrarily creating fake encountering evidences. A commitment is deleted after a successful match, which prevents attackers from poisoning the system by re-sending overheard evidences.

Malicious nodes may eavesdrop commitment parameters to forge an encountering evidence that can pass the commitment verification. However, this can be prevented since the creator of the forged evidence cannot be the same with the one in the commitment (Section IV-D2). Furthermore, there is no polynomial-time algorithm that can generate a fake commitment on a node with non-negligible probability. Then, even the intruder of a node cannot create commitments for its forged encountering evidences on the node.

4) Preventing Eavesdropping: FaceChange can prevent malicious nodes from acquiring meaningful private information by overhearing the encountering evidences and packets transmitted between two nodes. First, as mentioned in Section IV-D, the encountering evidence is encrypted by a key originated from two randomly generated numbers from the two encountering nodes, which are not disclosed in the network. Then, the eavesdropper cannot understand the content in the transmitted encountering evidences. Second, in MOSN routing, the receiver of a packet is not necessary the destination of the packet. As a result, the eavesdropper cannot determine the ID of a node based on packets it receives.

5) Preventing Tracking Attack: We define the "tracking" attack as the ability to track a node, though the node's real ID is not disclosed. Such an attack does not work in FaceChange. First, the non-linkable pseudonym (Section IV-B) prevents a node from identifying the same neighbor node. Second, as mentioned in Section IV-D, the information exchanged between two encountering nodes for evidence encryption and commitment generation is non-linkable. Third, as introduced in Sections IV-D2 and IV-E3, neighbor node anonymity is kept during encountering evidence encryption and relaying without disclosing linkable information. Fourth, as mentioned in Section IV-G, each node claims to be a better forwarder for packets and messages, i.e., Equations (4) and (5), destined for it, thus preventing malicious nodes from tracking a node by following packets/messages for it. Consequently, malicious node cannot continuously track a node through disclosed information in FaceChange.

V. Advanced Extensions

We have further designed three extensions to enhance FaceChange's practicality. The first extension, motivated by our daily experiences, designs a scheme to support the function of "white list" on top of FaceChange. It allows mutual-trusted nodes to collect the encountering information during the encountering directly. The second extension enhances the efficiency of the encountering evidence relaying by letting the recipient node specify more information about how to reach it. The third extension reduces the memory consumption in the process of encountering evidence collection. The details of the three extensions are introduced in the following.

A. White List

The design of FaceChange introduced in Section IV realizes strong anonymity among neighbors at the cost of indirect encountering information collection. However, in reality, we commonly see that a person has a few trusted peers and is willing to share his/her real identity with them during the encountering. Therefore, we further propose an advanced scheme to allow such a feature among mobile devices in FaceChange, which is named "white list" in this paper.

Since neighbor anonymity still needs to be maintained, we need to realize two functions to enable the "white list" feature. First, we need to enable anonymous trusted node identification, i.e., nodes can discover trusted nodes anonymously. Second, we need to ensure that two trusted nodes can share their real identifies secretly under eavesdropping.

1) Building the White List: We adopt a token based scheme to identify trusted nodes. When two nodes, say N_i and N_j, determine that they are trustworthy to each other, they would notify the TA about such a relationship. The TA then randomly generates a token that has not been used so far, denoted W_{ij}, for the two nodes with an associated TTL, after which the token will expire. The TA relays the token to both N_i and N_j. As a result, with such a scheme, each node will maintain a token list denoting all trustworthy relationships it has established so far.

2) Discovering Trusted Nodes: When two nodes, say N_i and N_j, meet, they first communicate to determine whether the "white list" feature is enabled. If not, they follow the basic FaceChange for encountering information collection. If yes, they identify whether they trust each other anonymously by exploiting the commutative encryption algorithm [19].

We use the example when N_i and N_j want to verify whether they are trustworthy to each other to demonstrate this process. We use GTK_i and GTK_j to denote the list of tokens hold by N_i and N_j, respectively. Both nodes first generate an encryption key randomly, denoted wk_i and wk_j. Then, N_i encrypts every token in GTK_i with wk_i, and N_j encrypts every token in GTK_j with wk_j. After this, both nodes send encrypted tokens to the other node, as shown in the following

$$N_i \rightarrow N_j : \mathbb{E}_{wk_i}(GTK_i) \quad and \quad N_j \rightarrow N_i : \mathbb{E}_{wk_j}(GTK_j)$$

where the encryption of a token list (i.e., $\mathbb{E}_{wk_i}(GTK_i)$ and $\mathbb{E}_{wk_j}(GTK_j)$) means encrypting every token in the list with the corresponding key. Both nodes further encrypt the received token list with their keys. After this step, N_i holds $\mathbb{E}_{wk_i}(\mathbb{E}_{wk_j}(GTK_j))$, and N_j holds $\mathbb{E}_{wk_j}(\mathbb{E}_{wk_i}(GTK_i))$. N_j then sends $\mathbb{E}_{wk_j}(\mathbb{E}_{wk_i}(GTK_i))$ to N_i for verification.

Finally, N_i tries to find one encrypted token that exists in both $\mathbb{E}_{wk_j}(\mathbb{E}_{wk_i}(GTK_i))$ and $\mathbb{E}_{wk_i}(\mathbb{E}_{wk_j}(GTK_j))$. If yes, this means that GTK_i and GTK_j share one common token. This is because the commutative encryption ensures that the same token, say W_{ij}, encrypted by key wk_i and wk_j in different sequences would generate the same result, i.e., $\mathbb{E}_{wk_i}(\mathbb{E}_{wk_j}(W_{ij})) = \mathbb{E}_{wk_j}(\mathbb{E}_{wk_i}(W_{ij}))$. Such a common token means that there is a token denoting the trustworthy relationship between N_i and N_j.

3) Information Exchange among Trusted Nodes: After determining that they are trustworthy to each other, N_i and N_j will share their real IDs with each other during the encountering. However, they cannot communicate with clear text directly since we assume the existence of eavesdroppers in this paper. To solve this problem, they can establish an encryption key through the Diffie-Hellman key exchange algorithm [43] to thwart eavesdroppers.

4) Security Analysis: The proposed "white list" scheme does not break neighbor node anonymity or make nodes trackable. First, when two nodes check whether they are trustworthy to each other, all tokens are encrypted by a key before being sent out to the other node. As a result, tokens owned by each node are not disclosed to other nodes, which prevents malicious nodes from learning tokens owned by others and claiming non-existing trustworthy relationships. Second, the key used to encrypt tokens is randomly generated for each encountering. As a result, the tokens transmitted by each node change from time to time, thus avoiding from being tracked by others based on the transmitted tokens. Each node can further enhance its anonymity by adding non-existing fake tokens to its token list in the verification. Then, the number of tokens it presents also changes in each encountering. Since the fake tokens used by a node do not exist on other nodes, they would not mistakenly validate a non-existing trustworthy relationship.

B. Advanced Encountering Evidence Relaying

The design of FaceChange in Section IV-E relies on the underlying MOSN routing algorithm to forward an encountering evidence from its creator to the relay node and from the relay node to the recipient node. As shown in later in Section VI-B, this leads to extra delays on encountering evidence collection. Therefore, we further design an extension to enhance the efficiency of the encountering evidence relaying.

The proposed scheme enables the community based routing that shows better routing efficiency in mobile opportunistic social networks [2], [5], [7], [22]. Such a routing method assumes that communities have been created based on node encountering records. Nodes in one community have a higher probability to meet with each other than with others. In such a method, a packet is first forwarded to the community holding the destination node and then relies on intra-community forwarding to reach the destination node. Thus, this routing algorithm requires each node to know the community to which the destination node of each packet it holds belongs to.

We solve this problem by letting the recipient node specify such information. Specifically, when a recipient node sends the information of the relay node to the creator of the encountering evidence, it attaches the community ID of the relay node and its own community ID that has been encrypted with the public key of the relay node. Consequently, the encountering evidence creator can use the community ID of the relay node to conduct community based routing to forward the encountering evidence to the relay node. After receiving the encountering evidence, the relay node can decrypt the community ID of the recipient node and use such information to forward the encountering evidence to the recipient node more efficiently. In this process, each node only discloses its encrypted community ID to neighboring nodes, which can only be decrypted by the selected relay node. As a result, the node anonymity is not broken in such an advanced extension.

VI. Performance Evaluation

In this section, we mainly examine the performance of the baseline FaceChange without advanced extensions unless otherwise explicitly indicated. Specifically, we evaluate FaceChange's performance on neighbor node anonymity, encountering evidence collection, packet routing, and energy consumption in Sections VI-A, VI-B, VI-C, VI-D, respectively. The performance of the advanced extensions proposed in Section V is evaluated in Section VI-E.

We adopted two real traces in the tests: the MIT Reality trace [44] and the Haggle project trace [45]. The former trace records the meetings between students and teachers on MIT campus for about 30 days, while the latter trace includes the encountering between scholars attending Infocom 2006 for about 4 days. We adopt the two traces since they represent typical MOSN scenarios in which mobile devices meet opportunistically. We wrote an event-driven simulator for the experiment. The connectivity between nodes is inferred from contact times in the trace.

Since there is no record of the distance between two encountered nodes in the trace, we assume a moderate data transmission rate of 500 kbs between encountered nodes in the simulation. The encountering duration follows the record in the trace. We also assume that the size of each packet is 200 kb, and each node has a memory size of 10 Mb. During each encountering, each node randomly selects one node from the top 5 most frequently met nodes as the relay node.

We adopted PROPHET [41] as the underlying routing algorithm for baseline FaceChange in the experiments. In PROPHET, each node maintains its future meeting probabilities with other nodes based on previous records to guide packet routing. When testing the advanced encountering evidence relaying proposed in Section V-B, we adopted a community based routing algorithm named BubbleRap [22].

A. Effectiveness of Privacy Protection

We first evaluate the effect of privacy protection. In this test, we measured the privacy leakage as duplicate pseudonyms (i.e., the average number of identical pseudonyms seen by a node) and disclosed IDs (i.e., the number of identical pseudonyms used by a node). The pseudonyms include those advertised by each node for the communication with neighbor nodes and encrypted IDs in the encountering evidences.

TABLE II: Effectiveness of Privacy Protection.

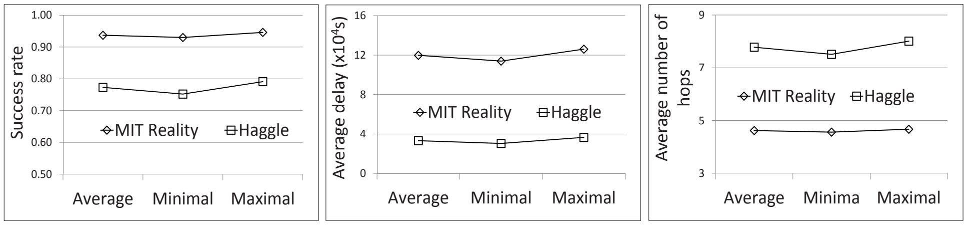
	Duplicate Pseudonyms	Disclosed IDs
MIT Reality	8	0
Haggle	4	0

The test results are shown in Table II. We found that only few identical pseudonyms can be seen by each node and all identical pseudonyms are from different nodes in the system in the experiments with both traces. This means that nodes cannot use the transmitted pseudonyms to identify neighbor nodes. Such a result in conjunction with the analysis in Sections IV-B, IV-D2, IV-E3, and IV-F5 justify that FaceChange can effectively protect node privacy.

B. Efficiency of the Encountering Evidence Collection

In this test, we measured the success rate, average delay, and average number of hops of collected encountering evidences. The success rate refers to the percentage of successfully collected encountering evidences. The average delay and average hops denote the time and the forwarding hops each collected encountering evidence experiences on average. The test results are shown in Figure 4.

We see from the figure that the success rates reach about 93% and 77% in the tests with the MIT Reality trace and the Haggle trace, respectively. This shows that most encountering



(a) Success rate. (b) Average delay. (c) Average number of hops.

Fig. 4: Evidence Collection Efficiency with Both Traces.

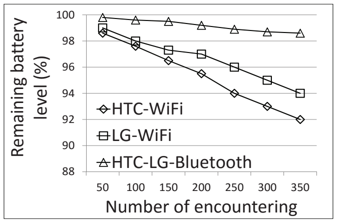


Fig. 5: Energy consumption in real test.

evidences can be successfully collected in FaceChange. The success rate is low in the Haggle trace because some nodes only exist for a short period of time in the trace.

We find that the average delays are about 120,000 seconds and 33,000 seconds in the tests with the two traces, respectively. Since the encountering frequencies between nodes in MOSNs usually follow a certain pattern, such delays do not degrade the packet routing efficiency significantly, as shown in next section. We also find that the average number of hops is small in the tests. This shows that the extra costs on encountering evidence relay are acceptable in FaceChange.

Combining the above results, we conclude that FaceChange can enable nodes to collect encountering evidences efficiently with acceptable costs. Therefore, it can well support MOSN applications, which will be demonstrated in next section by taking the packet routing as an example.

C. Influence on Packet Routing

We also evaluated the efficiency of PROPHET under FaceChange. In the test, 15,000 packets were generated with randomly selected sources and destinations. Since encountering evidence may not arrive at a node sequentially following their creation times, we cache each arrived evidence for a period of time (T_c) before processing it for packet routing. We varied T_c in this test to see its influence. We measured success rate and average delay in the test. The former refers to the percentage of successfully delivered packets and the latter refers to the average delay of these packets.

1) Success Rate: The success rates of the two methods in the tests with the two traces are shown in Figure 6(a) and Figure 7(a), respectively. We see that FaceChange has higher success rate than PROPHET for most of T_c values in tests with both traces. This is because in PROPHET, the meeting probability is updated immediately after an encountering happens, which may cause it deviate from the average value due to a burst on meeting nodes, leading to inaccurate packet forwarding. FaceChange has a delay in handing the encountering evidences, so it can calculate the meeting probability more fairly. Such a result demonstrates that FaceChange does not degrade the success rate of packet routing in MOSNs.

We also find that when T_c further grows, the success rate of FaceChange decreases in the test with the Haggle trace. This is because when T_c is very large, the meeting probabilities are not updated quickly enough to reflect the changes on meeting frequencies among nodes, leading to inaccurate guidance on packet routing and degraded success rate.

2) Average Delay: The average delays of the two methods in the tests with the two traces are shown in Figure 6(b) and Figure 7(b), respectively. We find that FaceChange has smaller delay than PROPHET, which is caused by the same reasons as explained in the previous subsection.

Combining the above results, we conclude that FaceChange can efficiently support packet routing in MOSNs.

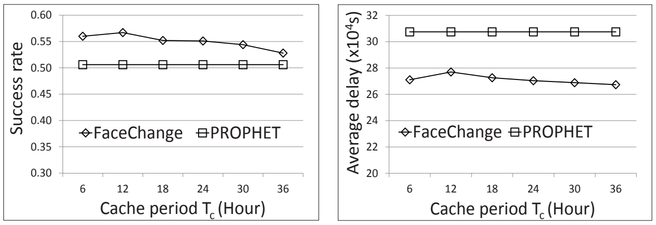
D. Energy Consumption

To evaluate the energy consumption of FaceChange, we conducted experiments with two Windows Phones: HTC Surround and LG Quantum. We tested the key components in FaceChange, i.e., blind policy checking and packet/encountering evidence relaying, with two wireless technologies. We first let the two phones communicate with a server through WiFi and then let the two phones communicate with each other through Bluetooth. We did not include the energy cost of bilinear pairing since it has been proven to be acceptable in a previous literature [11]. Since WiFi and Bluetooth have been mature in smart phones, we believe our results also apply to Android and iOS smart phones.

All phones were restored to factory setting and were fully charged before each test. We measured the energy consumption as the percentage of remaining battery level after certain rounds of encountering. In blind policy checking, we assume each phone has 5 type-based attributes and 5 value-based attributes. In packet and encountering evidence relaying, we assume a phone exchanges N_p packets and N_e evidences in each encountering. N_p and N_e were randomly obtained from [100, 300]. Such a setting matches the situation in the real trace. We measured the percentage of remaining battery level after every 50 encounters. Each test was run for 10 times. The test results are shown in Figure 5.

We see from the figure that 50 encounters consume roughly about 1% of total battery with WiFi and 0.2% with Bluetooth. Note that such results do not show the energy consumption when WiFi or Bluetooth is always turned on for neighbor discovery, which will be high for WiFi and low for Bluetooth. We focus on the additional cost incurred by the data exchange incurred by FaceChange between encountered nodes, which is shown to be acceptable for modern devices.

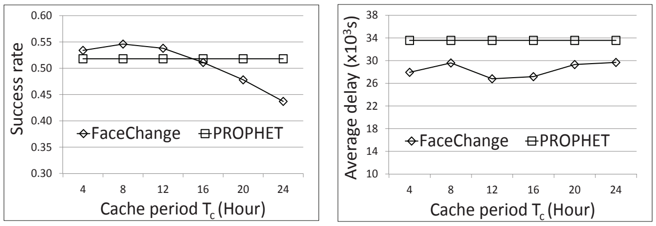
We further examined the real traces and found that each person (node) has 117 and 340 encounters every day on average in the MIT Reality trace and the Haggle trace, respectively. Combining with the results in the figure, we can see that FaceChange only consumes a small amount of total battery



(a) Success rate.

(b) Average delay.

Fig. 6: Packet routing efficiency with the MIT Reality trace.



(a) Success rate.

(b) Average delay.

Fig. 7: Packet routing efficiency with the Haggle trace.

daily in the crowd conference scenario. This demonstrates the applicability of FaceChange in real applications.

E. Evaluation of Advanced Extensions

In this section, we evaluate the three advanced extensions introduced in Section V.

1) White List: The security of the "white list" feature has been analyzed in Section V-A4. We further check how frequently such a feature can help nodes learn the encountering information immediately during the encountering. In this test, we let each node select four frequently met nodes as friends, i.e., mutually trusted nodes. When two friends meet, they can identity each other anonymously and share real IDs directly without the need of creating encountering evidences. We then measured the number of encountering evidences generated in the two traces with and without the "white list" feature.

TABLE III: Number of Encountering Evidences.

	with "White List"	without "White List"
MIT Reality	122817	275872
Haggle	113687	148448

We see from Table III that the number of encountering evidence is greatly reduced when each node selects only four trusted nodes in both traces. The reduction in the MIT Reality trace is higher than that in the Haggle trace because nodes in it meet more frequently with socially close nodes. Such results demonstrate that the "white list" feature can effectively enhance the efficiency of encountering information collection.

2) Advanced Encountering Evidence Relaying: In this section, we evaluate the performance of the advanced encountering evidence relaying scheme proposed in Section V-B. We followed our previous work in [7] to detect communities in which nodes share frequent contact. We identified 7 and 8 communities in the MIT Reality trace and the Haggle trace, respectively. Such community information is then used to assist the relaying of the encountering evidence. For better illustration, we have disabled the "white list" feature and only adopt the baseline FaceChange in this test.

TABLE IV: Average Success Rate.

	with Advanced Relaying	without Advanced Relaying
MIT Reality	0.949	0.937
Haggle	0.81	0.773

TABLE V: Average Delay (s).

	with Advanced Relaying	without Advanced Relaying
MIT Reality	112091	119773
Haggle	32407	33200

The test results on average success rate and average delay are shown in Table IV and Table V, respectively. We found from the two tables that when the advanced relaying scheme (i.e., community based routing) is applied, encountering evidences can be more effectively collected with higher success rate and lower average delay.

VII. Conclusion

In this paper, we propose FaceChange, a system that supports both neighbor anonymity and real ID based encountering information collection in MOSNs. In FaceChange, each node continually changes its pseudonyms and parameters when communicating with neighbors nodes to hide its real ID. Encountering evidences are then created to enable nodes to collect the real ID based encountering information. After two encountering nodes disconnect, the encountering evidence is relayed to the encountering node through a selected relay node. Practical techniques are adopted in these steps to ensure the security and efficiency of the encountering evidence collection. Trust based control over what information can be included in the encountering evidence is supported in FaceChange. Advanced extensions have also been proposed to support the "white list" feature and enhance the encountering evidence relaying efficiency. Extensive analysis and experiments are conducted to prove the effectiveness and energy efficiency of FaceChange in protecting node privacy and supporting the encountering information collection in MOSNs. In the future, we plan to investigate how to generalize the process about how to adapt applications in mobile opportunistic social networks to FaceChange seamlessly.

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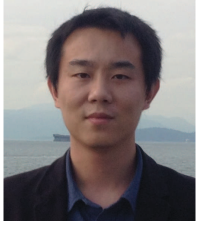

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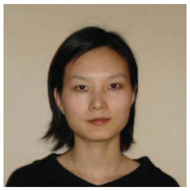

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