Security and Privacy Preservation in Mobile Social Networks

by

Xiaohui Liang

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I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Social networking extending the social circle of people has already become an important integral part of our daily lives. As reported by ComScore, social networking sites such as Facebook and Twitter have reached 82 percent of the world's online population, representing 1.2 billion users around the world. In the meantime, fueled by the dramatic advancements of smartphones and the ubiquitous connections of Bluetooth/WiFi/3G/LTE networks, social networking further becomes available for mobile users and keeps them posted on the up-to-date worldwide news and messages from their friends and families anytime anywhere. The convergence of social networking, advanced smartphones, and stable network infrastructures brings us a pervasive and omnipotent communication platform, named mobile social network (MSN), helping us stay connected better than ever. In the MSN, multiple communication techniques help users to launch a variety of applications in multiple communication domains including single-user domain, two-user domain, user-chain domain, and user-star domain. Within different communication domains, promising mobile applications are fostered. For example, nearby friend search application can be launched in the two-user or user-chain domains to help a user find other physically-close peers who have similar interests and preferences; local service providers disseminate advertising information to nearby users in the user-star domain; and health monitoring enables users to check the physiological signals in the single-user domain.

Despite the tremendous benefits brought by the MSN, it still faces many technique challenges among of which security and privacy protections are the most important ones as smartphones are vulnerable to security attacks, users easily neglect their privacy preservation, and mutual trust relationships are difficult to be established in the MSN. In this thesis, we explore the unique characteristics and study typical research issues of the MSN. We conduct our research with a focus on security and privacy preservation while considering human factors. Specifically, we consider the profile matching application in the two-user domain, the cooperative data forwarding in the user-chain domain, the trustworthy service evaluation application in the user-star domain, and the healthcare monitoring application in the single-user domain. The main contributions are, i) considering the human comparison behavior and privacy requirements, we first propose a novel family of comparison-based privacy-preserving profile matching (PPM) protocols. The proposed protocols enable two users to obtain comparison results of attribute values in their profiles, while the attribute values are not disclosed. Taking user anonymity requirement as an evaluation metric, we analyze the anonymity protection of the proposed protocols. From the analysis, we found that the more comparison results are disclosed, the less anonymity protection is achieved by the protocol. Further, we explore the pseudonym strategy and

an anonymity enhancing technique where users could be self-aware of the anonymity risk level and take appropriate actions when needed; ii) considering the inherent MSN nature — opportunistic networking, we propose a cooperative privacy-preserving data forwarding (PDF) protocol to help users forward data to other users. We indicate that privacy and effective data forwarding are two conflicting goals: the cooperative data forwarding could be severely interrupted or even disabled when the privacy preservation of users is applied, because without sharing personal information users become unrecognizable to each other and the social interactions are no longer traceable. We explore the morality model of users from classic social theory, and use game-theoretic approach to obtain the optimal data forwarding strategy. Through simulation results, we show that the proposed cooperative data strategy can achieve both the privacy preservation and the forwarding efficiency; iii) to establish the trust relationship in a distributed MSN is a challenging task. We propose a trustworthy service evaluation (TSE) system, to help users exchange their service reviews toward local vendors. However, vendors and users could be the potential attackers aiming to disrupt the TSE system. We then consider the review attacks, i.e., vendors rejecting and modifying the authentic reviews of users, and the Sybil attacks, i.e., users abusing their pseudonyms to generate fake reviews. To prevent these attacks, we explore the token technique, the aggregate signature, and the secret sharing techniques. Simulation results show the security and the effectiveness of the TSE system can be guaranteed; iv) to improve the efficiency and reliability of communications in the single-user domain, we propose a prediction-based secure and reliable routing framework (PSR). It can be integrated with any specific routing protocol to improve the latter's reliability and prevent data injection attacks during data communication. We show that the regularity of body gesture can be learned and applied by body sensors such that the route with the highest predicted link quality can always be chose for data forwarding. The security analysis and simulation results show that the PSR significantly increases routing efficiency and reliability with or without the data injection attacks.

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Dedication

To my family and teachers from whom I have learned so much.

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List of Abbreviations

MSN	Mobile Social Network
MANET	Mobile Ad hoc Network
SenN	Sensor Network
DTN	Delay Tolerant Network
VANET	Vehicular Ad hoc Network
PPM	Privacy-preserving Profile Matching
PDF	Privacy-preserving Data Forwarding
TSE	Trustworthy Service Evaluation
bTSE	Basic Trustworthy Service Evaluation
SrTSE	Sybil-resisted Trustworthy Service Evaluation
PSR	Prediction-based Secure and Reliable Routing
LSP	Local Service Provider
ISP	Internet Service Provider
TA	Trusted Authority
AR	Autoregressive
FHE	Fully Homomorphic Encryption
HBC	Honest-But-Curious Adversary Model
eCPM	Explicit Comparison-based Profile Matching
iCPM	Implicit Comparison-based Profile Matching
iPPM	Implicit Predicate-based Profile Matching
MNDPR	Minimum Number of Distinct Protocol Runs

Chapter 1

Introduction

1.1 Mobile Social Network and Applications

Social networking makes digital communication technologies sharpening tools for extending the social circle of people. It has already become an important integral part of our daily lives, enabling us to contact our friends and families. In the meantime, fueled by the pervasive adoption of smartphones, users have a growing tendency to access their social networks more often by smartphones via pervasive networking infrastructures than desktop computers or laptops [1]. With smartphones, users are able to check the digital personal schedules when lying in bed; read and reply to emails in the meeting room; contact friends to have a lunch together on the way to the mall; and send photos to families in the tourist areas. In other words, users can apply various communication techniques to share and request information to and from different kinds of information sources, and users are capable to choose the comfortable techniques to create and manage of social networking applications. The convergence of social networking, advanced smartphones, and various communication techniques brings us a pervasive and omnipotent communication platform, named mobile social network (MSN), helping us stay connected better than ever.

Over the past decade, smartphones evolve dramatically from appearance to functionality; they are no longer the clumsy devices with basic calling and messaging functions but nice-looking and portable "toys" with integrated sensing functions and countless mobile applications. Observing the potential commercial opportunity, developers and researchers design a wide range of mobile applications for different scenarios to keep up with the demand from users. As such, in nowadays, the MSN becomes the most popular communication platform with countless mobile applications. It also becomes a research focus

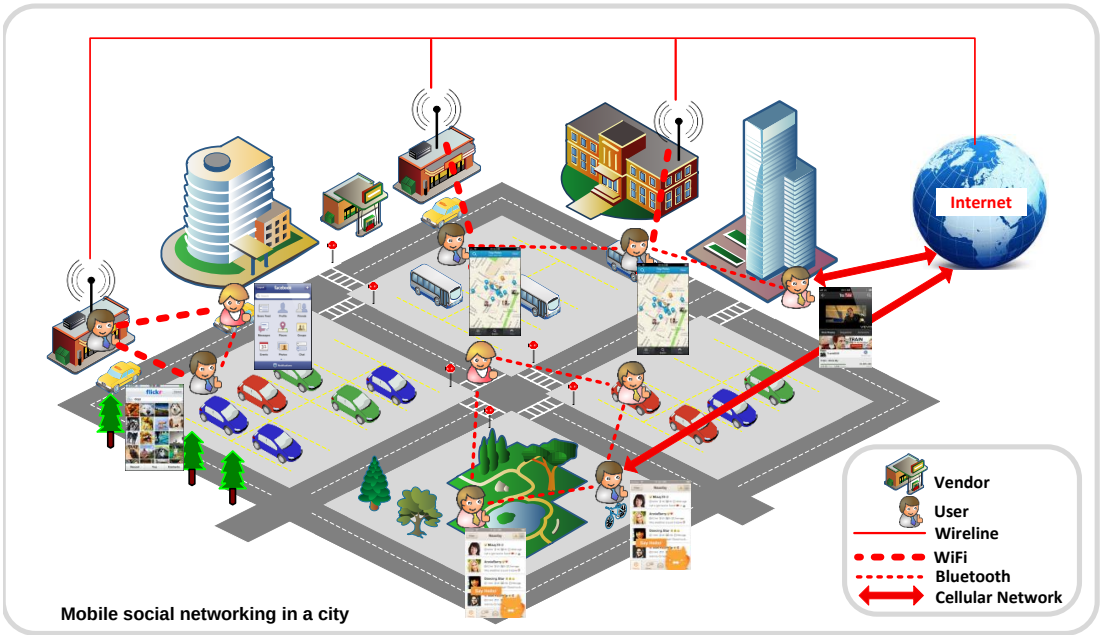


Figure 1.1: Mobile social network

where many research challenges and solutions become much urgent to be explored. In this section, we present the MSN architecture by introducing the communication entities, the communication patterns, and the MSN characteristics [2].

1.1.1 MSN Communication Entities

An MSN, as shown in Fig. 1.1, is a virtual environment composed of the users moving in a local geographical area, the local service providers (LSPs), and the Internet service providers (ISPs). It is formed upon the agreement of the participating users and LSPs. If a user/LSP is fully non-cooperative, the user/LSP should not belong to the MSN.

Smartphone Users

The users are able to not only access the Internet via cellular/WiFi networks but also communicate with neighboring users via Bluetooth and near field communication (NFC) techniques. The users choose the communication technologies for different applications. For example, the users may choose the Internet to obtain the service information, and

use Bluetooth to communicate with nearby users to obtain the service reviews. The users also consider their mobility model and their social behavior patterns when choosing the communication techniques.

Local Service Providers

The LSPs, either mobile or static, provide services to the users in vicinity. When an LSP is mobile, it can be equipped with a smartphone which disseminates service information to the encountered users. When an LSP is static, it could be a local shopping store or a restaurant that are visited by nearby users. The static LSP is equipped with better communication and storage devices which are placed on, in or around their buildings.

Internet Service Providers

The mobile access to the Internet service becomes available due to the pervasive deployment of cellular network infrastructures. Besides, the users can also access the Internet via WiFi hotspots which are widely distributed in restaurants, shopping malls, or even residential communities. As a result, the ISPs can be reached almost anytime anywhere. They provide service information to the users in the MSN whenever and wherever the users need it.

1.1.2 MSN Communication Patterns and Techniques

The communication patterns in the MSN can be generally divided into user-to-ISP, user-to-LSP, and user-to-user categories.

User-to-ISP

Two common communication techniques that are enabled on smartphones help user-to-ISP communications. One is the cellular networks. The users purchase the data plan from communication companies, such as Rogers and Bell. Their smartphones can connect to the Internet through the cellular network infrastructures maintained by the companies. For example, the users spend \$5/\$17/\$37 to purchase a monthly plan which provides 10mb/250mb/5gb Internet data to their smartphones. The other one is the WiFi technique. Compared to the previous, WiFi technique can offer the pervasive Internet access at cheaper costs and larger bandwidth. Many local service providers integrate the free WiFi access into their commercial business solutions. For example, the Canadian-wide coffee shop Tim

Hortons work with Bell Canada to roll out the national free WiFi service to more than 2,000 Tim Hortons locations in September 2012. In addition, more commercial solutions are developed by companies FatPort and Fon, encouraging distributed WiFi hotspots to cooperatively share the Internet access to nearby users.

User-to-LSP

The user-and-LSP communications help the users better obtain the service information of nearby LSPs. The communication techniques can be short-ranged wireless communications, such as WiFi and Bluetooth. Due to the easy-to-setup and low costs, many LSPs have been equipped with wireless routers to offer the Internet access to its customers. In other words, these LSPs are connected to its customers through WiFi. In addition, when the LSPs are mobile, they can carry smartphones and send the service information to the encountered users via Bluetooth.

User-to-User

When the users launch the autonomous mobile applications, the user-to-user communication helps the users share information in an efficient way. Bluetooth and NFC which are both short-range communication techniques that are integrated into smartphones to implement the user-to-user communication. NFC operates at slower speeds than Bluetooth, but consumes far less power and doesn't require pairing. NFC sets up more quickly than standard Bluetooth, but has a lower transfer rate than Bluetooth low energy. With a maximum working distance of less than 20 cm, NFC has a shorter range, which reduces the likelihood of unwanted interception. It makes NFC particularly suitable for crowded areas. In comparison, Bluetooth supports 1-100 m wireless communication range, more suitable for the users at distances to share information.

1.1.3 MSN Applications

The boom of mobile applications is one of the important factors to the MSN development. It is reported from WiKi that the Apple Company has greatly increased the number of mobile applications from 800 in July 2008 to over 825,000 in April 2013. Generally, the applications can be divided into four categories.

Mobile Version of Online Social Applications

The first category is the mobile version of online social applications which enables users to check social updates, share photos and watch online videos in a mobile environment. Successful online social applications such as Facebook and Youtube have been extended to a mobile version for smartphones.

Nowadays, hardware specifications of smartphones have been improved to the level of personal computers, along with friendly interface improvements and usability enhancements. In parallel to that, the deployment of 3G and LTE networks has considerably improved the available mobile bandwidth, enabling the provisioning of content and services powered by the ISPs. When the users launch the applications, they are able to quickly download/upload data from/to the ISPs.

With the mobile version of online social applications, the users have the capability to send the information out to the world in a fast and easy way, such as updating online status or changing head photos in their online spaces. The pervasive use of the applications raise a security issue, i.e., malicious attackers with the Internet access at any place is able to keep tracking other users' behavior. As such, when sharing any personal information, the users need to be careful about whether the personal information disclosure is necessary or not.

Location-based Applications

In addition to voice service available for any cellular telephone, smartphones distinguish themselves by powerful computing resources and, most significantly, their capability to understand their surrounding environments through many sensors that are built into them. As a result, the second category, called location-based application, becomes one of the most popular. It utilizes the information downloaded from the Internet to assist location-based activities. Such applications are widely supported by either social network giants like Facebook, or specialized service providers like Foursquare or Loopt. They work in the following way: the GPS chips detect the location coordinates of the users who then report the coordinates to the ISPs for downloading the information related to local services.

Foursquare is a typical location-based application that allows registered users to post their location at a venue ("check-in") and connect with friends. One can check into a certain floor/area of a building, or indicate a specific activity while at a venue. Users can choose to have their check-ins posted on their accounts on Twitter or Facebook.

Figure 1.2: Mobile version of online social applications and location-based applications

In addition, when the ISPs collect users' locations and categorize users' interests, they can not only provide location-based services but also coordinate users with similar interests and close locations to encourage more local social activities. They can further reveal the social relations under users' agreements to help them establish mutual trust and improve the communication security and efficiency. For example, the Google Latitude service enables users to visualize the locations of nearby friends on a map and launch social activities such as chatting or collaborative information filtering.

In general, the location-based application including Foursquare, collects and utilizes the locations which are most privacy-sensitive to the users. Inappropriate disclosure of locations to potential attacks may put the users' lives in danger or cause property loss.

Autonomous Mobile Applications

The third category is named autonomous mobile applications where the users are able to connect to neighboring users and LSPs through short-ranged wireless communications such as WiFi, Bluetooth, and NFC. For example, the nearby information search application [3] helps a user consult her nearby friends, who in turn will ask their friends, and so on, until the information is found. The users are not required to have the Internet connection. Besides, navigating for information via neighboring users could be better than the Internet search because the information from neighborhood is often more personalized, localized, and quickly updated. In addition, It is very likely that the information from other local users provide more trustable details for better service selections [4].

Carpool and ride sharing are promising solutions to the problems of urban growth and heavy traffic with more cars [5]. The increasing use of vehicle sharing and public transport is a simple, more effective way to reduce emissions as compared with the approach of producing slightly more energy efficient vehicles at a high cost. Carpooling also has a strong impact on the mode of commuting at the workplace level by only offering information, incentives and a partner matching program. Financial incentives such as reduced parking costs or fuel subsidies can drive that share higher [6]. However, in practise, users may not be willing to publish their privacy-sensitive destinations making the carpool information very limited. In the autonomous mobile applications, the direct communications between two smartphones can help users share the destinations in real-time and establish the trust relations in a distributed manner such that the chance to obtain a ride sharing largely increases.

Smartphones with mobile healthcare systems assist the seniors who have the same symptom to exchange their experiences, give mutual support and inspiration to each other [7]. The chat between two seniors can be initialized with the first step to check if they have similar experience and want to share information with each other. The autonomous mobile applications can also significantly contribute to the current medical systems.

Body Area Applications

The last category is named body area application. Recent advances in microcircuits and medical sensing have made it possible to deploy battery-powered miniaturized sensors on, in or around the human body for long-term healthcare monitoring and falling detection [8–10]. These body sensors report their sensory data to a smartphone via wireless communication channels. Then, under user's control, the smartphone can transmit the data to a remote healthcare agency via the Internet or trigger an alarm when some abnormal conditions

are detected. The body sensors and the sink together constitute a small-scale wireless sensor network, called wireless body area network (WBAN). The WBAN is particularly suitable for monitoring people having chronic diseases or working and living under extreme conditions, and help these people to know their health conditions in real-time. With the WBAN and the smartphone, the body area applications can be further extended to an emergency situation, i.e., after the body area application detects the emergency and trigger the alarm, the autonomous mobile application helps users send an emergency call to nearby people and find emergency medical care as quickly as possible [11].

1.2 MSN Characteristics

The MSN has its unique characteristics different from other traditional networks. The following Table 1.1 enumerates the typical characteristics of mobile ad hoc networks (MANET) [12–14], sensor networks (SenN) [15–17], delay tolerant networks (DTN) [18–21], vehicular ad hoc networks (VANET) [21–25], and mobile social network (MSN) [3, 4, 7, 26–32]. ◯ means the network is not limited to one specific definition in that aspect. It is summarized that the key component of the MSN is human who have a full control of their smartphones. As such, the network topology relies on the human mobility. Many research works have adopted either synthetic mobility model [33, 34] or trace-based mobility model [35–38] to evaluate the performance of their protocols. Besides, human social preferences and the security and privacy concerns impact the communication behavior of users. In the following, we will discuss the MSN characteristics in details.

Table 1.1: Comparison of network characteristics

	MANET	SenN	DTN	VANET	MSN
Node	◯	Sensors	◯	Vehicles	Human
Node Mobility	Random	Static	◯	On-Road	Human mobility
Node Connectivity	◯	Good	Poor	◯	◯
Network Infrastructure	No	Sink	No	RSU	No
Typical Research Issue	Routing	Coverage	Routing	Application	Application
Security	◯	Sensitive	◯	◯	Highly-sensitive

1.2.1 Multiple Communication Domains

The MSN has multiple communication domains where users could have various applications in each domain. In this thesis, we consider single-user communication domain, two-user

communication domain, user-chain communication domain, and user-star communication domain where we have study the applications for these domains.

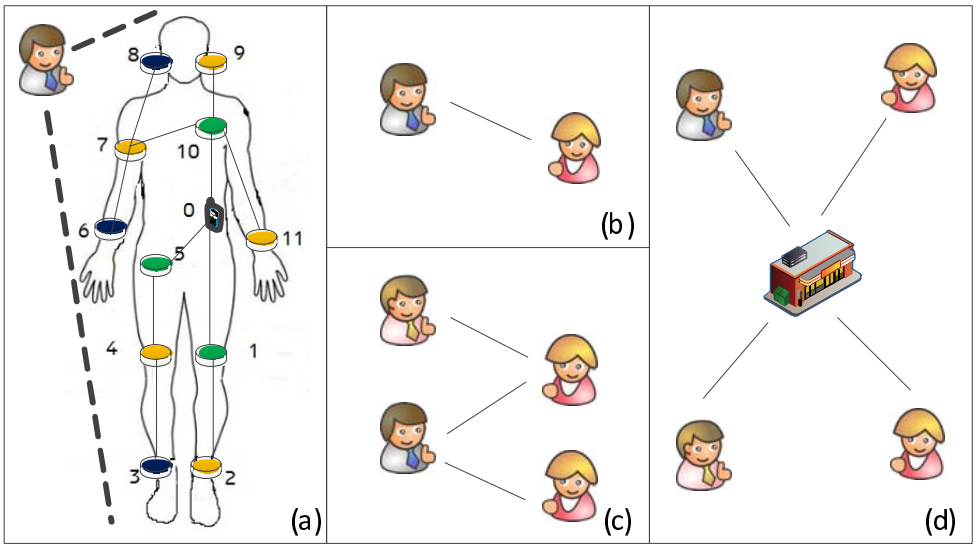


Figure 1.3: Communication domains in the MSN

Single-user communication domain: As shown in Fig. 1.3(a), a user is equipped with a smartphone and multiple body sensors which cooperatively communicate to support body-related applications, such as healthcare monitoring and falling detection.

Two-user communication domain: As shown in Fig. 1.3(b), any two users run a two-user communication protocol in order to obtain the personal information from the opponents, e.g., they want to know who the opponent is and what interests the opponent has. In the MSN, the typical application can be profile matching.

User-chain communication domain: As shown in Fig. 1.3(c), multiple users are connected in a chain structure to cooperatively forward the data from the start user of the chain to the end user of the chain. Due to the human mobility, the construction of chains depends on every user's selection of next-hop user. In the MSN, the typical applications can be data forwarding and information searching.

User-star communication domain: As shown in Fig. 1.3(d), multiple users are connected in a star topology where the central user receives and sends the data from and to multiple users nearby. In the MSN, the typical application can be trustworthy service evaluation, i.e., the central user could be a vendor who needs to receive the service reviews from the nearby users and disseminate its service information.

1.2.2 Social Behavior

User social behavior is of great importance to the design of communication protocols of the MSN. In the following, we review some interesting perspectives from the social theories.

Social works [39–41] indicate that in a fully autonomous system users behave independently based on the rational calculation of expediency. The decision on how to act in social interactions is viewed as either primarily economic and motivated by self-interest, or non-economic and motivated by collective interest and moral obligation. Different norms govern users' behavior in economic and non-economic spheres of activity, and appropriate behavior varies according to the context and the nature of the goods being exchanged. These norms are not just learned, but are incorporated by social users into their personalities. In reality, if users violate a deeply internalized norm, they would feel guilty to certain extent regardless of whether or not anyone else knew of their actions, and would likely "punish" themselves in some manner. The incentive from self-interest is known as social selfishness, while the incentive from collective interest or moral obligation is known as social morality.

Social study [42] also indicates that individuals who experience feeling of guilt (compared to individuals who feel no guilt) after pursuing a non-cooperative strategy in the first round of play, display higher levels of cooperation in the subsequent round of play. Experimental results demonstrate that non-cooperative individuals who experience a certain level of guilt in a social bargaining game may use this feeling state as "information" about the future costs of pursuing a non-cooperative strategy. Their findings that the guilt manipulation interacted with social motives (e.g., guilt tended to have its intense effect on non-cooperative individuals) also suggest that these results do not occur merely because of pre-existing individual differences in the tendency to cooperate or defect. Instead, it would appear that guilt actually provokes non-cooperative individuals to depart from their "typical" strategy of non-cooperative behavior.

The MSN users are often considered as rational and selfish entities which aim to maximize their own utility [20, 43]. Especially when privacy enhancing technique is adopted, non-cooperative behavior is hardly overcome because users act anonymously. According to the social theories, users will always choose the behavior considering both selfishness and morality. In the design of data forwarding protocols, selfishness and morality need to be considered interactively. In Chapter 4, a game theoretic approach [29] will be adopted to calculate the user utility of communications.

1.2.3 Social Graph

Social graph theory plays an important role in the cooperative communications of the MSN. Because user mobility is highly dynamic and unpredictable, the traditional data forwarding and dissemination protocols do not work efficiently in the MSN. Many research works [44, 45] indicate that the social relations and behaviors among the MSN users are built in a long-term fashion, which could be used to improve the communication efficiency. Specifically, from social graph theory, social community and centrality can be directly applied. For example, users in reality are often grouped based on their common interests. Sociologists found that these users are more likely to interact with the same-community members [46, 47]. Thus, many research works [48–50] consider that users may encounter with another in the same community at a high probability and propose to utilize this social characteristic to better select the relays for data forwarding. Other research works [51–53] aim to identify communities from the contacts in real traces [35, 36]. Besides, centrality is another important metric in the social graph to evaluate the capability of connecting other users. To build data forwarding protocols based on this feature also improves the delivery delay [54]. In the design of anonymity enhancing techniques (Chapter 3), the social community concept will be applied.

1.2.4 Security and Privacy

Trust Problem

Trust is the fundamental of mobile applications. The mobile applications can be only adopted by the users if the users have trust on the ISPs, the LSPs, and other users. While the users enjoy the conveniences brought by the mobile applications that are maintained by the ISPs, they realize that more and more personal information is revealed to the ISPs and start questioning how the ISPs keep the collected personal information, e.g., will the ISPs disclose the information for other purposes without proper consent. Some research works [55, 56] suggest that the users only disclose fuzzy identity and location information to the ISPs for privacy preservation.

Social community is a platform to build social relations among people who, for example, share interests, activities, backgrounds, or real-life connections. In the MSN, social community implies the trust relationships, and help the users and the LSPs build the trust relationships in a distributed way. When two users know that they belong to the same social community (university and company) or have some common interests (sports or tastes), they have a feeling that each other is more reliable and the shared opinions are

more trustful. Some research works [28,31,57] develop privacy-preserving profile matching protocols to help two users obtain the common interests. Besides, social ties representing the relationships between two users are the foundation for effective collaboration. In the MSN, the strength of social ties can be used to facilitate effective data forwarding [20,29] and service recommendation [58].

Private Information leakage

Private information, such as identities, pseudonyms, locations, and profiles, may be revealed in most mobile applications to some extent. The small amount of private information of a user has not been particularly correlated because the user is not the interest. In fact, the social networking plus mobile applications can be easily used to trace a user's behavior, if the user does not intentionally protect himself.

Research efforts [27, 59, 60] have been put on identification and privacy concerns in social networking sites. Gross and Acquisti [59] argued that users are putting themselves at risk both offline (e.g., stalking) and online (e.g., identity theft) based on a behavior analysis of more than 4,000 students who have joined a popular social networking site. Stutzman [60] presented a quantitative analysis of identity information disclosure in social network communities and subjective opinions from students regarding identity protection and information disclosure. When the social networking platforms are extended into the mobile environment, users require more extensive privacy-preservation because they are unfamiliar with the neighbors in close vicinity who may eavesdrop, store, and correlate their personal information at different time periods and locations. Once the personal information is correlated to the location information, the behavior of users will be completely disclosed to the public. Chen and Rahman [27] surveyed various mobile Social Networking Applications (SNAs), such as, neighborhood exploring applications, mobile-specific SNAs, and content-sharing applications, all of which provide no feedback or control mechanisms to users and may cause inappropriate location and identity information disclosure. Some research works [20] suggest to use past social contact history to facilitate the packet forwarding in the future, while not considering that the social contacts are privacy-sensitive and could be never shared by the users. Besides, the private information leakage in the profile matching protocols [7,21,26–29,31,57,61,62] also attracts great research efforts.

Malicious Behavior

Most mobile applications are ineffective at the presence of the users' malicious behavior. For example, in the cooperative packet forwarding, if the users always expect others' help

but refuse to help others, the cooperative packet forwarding may never succeed; in the trustworthy service evaluation (TSE) system, if the LSPs and the users can arbitrarily add positive reviews and delete negative reviews, the users cannot receive authentic and useful reviews and stop running the applications. Some research works [20, 29] consider social selfishness and social morality into the calculation of utility, and explore novel packet forwarding protocols. Some research work [58] studies the review attacks and the sybil attacks and propose corresponding defensive mechanisms in the distributed TSE system.

Forgery attacks are very typical attacks in a distributed environment. Since users know little about others, the forgery attacks can easily happen. As a defense mechanism, cryptographic signature scheme [63] can be used to resist such attacks. For example, group signature [64, 65] can prevent non-group members from forging a signature of group members. However, in the profile matching protocol [26, 28, 31, 57], forgery attacks on the profile matching are hardly resisted. In other words, users are able to arbitrarily choose forged profiles while other users cannot detect such behavior. Research works [28, 31] have to consider the honest-but-curious model where users honestly follow the protocol but act curiously to guess others' profiles. The work [26] requires users to make commitments about their profiles at the beginning such that they cannot change the profiles later on. However, in these works, users are always able to forge profiles without being detected. In [57], signatures of every transactions are recorded by users, and thus the forgery attacks can be caught with the help from an offline trusted authority. However, this consumes extra communication and computation overhead.

Sybil attacks are notorious attacks in a distributed system and very hard to prevent, particularly when privacy is required. Such attacks subvert the system by creating a large number of pseudonymous entities, using them to gain a disproportionately large influence [66–69]. Research efforts on resisting sybil attacks have two directions. One is to study the characteristics of sybil behavior and distinguish the sybil accounts before the attacks [69]. The other one is to detect sybil attacks by using cryptographic mechanisms [58].

1.3 Research Motivations and Contribution

The research in this thesis focuses on developing a suite of protocols to deal with the challenging security and privacy-preserving issues in mobile social networks. Specifically, the research motivation and contribution are summarized as follows:

- First, we study the profile matching application. Profile matching, as the initial step of user-to-user communication, enables users to find and socialize with others who

have similar interests or backgrounds. It normally requires two users to exchange their profile details so that each of them is able to check if two profiles have any similarities. However, users may have growing privacy concerns in sharing the constant and personalized profiles with the nearby strangers who may eavesdrop, store, and correlate their profiles at different time periods and locations. Once the profiles are identified or correlated to the location information, the behavior of users will be completely disclosed to the public. As such, the privacy-preserving profile matching (PPM) has been proposed: it enables two users to compare their profiles and obtain the comparison results without disclosing the profiles to each other. Many research efforts on the privacy preserving profile matching [7, 26, 28, 31, 61] have been carried out. The common goal of these works is to enable the handshake between two encountered users if both users satisfy each other's requirement while eliminating the unnecessary information disclosure. In this thesis, we review some related protocols and study the user anonymity issues. We find the existing works neglect the user anonymity requirement, and the defined privacy levels can hardly be related to the user-specific anonymity requirement. Instead, we address the profile matching from another novel perspective, i.e., user anonymity. We develop an anonymity-enhancing technique for users to be self-aware of the anonymity risk level and take appropriate actions to maintain the k-anonymity level where k is a parameter defined by each individual user. We also propose a fully anonymous profile matching protocol which enables users to share messages and does not disclose profile information at all [57].

- Second, by taking the human social behavior, we study the data forwarding strategy in the opportunistic MSN. The opportunistic MSN does not have the stable user-to-user connections due to the user mobility. Therefore, similar to the DTN, the data forwarding relies on the opportunistic contacts among cooperative users. Different from the DTN, the design of data forwarding strategies in the MSN must additionally consider human factors, i.e., cooperative incentive and privacy preservation. In the MSN, the incentive to act cooperatively from a user's aspect includes multiple factors. Users could be cooperative because of direct friendships. In this case, it is inevitable to disclose the personal information to the encountered users which could possibly violate privacy. If users do not share personal information to other peers for privacy preservation, it seems that no one would act cooperatively because they obtain no any benefits from the cooperation. Therefore, the cooperation could be severely interrupted or even disabled when privacy preservation is applied. Many research works [70–73] studied the cooperation incentives in the data forwarding and data dissemination protocols of the MSN. In this thesis, we will study the cooperation incentive of users from traditional social theory. We will present a morality-driven

privacy-preserving data forwarding (PDF) protocol [29]. We will consider multiple factors in the forwarding utility, such as forwarding capability, forwarding costs, and morality factor. Based on the game theoretic analysis, users always maximize their own utility and decide to forward their packets with certain probability. We are able to show that the cooperation and privacy preservation, two conflicting goals, can be achieved in the PDF among a group of users with social morality.

- Third, users in the MSN are often lack of trust toward others. How to establish trust in the distributed MSN is very challenging but useful. Trustworthy service evaluation (TSE) systems enable service providers or any third trusted authority to receive user feedback, known as service reviews or simply reviews, such as compliments and complaints about their services or products. By using the TSE, the service providers learn the service experiences of the customers and are able to improve their service strategy in time. In addition, the collected reviews can be made available to the public, which enhances service advertising and assists the users in making wise service selections. The TSE is often maintained by a third trusted authority that is trusted to host authentic reviews. Popular TSE can be found in web-based social networks such as Facebook, online stores like eBay, and third-party geo-social applications such as FourSquare. A trusted third party provides a platform for millions of people to interact with their friends and obtain their recommendations. These solutions are important marketing tools for service providers who target the global market. To move the TSE into the MSN context is not easy due to the lack of third trusted authorities. In the MSN, service providers (restaurants and grocery stores) offer location-based services to local users and aim to attract the users by employing various advertising approaches, for example, sending e-flyers to the nearby passengers via wireless communications. Unlike the global counterparts, the interests of the local service providers are in serving the users in close geographic vicinity because most users choose services based on the comparison of the service quality and the distance advantage. Some works propose to collect the service reviews in a distributed manner and integrate the service reviews into the current location based applications. However, it is still centralized control and the review management can be complicated and cause information delay. We propose a distributed system where the local service providers maintain the TSE by themselves. We study the potential malicious attacks conducted by both the service providers and the users. Note that, it is very challenging to restrict the malicious behavior from the service providers and the users in an untrusted distributed environment. We introduce the possible review attacks and the Sybil attacks [58]. We also devise effective defensive mechanisms to resist these attacks.

- Fourth, users in the MSN expect their information to be quickly transmitted to the online service providers. Such information can be their health conditions. Recent WBANs provide multiple in, on or around body sensors which continuously transmit the monitored body signals to user smartphones. We study the routing problem in WBANs. We propose a distributed Prediction-based Secure and Reliable routing framework (PSR). It can be integrated with a specific routing protocol to improve the latter's reliability and prevent data injection attacks during data communication. In the PSR, using past link quality measurements, each node predicts the quality of every incidental link, and thus any change in the neighbor set as well, for the immediate future. When there are multiple possible next hops for packet forwarding (according to the routing protocol used), the PSR selects the one with the highest predicted link quality among them. Specially-tailored lightweight source and data authentication methods are employed by nodes to secure data communication. Further, each node adaptively enables or disables source authentication according to predicted neighbor set change and prediction accuracy so as to quickly filter false source authentication requests. We demonstrate that the PSR significantly increases routing reliability and effectively resists data injection attacks through in-depth security analysis and extensive simulation study.

1.4 Outline of the Thesis

The organization of the remainder of the thesis is as follows. Chapter 2 reviews some basic techniques including multiple pseudonym technique, k-anonymity, prediction algorithm, and cryptographic techniques. Chapter 3 presents a family of profile matching protocols where user anonymity can be improved. Chapter 4 presents a morality-based data forwarding strategy with location privacy preservation. Chapter 5 presents a distributed, secure, and efficient trustworthy service evaluation system in the MSN where users are able to exchange their service reviews about the service providers. Chapter 6 presents a body-gesture-based routing protocol over human body with security enhancement and efficiency improvement. Finally, conclusions and future research work are described in Chapter 7.

Chapter 2

Basic Techniques

In this section, we will review some basic techniques that will be used in later chapters.

2.1 Multiple Pseudonym Technique

A pseudonym is a name that a person assumes for a particular purpose, which differs from his or her original or true name. Pseudonyms have no literal meanings, and they can be used to hide an individual's real identity. In a network environment, pseudonyms have been widely adopted to preserve user's identity privacy [25,74]. An offline trusted authority (TA) is considered to initialize pseudonyms for users prior to the network deployment. The TA will assign multiple pseudonyms for each individual user. These pseudonyms cannot be linked by anyone but the TA. Each user changes their pseudonyms in the communications when needed such that their behavior cannot be linked by the different pseudonyms. When users consume all the pseudonyms, they can contact with the TA to fill up with new pseudonyms.

To avoid the forgery attacks of pseudonyms, the TA assigns an additional secret to users according to their pseudonyms. Only with the secret, a user can prove that the pseudonym is legally held. The identity-based signature can be a solution. The TA generates a private key for each pseudonym, and assigns the private key to the user. The user can always sign on any message with the private key, and the generated signature can be verified with the pseudonym. In this way, the forgery attacks of pseudonyms can be prevented.

However, with pseudonyms, users may launch malicious attacks, such as sybil attacks. To prevent the abuse of pseudonyms, the TA needs to set a trapdoor when generating

the pseudonyms such that it can trace user behavior. Generally, there are two ways to implement traceable pseudonyms:

- Mapping function: The TA generates k pseudonyms $\{pid_{i,1}, \cdots, pid_{i,k}\}$ for user u_i. For each pseudonym $pid_{i,j}$, the TA also generates a corresponding pseudonym secret key $psk_{i,j}$ and sends the key to u_i in a secure channel. Then, u_i is able to use $pid_{i,j}$ in the communication protocols. He can generate a signature using $psk_{i,j}$ to make others confirm that u_i is the legal holder of $pid_{i,j}$. In the meantime, the TA maintains a map from these pseudonyms to the real identity id_i of u_i. When needed, others can always report the signature to the TA who is able to track u_i's behavior.
- Group signature: The TA generates k pairs of pseudonym and pseudonym secret key $(pid_{i,j}, psk_{i,j})$ for $1 \leq j \leq k$. Different from the previous method, the TA generates the pseudonym secret keys by using the key generation algorithms from group signatures [64, 65]. In this way, user u_i has to generate the group signature in the communication protocols. Although the group signature does not reveal user's real identity, the TA with a master key can always perform the trace algorithm to retrieve the real identity of the user from the group signature.

2.2 K Anonymity

The k-anonymity [75] is a classic concept for evaluating anonymity. Full anonymity [76, 77] of communication protocols implies that an adversary looking at the communication patterns should not learn anything about the origin or destination of a particular message. The k-anonymity is a weaker anonymity requirement, implying that the adversary is able to learn something about the origin or destination of a particular message, but cannot narrow down its search to a set of less than k users. In other words, the k-anonymity guarantees that in a network with N honest users, the adversary is not able to guess the sender or recipient of a particular message with probability non-negligibly greater than $1/k$, where $k \leq N$ is not necessarily related to N. In practise, the parameter k can be defined by the system or individual users. When users define k, users could have different anonymity requirements and choose the appropriate strategies in the communication protocols. Using multiple pseudonym technique is a solution. When users frequently change the pseudonyms, their transactions cannot be linked at all but the number of consumed pseudonyms becomes huge. In this case, the design goal of communication protocols is to develop multiple adaptive strategies for users such that their defined anonymity requirements can be satisfied with minimum consumed pseudonyms.

2.3 Prediction Method - Autoregression

The autoregressive (AR) model is a tool for understanding and predicting a time series of data [78]. It can be used to estimate the current term z_k of the series by a linear weighted sum of previous p terms (i.e., observations) in the series. The model order p is generally less than the length of the series. Formally, $\mathsf{AR}(p)$ is defined as

$$z_k = c + \sum_{i=1}^{p} \phi_o z_{k-i} + \epsilon_k, \tag{2.1}$$

where c is a constant standing for the mean of the series, ϕ_i autoregression coefficients, and ϵ_k the zero-mean Gaussian white noise error term. For simplicity, c is often omitted.

The derivation of $\mathsf{AR}(p)$ involves determining the coefficients ϕ_i for $i \in [1 \cdots p]$ that give a good prediction. The model can be updated continuously as new samples arrive so as to ensure accuracy, or it may be recomputed when the prediction error, i.e., the difference between the predicted value and the true measurement, is very large. In [79], a simplified AR model is presented and used for neighborhood prediction. This model can be updated through trivial calculus, greatly reducing the requirement on the computational power of the nodes that implement it.

2.4 Cryptographic Techniques

2.4.1 Bilinear Groups of Prime Order

Bilinear pairing is an important cryptographic primitive and has been widely adopted in many positive applications in cryptography [80, 81]. Let $\mathbb{G}$ be a cyclic additive group and $\mathbb{G}_T$ be a cyclic multiplicative group of the same prime order q. We assume that the discrete logarithm problems in both $\mathbb{G}$ and $\mathbb{G}_T$ are hard. A bilinear pairing is a mapping $e : \mathbb{G} \times \mathbb{G} \to \mathbb{G}_T$ which satisfies the following properties:

1. Bilinearity: For any $P, Q \in \mathbb{G}$ and $a, b \in \mathbb{Z}_q^*$, we have $e(aP, bQ) = e(P, Q)^{ab}$.
2. Non-degeneracy: There exists $P \in \mathbb{G}$ and $Q \in \mathbb{G}$ such that $e(P, Q) \neq 1_{\mathbb{G}_T}$.
3. Computability: There exists an efficient algorithm to compute $e(P, Q)$ for all $P, Q \in \mathbb{G}$.

From reference [80], we note that such a bilinear pairing may be realized using the modified Weil pairing associated with supersingular elliptic curve.

Definition 1 (Bilinear Generator) *A bilinear parameter generator $\mathcal{G}en_{bili}$ is a probability algorithm that takes a security parameter κ as input and outputs a 5-tuple $(q, P, \mathbb{G}, \mathbb{G}_T, e)$, where q is a κ-bit prime number, $(\mathbb{G}, +)$ and $(\mathbb{G}_T, \times)$ are two groups with the same order q, $P \in G$ is a generator, and $e : \mathbb{G} \times \mathbb{G} \to \mathbb{G}_T$ is an admissible bilinear map.*

In the following, we briefly introduce the complexity assumptions including Computational Diffie-Hellman (CDH) problem, Decisional Diffie-Hellman (DDH) problem, Bilinear Diffie-Hellman (BDH) problem, and Decisional Bilinear Diffie-Hellman (DBDH) problem.

Definition 2 (Computational Diffie-Hellman (CDH) problem) *The Computational Diffie-Hellman (CDH) problem in $\mathbb{G}$ is defined as follows: Given $P, aP, bP \in \mathbb{G}$ for unknown $a, b \in \mathbb{Z}_q^*$, compute $abP \in \mathbb{G}$.*

Definition 3 (CDH assumption) *We say that an algorithm $\mathcal{A}$ has advantages $\epsilon(\kappa)$ in solving the CDH problem for $\mathbb{G}$:*

$$\mathrm{Adv}_{\mathbb{G},\mathcal{A}}(\kappa) = \Pr[\mathcal{A}(q, \mathbb{G}, e, P, aP, bP) = P^{ab}] \geq \epsilon \tag{2.2}$$

We say that $\mathbb{G}$ satisfies the CDH assumption if for any randomized polynomial time (in κ) algorithm $\mathcal{A}$ we have that $\mathrm{Adv}_{\mathbb{G},\mathcal{A}}(\kappa)$ is a negligible function. When $\mathbb{G}$ satisfies the CDH assumption we say that CDH is hard in group $\mathbb{G}$.

Definition 4 (Decisional Diffie-Hellman (DDH) problem) *The Decisional Diffie-Hellman (DDH) problem in $\mathbb{G}$ is defined as follows: Given $P, aP, bP, cP \in \mathbb{G}$ for unknown $a, b, c \in \mathbb{Z}_q^*$, decide whether $c \stackrel{?}{=} ab$. The DDH problem in $\mathbb{G}$ is easy, since we can check whether $e(aP, bP) \stackrel{?}{=} e(P, cP)$ and use the results to decide $c \stackrel{?}{=} ab$.*

Definition 5 (Bilinear Diffie-Hellman (BDH) problem) *The Bilinear Diffie-Hellman (BDH) problem in $\mathbb{G}$ is defined as follows: Given $P, aP, bP, cP \in \mathbb{G}$ for unknown $a, b, c \in \mathbb{Z}_q^*$, compute $e(P, P)^{abc} \in \mathbb{G}_T$.*

Definition 6 (BDH assumption) *We say that an algorithm $\mathcal{A}$ has advantages $\epsilon(\kappa)$ in solving the BDH problem for $\mathcal{G}en_{bili}$ if for sufficiently large k:*

$$\mathrm{Adv}_{\mathcal{G}en_{bili},\mathcal{A}}(\kappa) = \Pr[\mathcal{A}(q, \mathbb{G}, \mathbb{G}_T, e, P, aP, bP, cP) = e(P,P)^{abc}] \geq \epsilon(\kappa) \tag{2.3}$$

We say that $\mathcal{G}en_{bili}$ satisfies the BDH assumption if for any randomized polynomial time (in κ) algorithm $\mathcal{A}$ we have that $\mathrm{Adv}_{\mathcal{G}en_{bili},\mathcal{A}}(\kappa)$ is a negligible function. When $\mathcal{G}en_{bili}$ satisfies the BDH assumption we say that BDH is hard in groups generated by $\mathcal{G}en_{bili}$.

Definition 7 (Decisional Bilinear Diffie-Hellman (DBDH) problem) *The Decisional Bilinear Diffie-Hellman (DBDH) problem in $\mathbb{G}$ is defined as follows: Given P, aP, bP, cP, T for unknown $a, b, c \in \mathbb{Z}_q^*$ and $T \in \mathbb{G}_T$, decide whether $T \stackrel{?}{=} e(P,P)^{abc}$.*

Definition 8 (DBDH assumption) *We say that an algorithm $\mathcal{A}$ has advantages $\epsilon(\kappa)$ in solving the DBDH problem for $\mathcal{G}en_{bili}$ if for sufficiently large k, $\mathcal{A}$ distinguishes the two tuples (P, aP, bP, cP) and (P, aP, bP, abP) with advantage $\epsilon(\kappa)$, i.e.,*

$$\begin{aligned} &|\Pr[\mathcal{A}(q, \mathbb{G}, \mathbb{G}_T, e, P, aP, bP, cP, e(P,P)^{abc}) = 1] \\ &- \Pr[\mathcal{A}(q, \mathbb{G}, \mathbb{G}_T, e, P, aP, bP, cP, T) = 1]| \geq \epsilon(\kappa) \end{aligned} \tag{2.4}$$

We say that $\mathcal{G}en_{bili}$ satisfies the DBDH assumption if for any randomized polynomial time (in κ) algorithm $\mathcal{A}$, it distinguishes the two tuples with a negligible probability. When $\mathcal{G}en_{bili}$ satisfies the DBDH assumption we say that DBDH is hard in groups generated by $\mathcal{G}en_{bili}$.

2.4.2 Bilinear Groups of Composite Order

In the previous definition, groups $\mathbb{G}$ and $\mathbb{G}_T$ have the same prime order q. In literature [64, 65], there have been many cryptographic scheme design using the bilinear groups of composite order. Generally, these works can provide additional anonymity protection and trace capability. We briefly review its definition as follows.

Let two finite cyclic groups $\mathbb{G}$ and $\mathbb{G}_T$ having the same order n, in which the respective group operation is efficiently computable and denoted multiplicatively [64, 65]. Assume that there exists an efficiently computable function $e : \mathbb{G} \times \mathbb{G} \to \mathbb{G}_T$, called a bilinear map or pairing, with the following properties:

1. Bilinearity: For any $u, v \in \mathbb{G}$ and $a, b \in \mathbb{Z}_q^*$, we have $e(u^a, v^b) = e(u, v)^{ab}$.

2. Non-degeneracy: $\exists g \in \mathbb{G}$ such that $e(g, g)$ has order n in $\mathbb{G}_T$. In other words, $e(g, g)$ is a generator of $\mathbb{G}_T$, whereas g generates $\mathbb{G}$.

Note that, the operation in $\mathbb{G}$ is denoted as multiplication, which is just for easy presentation. The bilinear groups of composite order differ from the previous ones by changing a prime order p to a composite order $n = pq$ where $p \neq q$ are two large primes. The factorization problem of n is assumed to be computationally-infeasible. The complexity assumptions in the bilinear groups of prime order also hold in the bilinear groups of composite order. In addition, we introduce the SubGroup Decision (SGD) Problem as follows:

Definition 9 (SubGroup Decision (SGD) Problem) *The SubGroup Decision (SGD) problem in $\mathbb{G}$ is defined as follows: Given $(e, \mathbb{G}, \mathbb{G}_T, n, h)$ where the element h is randomly drawn from either $\mathbb{G}$ or subgroup $\mathbb{G}_q$, decide whether $h \in \mathbb{G}_q$ or $h \in \mathbb{G}$.*

Definition 10 (SGD assumption) *We say that an algorithm $\mathcal{A}$ has advantages $\epsilon(\kappa)$ in solving the SGD problem for $\mathbb{G}$ and $\mathbb{G}_q$ if for sufficiently large k, $\mathcal{A}$ correctly guess either $h \in \mathbb{G}_q$ or $h \in \mathbb{G}$ with advantage $\epsilon(\kappa)$, i.e.,*

$$|\Pr[\mathcal{A}(h \in \mathbb{G}_q) = 1] - \Pr[\mathcal{A}(q \in \mathbb{G}) = 1]| \geq \epsilon(\kappa) \tag{2.5}$$

We say that $\mathbb{G}$ and $\mathbb{G}_q$ satisfy the SGD assumption if for any randomized polynomial time (in κ) algorithm $\mathcal{A}$, it correctly guesses either $h \in \mathbb{G}_q$ or $h \in \mathbb{G}$ with a negligible probability. When $\mathcal{G}en_{bili}$ satisfies the SGD assumption we say that SGD is hard in groups $\mathbb{G}$ and $\mathbb{G}_q$.

2.4.3 Identity Based Aggregate Signature

The identity based aggregate signature (IBAS) scheme [82] consists of five algorithms, *Setup*, *Private key generation*, *Individual Signing*, *Aggregation*, and *Verification*.

• *Setup:* The Private Key Generator (PKG) uses a bilinear generator $\mathcal{G}en_{bili}$ from the previous section to generate a 5-tuple $(q, P, \mathbb{G}, \mathbb{G}_T, e)$. The PKG also picks a random $s \in \mathbb{Z}_q$ and sets $Q = sP$. It chooses a cryptographic hash functions $H_1, H_2 : \{0,1\}^* \to \mathbb{G}_1$ and $H_3 : \{0,1\}^* \to \mathbb{Z}_q$.

• *Private key generation:* The user u_i with identity ID_i receives from the PKG the private key $sP_{i,j}$ for $j \in \{0,1\}$, where $P_{i,j} = H_1(ID_i, j) \in \mathbb{G}$.

• *Individual signing:* The first signer chooses a string w that it has never used before. Each subsequent signer checks that it has not used the string w chosen by the first signer. To sign m_i, the signer with identity ID_i:

1. computes $P_w = H_2(w) \in \mathbb{G}$;
2. computes $c_i = H_3(m_i, ID_i, w) \in \mathbb{Z}_q$;
3. generates random $r_i \in \mathbb{Z}_q$;
4. computes its signature (w, S_i', T_i'), where $S_i' = r_i P_w + sP_{i,0} + c_i sP_{i,1}$ and $T_i' = r_i P$.

• *Aggregation:* Anyone can aggregate a collection of individual signatures that use the same string w. For example, individual signatures (w, S_i', T_i') for $1 \leq i \leq n$ can be aggregated into (w, S_n, T_n), where $S_n = \sum_{i=1}^{n} S_i'$ and $T_n = \sum_{i=1}^{n} T_i'$.

• *Verification:* Let (w, S_n, T_n) be the identity-based aggregate signature where n is the number of signers. The verifier checks that:

$$e(S_n, P) = e(T_n, P_w) e(Q, \sum_{i=1}^{n} P_{i,0} + \sum_{i=1}^{n} c_i P_{i,1}), \tag{2.6}$$

where $P_{i,j} = H_1(ID_i, j)$, $P_w = H_2(w)$ and $c_i = H_3(m_i, ID_i, w)$.

2.4.4 Shamir Secret Sharing

The goal of a secret sharing scheme [83] is to divide a secret s into n pieces $s_1, s_2, \cdots, s_n$ in such as way that:

- knowledge of any k or more s_i pieces makes s easily computable;
- knowledge of any $k-1$ or fewer s_i pieces leaves s completely undetermined (in the sense that all its possible values are equally likely).

Such a scheme is called a (k, n) threshold scheme.

The following scheme [83] is an example of a (k, n) secret sharing. Denote $\mathbb{G}$ as a group. Suppose that a user has a secret $s \in \mathbb{G}$.

- Secret shares generation: To generate n s_i, the user chooses a polynomial with a degree k, i.e., $f(x) = x^k + a_{k-1}x^{k-1} + \cdots a_1 x + a_0 (= s)$ where $a_0, \cdots, a_{k-1}$ are randomly chosen from $\mathbb{G}$. Then, the user generates $s_i = f(i)$ for $i = 1, \cdots, n$.

- Secret recovery: To recover the secret s, a lagrange interpolation is used to calculate s from n pieces $s_1, \cdots, s_n$ following the equation.

$$s = f(0) = \sum_{i=1}^{n} \alpha_i \cdot s_i, \text{ where } \alpha_i = \prod_{j=1, j\neq i}^{n} \frac{-j}{i-j}. \tag{2.7}$$

2.4.5 Homomorphic Encryption

There are several existing homomorphic encryption schemes that support different operations such as addition and multiplication on ciphertexts, e.g. [84, 85]. By using these schemes, a user is able to process the encrypted plaintext without knowing the secret keys. Due to this property, homomorphic encryption schemes are widely used in data aggregation and computation specifically for privacy-sensitive content [86]. We review the homomorphic encryption scheme [85].

Suppose user u_i has a public/private key pair (pk_i, sk_i) from the fully homomorphic encryption (FHE) scheme. The Encryption Enc, Decryption Dec, Addition Add, and Multiplication Mul functions must be satisfied.

- Correctness: $Dec(sk_i, Enc(pk_i, m)) = m$;
- Addition of plaintexts: $Dec(sk_i, Add(Enc(pk_i, m_1), Enc(pk_i, m_2))) = m_1 + m_2$;
- Multiplication of plaintexts: $Dec(sk_i, Mul(Enc(pk_i, m_1), Enc(pk_i, m_2))) = m_1 \cdot m_2$.

The following scheme is an example of the FHE scheme. A trusted authority runs a generator $\mathcal{G}en_{homo}$ which outputs $\langle p, q, R, R_q, R_p, \chi \rangle$ as system public parameters:

- $p < q$ are two primes s.t. $q \equiv 1 \mod 4$ and $p \gg l$;
- Rings $R = \mathbb{Z}[\mathtt{x}]/\langle \mathtt{x}^2 + 1 \rangle$, $R_q = R/qR = \mathbb{Z}_q[\mathtt{x}]/\langle \mathtt{x}^2 + 1 \rangle$;
- Message space $R_p = \mathbb{Z}_p[\mathtt{x}]/\langle \mathtt{x}^2 + 1 \rangle$;
- A discrete Gaussian error distribution $\chi = D_{\mathbb{Z}^n, \sigma}$ with standard deviation σ.

Suppose user u_i has a public/private key pair (pk_i, sk_i) such that $pk_i = \{a_i, b_i\}$, with $a_i = -(b_i s + pe)$, $b_i \in R_q$ and $s, e \leftarrow \chi$, and $sk_i = s$. Let $b_{i,1}$ and $b_{i,2}$ be two messages encrypted by u_i.

- Encryption $E_{pk_i}(b_{i,1})$: $c_{i,1} = (c_0, c_1) = (a_i u_t + p g_t + b_{i,1}, b_i u_t + p f_t)$, where u_t, f_t, g_t are samples from χ.
- Decryption $D_{sk_i}(c_{i,1})$: If denoting $c_{i,1} = (c_0, \cdots, c_{\alpha_1})$, $b_{i,1} = (\sum_{k=0}^{\alpha_1} c_k s^k) \mod p$.

Consider the two ciphertexts $c_{i,1} = E(b_{i,1}) = (c_0, \cdots, c_{\alpha_1})$ and $c_{i,2} = E(b_{i,2}) = (c'_0, \cdots, c'_{\alpha_2})$.

- Addition: Let $\alpha = max(\alpha_1, \alpha_2)$. If $\alpha_1 < \alpha$, let $c_{\alpha_1+1} = \cdots = c_\alpha = 0$; If $\alpha_2 < \alpha$, let $c'_{\alpha_2+1} = \cdots = c'_\alpha = 0$. Thus, we have $E(b_{i,1} + b_{i,2}) = (c_0 \pm c'_0, \cdots, c_\alpha \pm c'_\alpha)$.
- Multiplication: Let v be a symbolic variable and compute $(\sum_{k=0}^{\alpha_1} c_k v^k) \cdot (\sum_{k=0}^{\alpha_2} c'_k v^k) = \hat{c}_{\alpha_1+\alpha_2} v^{\alpha_1+\alpha_2} + \cdots + \hat{c}_1 v + \hat{c}_0$. Thus, we have $E(b_{i,1} \times b_{i,2}) = (\hat{c}_0, \cdots, \hat{c}_{\alpha_1+\alpha_2})$.

Chapter 3

Profile Matching Protocol with Anonymity Enhancing Techniques

3.1 Introduction

In this chapter, we introduce a popular research topic, called privacy-preserving profile matching (PPM). The PPM can be very useful in an application scenario where two users both want to know something about each other but they do not want to disclose too much personal information. The PPM occurs quite frequently in our daily life. For example, in a restaurant or a sports stadium, people like finding their friends and chatting with friendly neighbors. To initialize the communication, they may expect to know if others have similar preferences or share the similar opinions. In a mobile healthcare system, patients may be willing to share personal symptoms with others. However, they expect the listeners to have similar experiences such that they could receive comforts and suggestions. Based on the above application scenarios, we can see that the common design goal of the PPM is to help two users exchange personal information while preserving their privacy. It could serve as the initial communication step of many mobile social networking applications.

We will introduce a family of the PPM protocols. Specifically, these protocols rely on the homomorphic encryption to protect the content of user profiles from disclosure. They provide increasing levels of user anonymity (from conditional to full). Furthermore, we will study the social community concept and adopt the prediction method and the multiple-pseudonym technique to improve the user anonymity protection in the protocol. The extensive trace-based simulation results show that the protocol with the anonymity

enhancing technique achieves significantly higher anonymity strength with slightly larger number of used pseudonyms than the protocol without the technique.

The remainder of this chapter is organized as follows: In Section 3.2, we present the network model and the design goal. Then, we introduce three protocols in Section 3.3. We introduce the anonymity enhancing techniques in Section 3.4 and provide the simulation-based performance evaluations of the protocols and techniques in Section 3.5. Lastly, we review the related work and draw our summary respectively in Section 3.6 and Section 3.7.

3.2 Network Model and Design Goal

3.2.1 Network Model

We consider an MSN composed of a set $\mathcal{V} = \{u_1, \cdots, u_N\}$ of mobile users with the network size $|\mathcal{V}| = N$. Users have equal wireless communication range, and the communication is bi-directional. Each user obtains multiple pseudonyms from a TA and uses these pseudonyms instead of their real identities to preserve their privacy (Section 2.1).

Profile: Each user has a profile spanning w attributes $W = \{a_1, \cdots, a_w\}$. These w attributes represents every aspect of a user. Each profile is a w-dimension vector, and each dimension has an integer value between 1 and l. The profile of user u_i is denoted by $p_i = (v_{i,1}, \cdots, v_{i,w})$ where $v_{i,h} \in \mathbb{Z}$ and $1 \leq v_{i,h} \leq l$ for $1 \leq h \leq w$.

Matching operation: A matching operation between two profiles $p_i = (v_{i,1}, \cdots, v_{i,w})$ and $p_j = (v_{j,1}, \cdots, v_{j,w})$ can be

- Inner product $f_{dot}(p_i, p_j) = f_{dot}(p_i, p_j) = \sum_{t=1}^{w} v_{i,t} \cdot v_{j,t}$.
- Manhattan distance $f_{man}(p_i, p_j, \alpha) = f_{man}(p_i, p_j) = (\sum_{t=1}^{w} |v_{i,t} - v_{j,t}|^{\alpha})^{\frac{1}{\alpha}}$.
- Max distance $f_{max}(p_i, p_j) = max\{|v_{i,1} - v_{j,1}|, \cdots, |v_{i,w} - v_{j,w}|\}$.
- Comparison-based

$$f_{cmp}(p_i, p_j, x) = \begin{cases} -1, v_{i,x} < v_{j,x} \\ 0, v_{i,x} = v_{j,x} \\ 1, v_{i,x} > v_{j,x} \end{cases} \tag{3.1}$$

- Predicate-based

$$f_{cmp}(p_i, p_j, \Pi) = \begin{cases} 1, (p_i, p_j) \in \Pi \\ -1, (p_i, p_j) \notin \Pi \end{cases} \tag{3.2}$$

Note, Π = "$\bar{t}$ of $\{(v_{i,x}, opt, v_{j,x})|a_x \in A\}$ are satisfied" is a predicate where $A \subseteq W$ and the comparison operator opt is either $>$ or $<$ and $\bar{t} \leq |A|$. $f_{cmp}(p_i, p_j, \Pi) = 1$ if (p_i, p_j) satisfies at least $\bar{t}$ equations; $f_{cmp}(p_i, p_j, \Pi) = -1$ otherwise.

3.2.2 Design Goals

The objective of a privacy-preserving profile matching protocol is to enable two users to compare their profiles while not disclosing the profiles to each other. The matching operations in previous section can be easily done if (p_i, p_j) can be obtained by any single user. However, users will not disclose their profiles p_i and p_j to others, and no trusted authority exists. This makes the implementation of the matching operations very difficult. Recent secure multi-party computation (MPC) is developed to enable users to jointly compute a function over their inputs, while at the same time keeping these inputs private. The two-party computation can be used for profile matching. In addition, many recent works [26,31] realize that the explicit matching result may reveal the uniqueness of profiles, and extend their protocols to show fuzzy matching results instead of explicit results, i.e., users are able to know if the matching result is larger or smaller than a pre-defined threshold. In the following, we review three kinds of matching results.

- Explicit matching result: the matching result $f_*()$ is directly disclosed to users u_i and/or u_j.
- Fuzzy matching result: the relationship between the matching result $f_*()$ and a predefined threshold T (i.e., if $f_*() > T$) is disclosed to users u_i and/or u_j.
- Implicit matching result: a message $F_i(f_*())$ is implicitly disclosed to users u_j where $F_i()$ is a secret mapping function defined by u_i and u_i is unaware of $f_*()$.

Note that, the amount of disclosed information is reduced from explicit, fuzzy to implicit matching results. In practise, users expect to know how much profile information disclosed in each profile matching protocol. They do not want to over-disclose the profile information. Especially, when the disclosed information can be linked in multiple runs, the behavior of an individual user will be more easily to track. We consider that users apply the multiple pseudonym technique (Section 2.1). Then, the problem will be how to minimally change the pseudonyms such that the leaked information cannot be used to identify the user.

In our protocols, instead of minimizing the disclosed information in each protocol run, we focus on how to protect user anonymity in the multiple protocol runs. To address this

point, we define the anonymity level for the profile matching protocols as the probability of correctly guessing the profile of the user from the published profile samples. Note that, if a user does not change the pseudonym, its anonymity continuingly decreases as the protocol runs because the disclosed information will help narrow down the possibilities of the profile. If a user changes the pseudonym, its anonymity is changed to the highest level because the previous disclosed information will not be linked to the new pseudonym. In literature, user privacy level and user anonymity level are both metrics for evaluating the protocols. The user privacy level is often related to the disclosed information in one protocol run, while the user anonymity level is a user-specific property that is defined in multiple protocol runs. From our perspective, the user anonymity level is more practical for users to be adapted.

Considering a user u_i has a profile p_i from the profile sets $(p_1, \cdots, p_\nu)$ where any two profiles are different. Denote the profile matching protocol as $\mathcal{P}(u_i, pid_i, u_j, pid_j)$ where u_i and u_j run the protocol with their pseudonyms pid_i and pid_j. $\mathcal{P}_i(u_i, pid_i, u_j, pid_j)$ returns the transactions that u_i obtains from the protocol run, while $\mathcal{P}_j(u_i, pid_i, u_j, pid_j)$ returns those of u_j. An attacker $\mathcal{A}$ knows all profile samples and has many pseudonyms denoted by $(pid_{a_1}, \cdots, pid_{a_x})$. In the following, we define three types of user anonymity levels for profile matching protocols, i.e., non-anonymity, conditional anonymity, and full anonymity.

Definition 11 (Non-Anonymity) *A profile matching protocol provides non-anonymity if* $\Pr[\mathcal{A}(\sum_{z=1}^{x} \mathcal{P}_{\mathcal{A}}(\mathcal{A}, pid_{a_z}, u_i, pid_i)) = p_i] = 1$.

Definition 12 (Conditional Anonymity) *A profile matching protocol achieves conditional anonymity if* $\Pr[\mathcal{A}(\sum_{z=1}^{x} \mathcal{P}_{\mathcal{A}}(\mathcal{A}, pid_{a_z}, u_i, pid_i)) = p_i] > \frac{1}{\nu}$.

Definition 13 (Full Anonymity) *A profile matching protocol achieves full anonymity if* $\Pr[\mathcal{A}(\sum_{z=1}^{x} \mathcal{P}_{\mathcal{A}}(\mathcal{A}, pid_{a_z}, u_i, pid_i)) = p_i] = \frac{1}{\nu}$.

In most recent works [26, 31], the explicit and fuzzy matching results could be possibly used to track user behavior. Thus, these works provide non-anonymity and conditional anonymity. In comparison, the implicit matching results do not reveal the profile information and the corresponding protocols achieve full anonymity. In the following, we introduce three comparison-based profile matching protocols: an explicit Comparison-based Profile Matching protocol (eCPM), an implicit Comparison-based Profile Matching protocol (iCPM), and an implicit Predicate-based Profile Matching protocol (iPPM) [57]. The eCPM achieves conditional anonymity while the eCPM and the iCPM achieve full anonymity.

3.3 PPM Solutions

We first use an example to describe the profile matching with the comparison operation. Consider two CIA agents have two different priority levels in the CIA system, A with a low priority l_A and B with a high priority l_B. They know each other as a CIA agent. However, they do not want to reveal their priority levels to each other. B wants to share some messages to A. The messages are not related to user profile, and they are divided into multiple categories, e.g., the messages related to different regions (New York or Beijing) in different years (2011 or 2012). B shares one message of a specified category T at a time. The category T is chosen by A, but the choice is unknown to B. For each category, B prepares two self-defined messages, e.g., a message m_1 for the CIA agent at a lower level and another message m_2 for the agent at a higher level. Because $l_A < l_B$, A eventually obtains m_1. In the meantime, B does not know which message A receives. The above profile matching offers both A and B the highest anonymity since neither the comparison result between l_A and l_B is disclosed to A or B nor the category T of A's interest is disclosed to B. In the following, we refer to A as the initiator u_i, B as the responder u_j, the attribute used in the comparison (i.e., priority level) as a_x, and the category T of A's interest as T_y. The attribute values of u_i and u_j on the attribute a_x are denoted by $v_{i,x}$ and $v_{j,x}$, respectively. We first formally describe two scenarios from the above examples: (a) Attribute value $v_{i,x}$ and attribute value $v_{j,x}$ will not be disclosed to u_j and u_i, respectively. The initiator obtains the comparison result at the end of the protocol. (b) $v_{i,x}$ and $v_{j,x}$ will not be disclosed to u_j and u_i, respectively. In addition, category T_y will not be disclosed to u_j, and the comparison result will not be disclosed to any of u_i and u_j. The initiator obtains either $s_{1,y}$ or $s_{0,y}$ depending on the comparison result between $v_{i,x}$ and $v_{j,x}$.

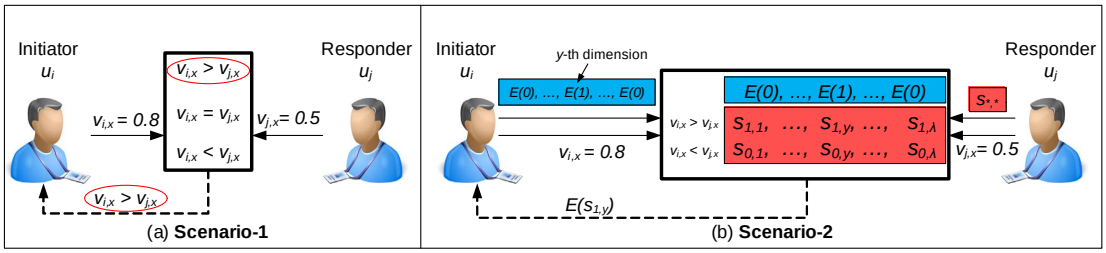


Figure 3.1: Scenarios in privacy-preserving profile matching

Scenario-1: The initiator wants to know the comparison result, i.e., whether it has a value larger, equal, or smaller than the responder on a specified attribute. For example, as shown in Fig. 3.1 (a), the initiator u_i expects to know if $v_{i,x} > v_{j,x}$, $v_{i,x} = v_{j,x}$, or $v_{i,x} < v_{j,x}$.

Scenario-2: The initiator expects that the responder shares one message related to the category of its interest, which is however kept unknown to the responder. In the meantime, the responder wants to share with the initiator one message which is determined by the comparison result of their attribute values. For example, as shown in Fig. 3.1 (b), both u_i and u_j know that a_x is used in the comparison and the categories of messages are $T_1, \cdots, T_\lambda$. The initiator u_i first generates a $(0,1)$-vector where the y-th dimension value is 1 and other dimension values are 0. Then, u_i encrypts the vector with its own public key and sends the ciphertexts $(E(0), \cdots, E(1), \cdots, E(0))$ to the responder u_j. The ciphertexts imply u_i's interested category T_y, but u_j is unable to know T_y since $E(0)$ and $E(1)$ are non-distinguishable without a decryption key. u_i also provides its attribute value $v_{i,x}$ in an encrypted form so that u_j is unable to obtain $v_{i,x}$. On the other hand, u_j prepares λ pairs of messages, each pair $(s_{1,h}, s_{0,h})$ relating to one category $T_h (1 \leq h \leq \lambda)$. u_j executes a calculation over the ciphertexts and sends the result to u_i. Finally, u_i obtains $E(s_{1,y})$ if $v_{i,x} > v_{j,x}$ or $E(s_{0,y})$ if $v_{i,x} < v_{j,x}$, and obtains $s_{1,y}$ or $s_{0,y}$ by the decryption.

3.3.1 Approach 1: Explicit Comparison-based Approach

In this section, we present the explicit Comparison-based Profile Matching protocol, i.e., eCPM. This protocol allows two users to compare their attribute values on a specified attribute without disclosing the values to each other. But, the protocol reveals the comparison result to the initiator, and therefore offers conditional anonymity.

Bootstrapping: The protocol has a fundamental bootstrapping phase, where the TA generates all system parameters, user pseudonyms, and keying materials. Specifically, the TA runs $\mathcal{G}$ to generate $\langle p, q, R, R_q, R_p, \chi \rangle$ for initiating the homomorphic encryption (see Section 2.4.5). The TA generates a pair of public and private keys (pk_{TA}, sk_{TA}) for itself. The public key pk_{TA} is open to all users; the private key sk_{TA} is a secret which will be used to issue certificates for user pseudonyms and keying materials, as shown below.

The TA generates disjoint sets of pseudonyms (pid_i) and disjoint sets of homomorphic public keys (pk_i) for users (u_i). For every pid_i and pk_i of u_i, the TA generates the corresponding secret keys psk_i and sk_i. In correspondence to each pseudonym pid_i, it assigns a certificate $cert_{pid_i}$ to u_i, which can be used to confirm the validity of pid_i. Generally, the TA uses sk_{TA} to generate a signature on pid_i and pk_i. The TA outputs $cert_{pid_i}$ as a tuple $(pk_i, Sign_{sk_{TA}}(pid_i, pk_i))$. The homomorphic secret key sk_i is delivered to u_i together with psk_i; pk_i is tied to pid_i and varies as the change of pseudonyms.

Protocol Steps: Consider user u_i with a neighboring user u_j. Denote by pid_i the current pseudonym of u_i and by pid_j that of u_j. Recall that a_x is an attribute, $v_{i,x}$ and $v_{j,x}$ the

values of u_i and u_j on a_x, and l the largest attribute value. Suppose that u_i as an initiator starts profile matching on a_x with a responder u_j. Let psk_i and psk_j be the secret keys corresponding to pid_i and pid_j, respectively. The protocol is executed as follows.

Step 1. u_i calculates $d_i = E_{pk_i}(v_{i,x})$, and sends the following 5-tuple to u_j.

$$(pid_i, cert_{pid_i}, a_x, d_i, Sign_{psk_i}(a_x, d_i))$$

Step 2. After receiving the 5-tuple, u_j opens the certificate $cert_{pid_i}$ and obtains the homomorphic public key pk_i and a signature. It checks $cert_{pid_i}$ to verify that (pk_i, pid_i) are generated by the TA, and it checks the signature to validate (a_x, d_i). If any check is failed, u_j stops; otherwise, u_j proceeds as follows. It uses pk_i to encrypt its own attribute value $v_{j,x}$, i.e., $d_j = E_{pk_i}(v_{j,x})$; it chooses a random value $\varphi \in \mathbb{Z}_p$ such that $1 \leq \varphi < \lfloor p/(2l) \rfloor$ and $m|\varphi$ for any integer $m \in [1, l-1]$ (φ can be chosen dependent on u_j's anonymity requirement). By the homomorphic property, it calculates $E_{pk_i}(v_{i,x} - v_{j,x})$ and $d'_j = E_{pk_i}(\varphi(v_{i,x} - v_{j,x}))$; it finally sends a 5-tuple $(pid_j, cert_{pid_j}, a_x, d'_j, Sign_{psk_j}(a_x, d'_j))$ to u_i.

Step 3. After receiving the 5-tuple, u_i opens the certificate $cert_{pid_j}$ and checks the signature to make sure the validity of pid_j and (a_x, d'_j). If the check is successful, u_i uses sk_i to decrypt d'_j and obtains the comparison result $c = \varphi(v_{i,x} - v_{j,x})$. u_i knows $v_{i,x} > v_{j,x}$ if $0 < c \leq \frac{p-1}{2}$, $v_{i,x} = v_{j,x}$ if $c = 0$, or $v_{i,x} < v_{j,x}$ otherwise.

Effectiveness Discussion: The effectiveness of the eCPM is guaranteed by the following theorems.

Theorem 1 (Correctness) *In the eCPM, the initiator u_i is able to obtain the correct comparison result with the responder u_j on a specified attribute a_x.*

Proof 1 *Recall $p \gg l$ and $1 \leq \varphi < \lfloor p/(2l) \rfloor$. As $1 \leq v_{i,x}, v_{j,x} \leq l$, we have $-l < v_{i,x} - v_{j,x} < l$. If $v_{i,x} > v_{j,x}$, we have $0 < \varphi(v_{i,x} - v_{j,x}) < \lfloor p/(2l) \rfloor \times l \leq p/2$. Because p is a prime and $\varphi(v_{i,x} - v_{j,x})$ is an integer, we have $0 < \varphi(v_{i,x} - v_{j,x}) \leq (p-1)/2$. In case of $v_{i,x} < v_{j,x}$, we may similarly derive $(p+1)/2 \leq \varphi(v_{i,x} - v_{j,x}) < p$. Thus, by comparing $\varphi(v_{i,x} - v_{j,x})$ with 0, $(p-1)/2$ and $(p+1)/2$, u_i is able to know whether $v_{i,x} > v_{j,x}$, $v_{i,x} = v_{j,x}$, or $v_{i,x} < v_{j,x}$.*

Theorem 2 (Anonymity) *The eCPM does not disclose the attribute values of participating users.*

Proof 2 *The initiator u_i who starts the protocol for attribute a_x encrypts its attribute value $v_{i,x}$ using its homomorphic public key pk_i. Thus, the responder u_j is unable to know any*

information about $v_{i,x}$. On the other side, the responder u_j does not transmit its attribute value $v_{j,x}$, but returns $\varphi(v_{i,x} - v_{j,x})$ to u_i, where φ is a random factor added for anonymity. Since $m|\varphi$ for $1 \leq m \leq l-1$, we have $m|(\varphi(v_{i,x} - v_{j,x}))$. Thus, $(v_{i,x} - v_{j,x})$ can be any value between $-(l-1)$ and $l-1$ from u_i's view, and the exact value of $v_{j,x}$ is thus protected.

Theorem 3 (Non-forgeability) *The eCPM discourages profile forgery attack at the cost of involving the TA for signature verification and data decryption.*

Proof 3 *Consider two users u_i and u_j running the eCPM with each other on attribute a_x. Their public keys pk_i and pk_j used for homomorphic encryption are generated by the TA, and the TA has full knowledge of the corresponding private keys sk_i and sk_j. In addition, their attribute values are generated by the TA and recorded in the TA's local repository, and the TA can retrieve any attribute value of users (e.g. $v_{i,x}$ or $v_{j,x}$) anytime when necessary. After the two users finish the protocol, u_i will have $Sign_{psk_j}(d'_j)$, and u_j will have $Sign_{psk_i}(d_i)$. If $u_i(u_j)$ uses the forged profile in the protocol, $u_j(u_i)$ can cooperate with the TA to trace such malicious attack. Specifically, $u_j(u_i)$ can send $Sign_{psk_i}(d_i)$ ($Sign_{psk_j}(d'_j)$) to the TA. the TA will be able to check if the signatures are valid and the encrypted values are consistent with $v_{i,x}$ and $v_{j,x}$. Thus, any profile forgery attack can be detected with the help from the TA, and such attacks will be discouraged.*

3.3.2 Approach 2: Implicit Comparison-based Approach

In this section, we introduce the implicit Comparison-based Profile Matching (iCPM) by adopting the oblivious transfer cryptographic technique [87]. We consider users have distinct values for any given attribute. As shown in Fig. 3.2, the iCPM consists of three main steps. In the first step, u_i chooses an interested category T_y by setting y-th element to 1 and other elements to 0 in a λ-length vector V_i. u_i then encrypt the vector by using the homomorphic encryption and sends the encrypted vector to u_j. Thus, u_j is unable to know T_y but still can process on the ciphertext. In the second step, u_j computes the ciphertexts with input of self-defined messages $(s_{1,h}, s_{0,h})$ for $1 \leq h \leq \lambda$, two encrypted vectors (m_i, d_i), and its own attribute value $v_{j,x}$. In the last step, u_i decrypts the ciphertext and obtain $s_{1,y}$ if $v_{i,x} > v_{j,x}$ or $s_{0,y}$ if $v_{i,x} < v_{j,x}$.

Protocol Steps: In the iCPM, the responder u_j prepares λ pairs of messages $(s_{0,h}, s_{1,h})$ for category T_h $(1 \leq h \leq \lambda)$ where $s_{0,h}, s_{1,h} \in \mathbb{Z}_p$ and $s_{0,h}, s_{1,h} \leq (p-1)/2$. These messages are not related to u_j's profile. The initiator u_i first decides which category T_y it wants to receive messages related to. But u_i does not disclose T_y to u_j. Then, the responder u_j

shares either $s_{0,y}$ or $s_{1,y}$ to u_i without knowing which one will be received by u_i. When the protocol finishes, u_i receives one of $s_{0,y}$ and $s_{1,y}$ with no clue about the comparison result. We elaborate the protocol steps below.

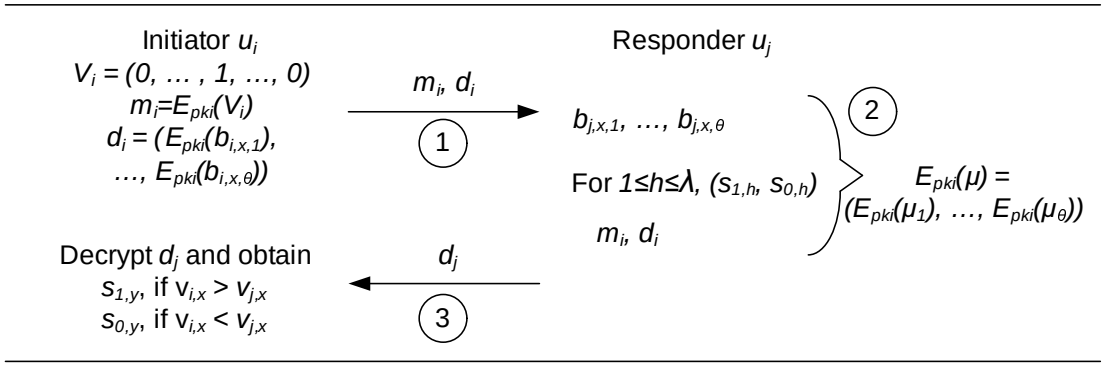


Figure 3.2: The iCPM flow

Step 1. u_i generates a vector $V_i = (v_1, \cdots, v_\lambda)$, where $v_y = 1$ and $v_h = 0$ for $1 \le h \le \lambda$ and $h \ne y$. This vector implies that u_i is interested in the category T_y. u_i sets $m_i = E_{pk_i}(V_i) = (E_{pk_i}(v_1), \cdots, E_{pk_i}(v_\lambda))$. It converts $v_{i,x}$ to binary bits $\langle b_{i,x,1}, \cdots, b_{i,x,\theta} \rangle$, where $\theta = \lceil \log l \rceil$, and sets $d_i = (E_{pk_i}(b_{i,x,1}), \cdots, E_{pk_i}(b_{i,x,\theta}))$. It sends u_j a 6-tuple $(pid_i, cert_{pid_i}, a_x, d_i, m_i, Sign_{psk_i}(a_x, d_i, m_i))$.

Step 2. After receiving the 6-tuple, u_j checks if $(pid_i, cert_{pid_i})$ are generated by the TA and the signature is generated by u_i. If both checks are successful, it knows that (a_x, d_i, m_i) is valid. u_j proceeds as follows:

1. Convert $v_{j,x}$ to binary bits $\langle b_{j,x,1}, \cdots, b_{j,x,\theta} \rangle$ and compute $E_{pk_i}(b_{j,x,t})$ for $1 \le t \le \theta$.
2. Compute $e'_t = E_{pk_i}(b_{i,x,t}) - E_{pk_i}(b_{j,x,t}) = E_{pk_i}(\zeta'_t)$.
3. Compute $e''_t = (E_{pk_i}(b_{i,x,t}) - E_{pk_i}(b_{j,x,t}))^2 = E_{pk_i}(\zeta''_t)$.
4. Set $\gamma_0 = 0$, and compute $E_{pk_i}(\gamma_t)$ as $2E_{pk_i}(\gamma_{t-1}) + e''_t$, which implies $\gamma_t = 2\gamma_{t-1} + \zeta''_t$.
5. Select a random $r_t \in R_p$ in the form of $a\mathbf{x} + b$ where $a, b \in \mathbb{Z}_p, a \ne 0$, and compute $E_{pk_i}(\delta_t)$ as $E_{pk_i}(\zeta'_t) + E_{pk_i}(r_t) \times (E_{pk_i}(\gamma_t) - E_{pk_i}(1))$, which implies $\delta_t = \zeta'_t + r_t(\gamma_t - 1)$.

6. Select a random $r_p \in \mathbb{Z}_p$ ($r_p \neq 0$), and compute $E_{pk_i}(\mu_t)$ as

$$\begin{aligned}&\sum_{h=1}^{\lambda}((s_{1,h}+s_{0,h})E_{pk_i}(1)+s_{1,h}E_{pk_i}(\delta_t)-s_{0,h}E_{pk_i}(\delta_t))\\&\times(r_p((E_{pk_i}(v_h))^2-E_{pk_i}(v_h))+E_{pk_i}(v_h))\\&+r_p(\sum_{h=1}^{\lambda}E_{pk_i}(v_h)-E_{pk_i}(1)).\end{aligned} \tag{3.3}$$

which implies $\mu_t = \sum_{h=1}^{\lambda}(s_{1,h}(1+\delta_t)+s_{0,h}(1-\delta_t))((v_h^2-v_h)r_p+v_h)+(\sum_{h=1}^{\lambda}v_h-1)r_p$.

Then, u_j compiles $E_{pk_i}(\mu) = (E_{pk_i}(\mu_1), \cdots, E_{pk_i}(\mu_\theta))$, and makes a random permutation to obtain $d_j = \mathcal{P}(E_{pk_i}(\mu))$. It finally sends a 5-tuple (pid_j, $cert_{pid_j}$, $a_x, d_j, Sign_{psk_j}(a_x, d_j)$) to u_i.

Step 3. u_i checks the validity of the received 5-tuple. Then, it decrypts every ciphertext $E_{pk_i}(\mu_t)$ in d_j as follows: for $E_{pk_i}(\mu_t) = (c_0, \cdots, c_\alpha)$, obtain μ_t by $\mu_t = (\sum_{h=0}^{\alpha} c_h s^h) \mod p$. If $v_{i,x} > v_{j,x}$, u_i is able to find a plaintext $\mu_t \in \mathbb{Z}_p$ and $\mu_t = 2s_{1,y} \leq p-1$ and computes $s_{1,y}$; if $v_{i,x} < v_{j,x}$, u_i is able to find $\mu_t = 2s_{0,y}$ and computes $s_{0,y}$.

Effectiveness Discussion: The correctness of the iCPM can be verified as follows. If $v_{i,x} > v_{j,x}$, then there must exist a position, say the t^*-th position, in the binary expressions of $v_{i,x}$ and $v_{j,x}$ such that $b_{i,x,t^*} = 1, b_{j,x,t^*} = 0$ and $b_{i,x,t'} = b_{j,x,t'}$ for all $t' < t^*$. Since $\gamma_t = 2\gamma_{t-1} + \zeta_t''$, we have $\gamma_{t'} = 0$, $\gamma_{t^*} = 1$, and $\delta_{t^*} = 1$. For $t'' > t^*$, we have $\gamma_{t''} \geq 2$, and δ_t is a random value due to $r_{t''}$. Since $s_{0,y}$ and $s_{1,y}$ are elements of $\mathbb{Z}_p$ and r_t is in the form of $a\mathtt{x}+b$ ($a, b \in \mathbb{Z}_p, a \neq 0$), u_i can always determine the effective plaintext from others. The effective plaintext will be $\mu_t = \sum_{h=1}^{\lambda}(s_{1,h}(1+\delta_{t^*})+s_{0,h}(1-\delta_{t^*}))((v_h^2-v_h)r_p+v_h)+(\sum_{h=1}^{\lambda}v_h-1)r_p$. If the vector V_i from u_i does not satisfy $\sum_{h=1}^{\lambda} v_h = 1$ or $v_h \in \{0, 1\}$, u_i cannot remove the random factor r_p; if V_i satisfies the conditions, only $s_{1,y}$ and $s_{0,y}$ will be involved in the computation. Because $\delta_{t^*} = 1$, u_i can obtain $\mu_t = 2s_{1,y} \leq p-1$ and recovers $s_{1,y}$. If $v_{i,x} < v_{j,x}$, we similarly have $\mu_t = 2s_{0,y}$ and u_i can obtain $s_{0,y}$.

The confidentiality of user profiles is guaranteed by the homomorphic encryption. The comparison result δ_t is always in the encrypted format, and δ_t is not directly disclosed to u_i. The revealed information is either $s_{1,y}$ or $s_{0,y}$ which is unrelated to user profiles. Therefore, the protocol transactions do not help in guessing the profiles, and the full anonymity is provided. In the meantime, vector V_i is always in an encrypted format so that u_j is unable to know the interested category T_y of u_i. In addition, u_j ensures that only one of $s_{1,y}$ and $s_{0,y}$ will be revealed to u_i. The non-forgeability property is similar to that of the eCPM.

u_i will not lie as it makes signature $Sign_{psk_i}(a_x, d_i)$ and gives it to u_j. The profile forgery attack will be detected if u_j reports the signature to the TA. Moreover, u_j has no need to lie as it can achieve the same objective by simply modifying the contents of $s_{1,y}$ and $s_{0,y}$.

3.3.3 Approach 3: Implicit Predicate-based Approach

Both the eCPM and the iCPM perform profile matching on a single attribute. For a matching involving multiple attributes, they have to be executed multiple times, each time on one attribute. In this section, we extend the iCPM to the multi-attribute cases, without jeopardizing its anonymity property, and obtain an implicit Predicate-based Profile Matching protocol, i.e., iPPM. This protocol relies on a predicate which is a logical expression made of multiple comparisons spanning distinct attributes and thus supports sophisticated matching criteria within a single protocol run (similar to [88]).

As shown in Fig. 3.3, the iPPM is composed of three main steps. In the first step, different from the iCPM, u_i sends to u_j n encrypted vectors of its attribute values corresponding to the attributes in A where A ($|A| = n \leq w$) is the attribute set of the predicate Π. In the second step, u_j sets 2λ polynomial functions $f_{sat,h}(x), f_{unsat,h}(x)$ for $1 \leq h \leq \lambda$. u_j then generates $2\lambda n$ secret shares from $f_{sat,h}(x), f_{unsat,h}(x)$ by choosing $1 \leq h \leq \lambda, 1 \leq x \leq n$, and arranges them in a certain structure according to the predicate Π. For every 2λ secret shares with the same index h, similar to the step 2 of the iCPM, u_j generates θ ciphertexts. u_j obtains $n\theta$ ciphertexts at the end of the second step. In the third step, u_i decrypts these $n\theta$ ciphertexts and finds n secret shares of $s_{1,y}$ and $s_{0,y}$. u_j finally can obtain $s_{1,y}$ or $s_{0,y}$ from the secret shares.

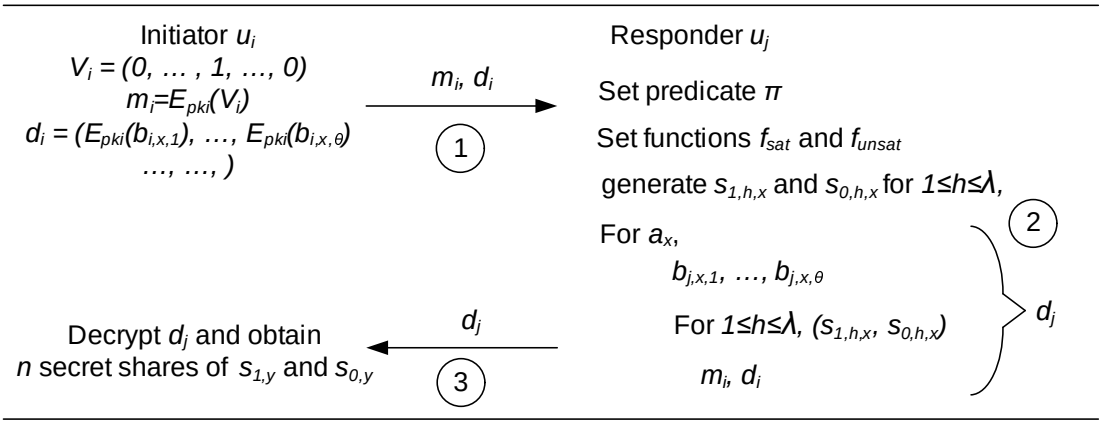


Figure 3.3: The iPPM flow

The iPPM is obtained by combining the iCPM with a secret sharing scheme [83] to support a predicate matching. The initiator u_i sends its attribute values corresponding to the attributes in A to the responder u_j. Without loss of generality, we assume $A = \{a_1, \cdots, a_n\}$. Then, u_j defines a predicate $\Pi =$ "$\bar{t}$ of $\{(v_{i,x}, opt, v_{j,x}) | a_x \in A\}$", where the comparison operator opt is either $>$ or $<$ and $\bar{t} \leq n$. The predicate contains n number of requirements (i.e., comparisons), each for a distinct a_x. The responder u_j determines λ pairs of messages $(s_{0,h}, s_{1,h})$ for attributes a_h $(1 \leq h \leq \lambda)$. The initiator u_i receives $s_{1,h}$ if at least $\bar{t}$ of the n requirements are satisfied, or $s_{0,h}$ otherwise. Similar to the iCPM, T_y is determined by u_i but unknown to u_j. The threshold gate $1 \leq \bar{t} \leq n$ is chosen by u_j. When $n = 1$, the iPPM reduces to the iCPM. The protocol steps are given below.

Step 1. u_i generates a vector $V_i = (v_1, \cdots, v_\lambda)$, where $v_y = 1$ and $v_h = 0$ for $1 \leq h \leq \lambda$ and $z \neq y$, and sets $m_i = E_{pk_i}(V_i) = (E_{pk_i}(v_1), \cdots, E_{pk_i}(v_\lambda))$. In addition, u_i selects the attribute set A $(|A| = n)$, and sends u_j a 6-tuple:

$$(pid_i, cert_{pid_i}, A, d_i, m_i, Sign_{psk_i}(A, d_i, m_i)),$$

where d_i contains $n\theta$ $(\theta = \lceil \log l \rceil)$ ciphertexts as the homomorphic encryption results of each bit of $v_{i,x}$ for $a_x \in A$.

Step 2. u_j checks the validity of the received 6-tuple (similar to the Step 2 of the iCPM). It creates a predicate Π and chooses the threshold gate $\bar{t}$. Using the secret sharing scheme [83], u_j creates 2λ polynomials: $f_{sat,h}(v) = \rho_{\bar{t}-1,h} v^{\bar{t}-1} + \cdots + \rho_{1,h} v + s_{1,h}$ and $f_{unsat,h}(v) = \rho'_{n-\bar{t},h} v^{n-\bar{t}} + \cdots + \rho'_{1,h} v + s_{0,h}$ for $1 \leq h \leq \lambda$, where $\rho_{\bar{t}-1,h}, \cdots, \rho_{1,h}, \rho'_{n-\bar{t},h}, \cdots, \rho'_{1,h}$ are random numbers from $\mathbb{Z}_p^*$. For each attribute $a_x \in A$, it calculates the secret shares of $s_{1,h,x}$ and $s_{0,h,x}$ as follows ($s_{1,h,x}, s_{0,h,x} \leq (p-1)/2$ are required):

$$\begin{cases} s_{0,h,x} = 0 || f_{unsat,h}(x), \\ s_{1,h,x} = 1 || f_{sat,h}(x), & \text{if } \text{“}v_{i,x} > v_{j,x}\text{”} \in \Pi; \\ s_{0,h,x} = 1 || f_{sat,h}(x), \\ s_{1,h,x} = 0 || f_{unsat,h}(x), & \text{if } \text{“}v_{i,x} < v_{j,x}\text{”} \in \Pi. \end{cases} \tag{3.4}$$

Note that u_j adds a prefix 0 or 1 to each secret share such that u_i is able to differentiate the two sets of shared secrets, one for $s_{1,h}$, the other for $s_{0,h}$. u_j runs the Step 2 of the iCPM n times, each time for a distinct attribute $a_x \in A$ and with $(s_{1,h,x}, s_{0,h,x})$ for $(1 \leq h \leq \lambda)$ being input as $s_{1,h}$ and $s_{0,h}$, respectively. u_j then obtains d_j including $n\theta$ ciphertexts. Finally, it sends a 6-tuple $(pid_j, cert_{pid_j}, \bar{t}, A, d_j, Sign_{psk_j}(d_j))$ to u_i.

Step 3. u_i checks the validity of the received 6-tuple. u_i can obtain n secret shares, and each of these shares is either for $s_{0,y}$ or $s_{1,y}$. It then classifies the n shares into two

groups by looking at the starting bit (either '0' or '1'). Thus, if Π is satisfied, u_i can obtain at least $\bar{t}$ secret shares of $s_{1,y}$ and be able to recover $s_{1,y}$; otherwise, it must obtain at least $n - \bar{t} + 1$ secret shares of $s_{0,y}$ and can recover $s_{0,y}$.

The correctness of the iPPM is as follows. At Step 2, the responder u_j executes the Step 2 of the iCPM n times, each time it effectively delivers only one secret share of either $s_{0,y}$ or $s_{1,y}$ to u_i. When u_i receives either $\bar{t}$ shares of $s_{1,y}$ or $n-\bar{t}+1$ shares of $s_{0,y}$, it can recover either $s_{1,y}$ or $s_{0,y}$. The interpolation function corresponding to the secret sharing scheme always guarantees the correctness. The anonymity and non-forgeability of the iPPM are achieved similar to those of the iCPM and the eCPM, respectively.

Efficiency Discussion: Let $|R|$ be the size of one ring element in R_q. In the eCPM, the initiator and the responder both need to send ciphertexts in size of $2|R|$, and the communication overhead is thus subject only to the system parameter $|R|$.

In order to achieve full anonymity, the iCPM constructs ciphertext in a sequence of operations. From Section 2.4.5, we know $|Enc(b)| = 2|R|$. Thus, the communication overhead of the initiator is $2(\theta + \lambda)|R|$ with $\theta = \lceil \log l \rceil$. It can be seen that the initiator's communication overhead increases with system parameters (θ, λ). According to Section 2.4.5 an addition operation of homomorphic encryption does not increase the ciphertext size, while a multiplication with inputs of two ciphertexts of lengths $a|R|$ and $b|R|$ outputs a $(a + b - 1)|R|$-length ciphertext. Thus, in the iCPM, the communication overhead of the responder increases to $6\theta|R|$. It is concluded that the communication overhead of the eCPM and the iCPM is constantly dependent on system parameters (θ, λ).

The iPPM extends the iCPM by building complex predicates. From the protocol description, we observe that if a predicate includes $n \geq 1$ comparisons, the communication overhead of the iPPM would be approximately n times of that in the iCPM.

3.4 Anonymity Enhancing Techniques

3.4.1 Anonymity Measurement

Suppose that user u_i is currently using pseudonym pid_i to execute profile matching with others. We consider an adversary aiming to break the *k-anonymity* of u_i. We have the following definition:

Definition 14 *The k-anonymity risk level of a user is defined as the inverse of the* minimum number of distinct protocol runs (MNDPR) *that are required to break the user's k-anonymity.*

From this definition, the k-anonymity risk level reflects the difficulty that the adversary can break a user's k-anonymity. In the iCPM and the iPPM, the profile matching initiator does not reveal its attribute values to the responder, and the responder has no clue about the comparison result and only reveals the self-defined messages which are not related to the profile. In this case, a user's k-anonymity risk level can be minimum, i.e., no matter how many protocol runs are executed, its k-anonymity risk level is always the lowest. Therefore, the iCPM and the iPPM both provide full anonymity (put users at minimum anonymity risk).

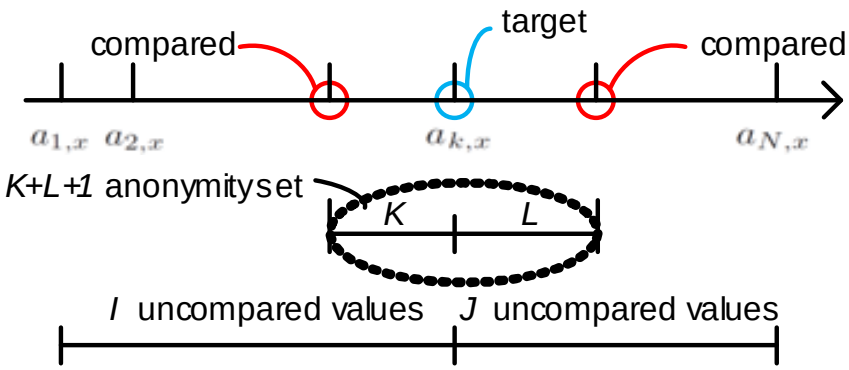
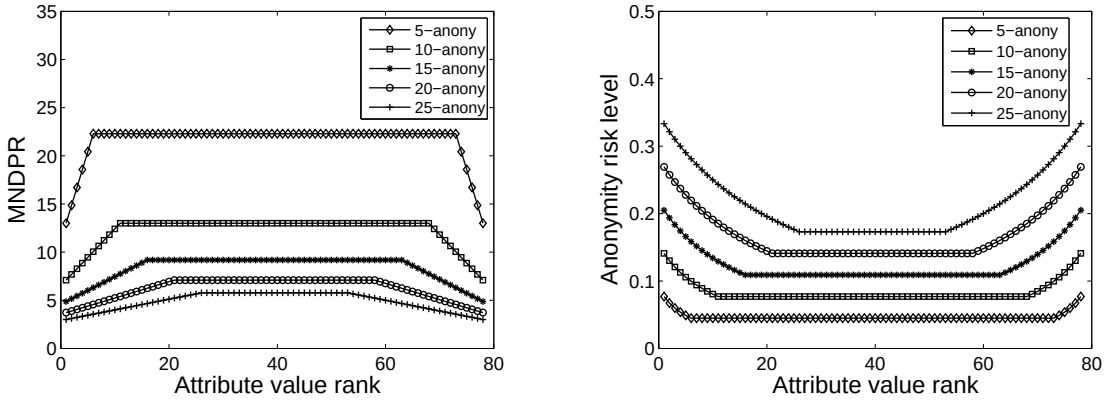


Figure 3.4: Identifying the target from others

For the eCPM, it exposes the comparison results to users and thus obviously puts users at risk of the disclosure of attribute values. Because every eCPM run is executed for a particular attribute (which is specified by the initiator), any user u_i has a k-anonymity risk level on its each individual attribute. When "=" case happens, users have higher anonymity level because they will be indistinguishable from other users with the same attribute values. In the following, we consider the worst case where users have distinctive attribute values on a single attribute. For a given attribute a_x, we assume $a_{1,x} > a_{2,x} > \cdots > a_{N,x}$, where $v_{i,x}$ is the value of u_i on a_x. In order to break u_i's k-anonymity on a_x, the adversary has to make comparisons '$a_{\alpha,x} > v_{i,x}$' and '$v_{i,x} > a_{\beta,x}$' for $\beta - \alpha - 1 < k$ so that the anonymity set of $v_{i,x}$ has a size smaller than k. Let I and J respectively be the numbers of larger and smaller values on a_x among all the users that have not been compared to $v_{i,x}$. Let $K \leq I$ and $L \leq J$ respectively be the number of such un-compared values in the k-anonymity set of $v_{i,x}$. The relations among I, J, K, and L are shown in Fig. 3.4. Assuming the contact is uniformly random, we define a recursive function f as shown in Eqn. (3.5).

$$f(I,J,K,L) = \begin{cases} 0, & \text{if } K+L < k-1 \text{ or } I < K \text{ or } J < L; \\ \frac{I-K}{I+J}(f(I-1,J,K,L)+1) + \frac{J-L}{I+J}(f(I,J-1,K,L)+1) + \\ \frac{\sum_{z=1}^{K}(f(I-1,J,K-z,L)+1)}{I+J} + \frac{\sum_{z=1}^{L}(f(I,J-1,K,L-z)+1)}{I+J}, & \text{otherwise} \end{cases} \tag{3.5}$$

The above function $f(I,J,K,L)$ returns the MNDPR with respect to a user's k-anonymity on a_x in the eCPM. Thus, the user's anonymity risk level in this case is defined as $\mathcal{L} = 1/f(I,J,K,L)$. Since we assumed $a_{1,x}, \cdots a_{N,x}$ are sorted in a descending order, the index i actually reflects the rank of $v_{i,x}$ among the attribute values. Fig. 3.5 plots the MNDPR $f(I,J,K,L)$ and the k-anonymity risk level $\mathcal{L}$ in terms of 78 users' attribute values where $k = 5, 10, \cdots, 25$. It can be seen that a user with a median attribute value will have a lower k-anonymity risk level than those with larger or smaller values. This is reasonable because the user with a median attribute value is less distinctive from other users.



(a) MNDPR per 78 users

(b) Anonymity risk level

Figure 3.5: Numerical results on user anonymity risk level

3.4.2 Anonymity Enhancement

We have derived the maximum number of distinct eCPM runs (MNDPR) before a user's k-anonymity is broken. This number is obtained under an assumption of uniformly random

contact. However, in reality, users as social entities are likely to gather with others who have similar attribute values. This situation increases user anonymity risk level quickly when profile matching is executed frequently, and the k-anonymity can be broken within a much smaller number of the eCPM runs as a result. Recall that multi-pseudonym techniques are used to protect user identity and location privacy. Similar to previous work [25, 74], here we consider that pseudonyms themselves are unlinkable. In the eCPM, if a user does not change the pseudonym, the comparison result will be easily linked to break the k-anonymity. If a user changes pseudonym for each protocol run, information revealed by the protocol cannot be directly linked, and the user obtains highest anonymity. Nevertheless, it is desirable that the user changes pseudonym only when necessary, since pseudonyms are limited resources and have associated cost [25, 74] (e.g., communication cost for obtaining them from the TA and computation cost for generating them on the TA). Thus, user anonymity is tightly related with pseudonym change frequency.

Our goal is to improve the anonymity strength of the eCPM by combining it with a pre-adaptive pseudonym change strategy which enables users to take necessary pseudonym change action before their k-anonymity is broken. The new verso of the eCPM is referred to as eCPM+. Before presenting the pre-adaptive strategy, we first introduce a post-adaptive pseudonym change strategy, where users measure their anonymity risk levels periodically and change their pseudonym after their anonymity risk levels becomes larger than a predefined threshold value.

The post-adaptive strategy assumes that a user u_j as responder runs the protocol on an attribute a_x with an initiator u_i (recognized by seeing the same pseudonym) only once, and refuses to participate any subsequent protocol running on the same a_x with u_i. However, if u_i has changed its pseudonym since the last protocol running with u_j, then u_j will consider u_i as a *new partner* and participate the protocol. Time is divided into slots of equal duration. The *neighborhood status* of u_i on attribute a_x in a time slot is characterized by a pair of values $NS_{i,x} = (n_{i,x,s}, n_{i,x,l})$, respectively implying the number of new partners (identified in the time slot) with attribute values smaller than $v_{i,x}$ and the number of those with attribute values larger than $v_{i,x}$. It varies over time due to user mobility and can be modeled as a time series data.

The centre of this strategy is the continuous measurement of user anonymity risk level based on neighborhood status. In the iCPM, attribute values are protected, and users obtain the matching results. For every attribute a_x, user u_i maintains the numbers $N_{i,x,s}$ and $N_{i,x,l}$ of discovered values that are smaller and larger than its own value $v_{i,x}$ since the last change of pseudonyms. These two numbers are respectively the sum of individual $n_{i,x,s}$ and the sum of $n_{i,x,l}$ corresponding to the past several time slots. Recall that $v_{i,x}$ is ranked the i-th largest among all N users in the network. Let $I = i - 1$ and $J = N - i$. u_i is not

able to compute the accurate MNDPR because it does not have the information of the last two arguments of function $f()$ (see Eqn. 3.5). The anonymity risk level of u_i on a_x may be estimated as $\mathcal{L} = 1/f'(N_{i,x,s}, N_{i,x,l})$, where $f'(N_{i,x,s}, N_{i,x,l})$ approximates the MNDPR of u_i regarding a_x and is given as $\sum_{\substack{1\le\alpha\le I-N_{i,x,s}\\ 1\le\beta\le J-N_{i,x,l}}} \Pr[(\alpha,\beta)] \cdot f(I-N_{i,x,s}, J-N_{i,x,l}, \alpha, \beta)$. For simplicity, we assume that the $N_{i,x,s}$ values are randomly distributed among the $I-\alpha$ users ($0 \le \alpha \le I - N_{i,x,s}$) with larger values on a_x than u_i and the $N_{i,x,l}$ values are randomly distributed among the $J-\beta$ smaller-value users ($0 \le \beta \le J - N_{i,x,l}$). Thus, for $N_{i,x,s} \ge 1$ and $N_{i,x,l} \ge 1$, we have $f'(N_{i,x,s}, N_{i,x,l})$ as

$$\sum_{\substack{0\le\alpha\le I-N_{i,x,s}\\ 0\le\beta\le J-N_{i,x,l}}} \frac{\binom{I-\alpha-1}{N_{i,x,s}-1}\binom{J-\beta-1}{N_{i,x,l}-1}}{\binom{I}{N_{i,x,s}}\binom{J}{N_{i,x,l}}} f(I-N_{i,x,s}, J-N_{i,x,l}, \alpha, \beta). \tag{3.6}$$

For $N_{i,x,s} = 0$ and $N_{i,x,l} \ge 1$, $f'(N_{i,x,s}, N_{i,x,l})$ is

$$\sum_{0\le\beta\le J-N_{i,x,l}} \frac{\binom{J-\beta-1}{N_{i,x,l}-1}}{\binom{J}{N_{i,x,l}}} \cdot f(I, J-N_{i,x,l}, I, \beta). \tag{3.7}$$

For $N_{i,x,s} \ge 1$ and $N_{i,x,l} = 0$, $f'(N_{i,x,s}, N_{i,x,l})$ is

$$\sum_{0\le\alpha\le I-N_{i,x,s}} \frac{\binom{I-\alpha-1}{N_{i,x,s}-1}}{\binom{I}{N_{i,x,s}}} \cdot f(I-N_{i,x,s}, J, \alpha, J). \tag{3.8}$$

In the above computation, u_i needs to know N and its value rank i. The information can be obtained from the TA when u_i registers to the TA. If users are allowed to freely leave and enter the network, they will need to de-register/re-register themselves with the TA when leaving/joining the network. In this case, (N, t) are changing, and the TA has to be involved in the network operation in order to maintain latest network status and update users with the latest information.

The post-adaptive strategy also relies on *pseudonym lifetime* for making pseudonym change decisions. Suppose that user u_i is currently using pseudonym pid_i. The longer pid_i has been used, the more private information of u_i is leaked in case its anonymity has been broken. Hence, when u_i's anonymity risk level $\mathcal{L}_i$ has stayed unchanged for a certain duration, called the lifetime of pid_i and denoted by $\tau(pid_i)$, u_i changes its pseudonym for damage control. However, $\tau(pid_i)$ should not be given as a constant value, but subject to $\mathcal{L}_i$. The higher $\mathcal{L}_i$ is, the more possible the anonymity of u_i is broken, and therefore the

smaller $\tau(pid_i)$ is. We define $\tau(pid_i) = \xi \frac{\text{MNDPR}_i}{\mathcal{L}_i}$, where MNDPR_i is obtained by Eqn. 3.5 and $\xi > 1$ is the pseudonym lifetime factor.

For the pre-adaptive pseudonym change strategy, each user u_i initializes an ARMA model for its neighborhood status on every attribute when entering the network. Since it has w attributes, the number of ARMA models to be initialized is w. At the end of each time slot, it measures its current neighborhood status on each attribute and updates the corresponding ARMA models. It takes the post-adaptive strategy for each attribute to determine whether to change its pseudonym. In case pseudonym change is not suggested, it proceeds to predict the neighborhood status on all the attributes in the following time slot using the ARMA models. If one of the predicted neighborhood status leads to an unacceptable anonymity risk level, it changes its pseudonym; otherwise, it does not. The pre-adaptive strategy strengths the post-adaptive strategy by one-step ahead prediction based decision making and generally enhances user anonymity.

3.5 Performance Evaluation

The eCPM+ addresses accumulative anonymity risk in multiple protocol runs and tunes itself automatically to maintain desired anonymity strength. Some previous works [28, 31] are concerned only with the anonymity risk brought by each individual protocol run, and some works [26] reduce anonymity risk by manually adjusting certain threshold values. Though they provide the conditional anonymity as the eCPM, they are not comparable to the eCPM and the eCPM+ because the anonymity protection of users is considered in terms of consecutive protocol runs. Therefore, in this section we evaluate the eCPM+ (which uses a pre-adaptive pseudonym change strategy) in comparison with two other eCPM variants, respectively employing a constant pseudonym change interval z (CONST-z) and a post-adaptive pseudonym change strategy (Post).

3.5.1 Simulation Setup

Our simulation study is based on the real trace [35] collected from 78 users attending a conference during a four-day period. A contact means that two users come close to each other and their attached Bluetooth devices detect each other. The users' Bluetooth devices run a discovery program every 120 seconds on average and logged about 128, 979 contacts. Each contact is characterized by two users, a start-time, and a duration. In CONST-z, we set the pseudonym change interval z from 1 to 40 (time slots); in the post-adaptive

and pre-adaptive strategies, we set pseudonym lifetime factor $\xi = 30$. In the pre-adaptive strategy, we use ARMA order $(10, 5)$.

We use the contact data to generate user profiles. According to social community observations [89], users within the same social community often have common interests and are likely interconnected through strong social ties [20]. The stronger tie two users have, the more likely they contact frequently. Let $f_{i,j}$ denote the number of contacts of users u_i and u_j. We build a complete graph of users and weight each edge (u_i, u_j) by $f_{i,j}$. By removing the edges with a weight smaller then 100, we obtain a graph G containing 78 vertices and 2863 edges. We find all maximal cliques in G using the Bron-Kerbosch algorithm [90]. A clique is a complete subgraph. A maximal clique is a clique that cannot be extended by including one more adjacent vertex. We obtain the 7550 maximal cliques $C_1, \cdots, C_{7550}$ that all contain ≥ 15 users.

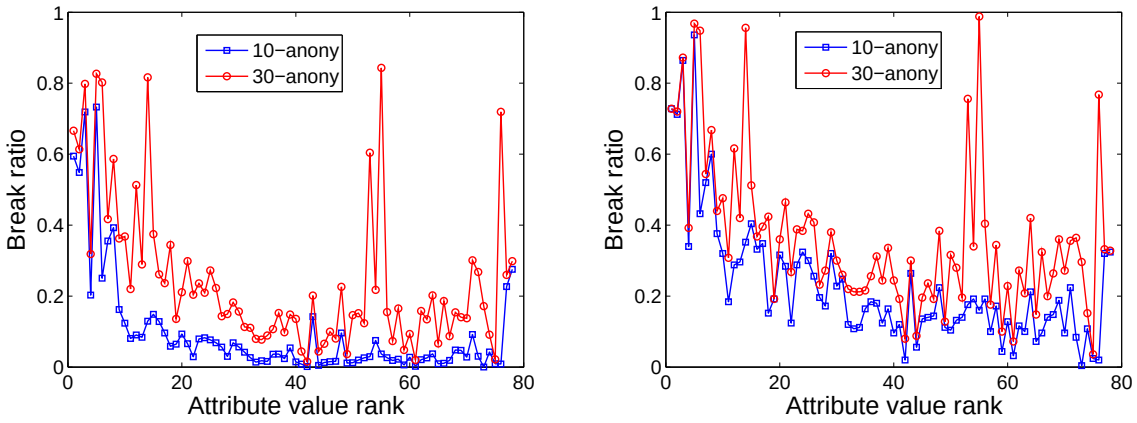
Without loss of generality, we assume that these cliques are sorted in the descending order of the weight sum of their edges (the weight sum of C_1 is the largest). We then construct communities in the following way. Scan the sequence of cliques from C_1 to C_{7550}. For a scanned clique C_i, find a clique C_j that has been previously scanned and identified as *core clique* and contains $\geq 80\%$ vertices of C_i. If there are multiple such cliques, take the one with largest weight sum as C_j. If C_j is found, assign C_i with the same attribute as C_j; otherwise, generate a new attribute, assign it to C_i, and mark C_i as a core clique. After the attribute generation and assignment, merge the cliques with the same attribute into a community. A community contains multiple users, and a user may belong to multiple communities. From the above settings, we generate 349 attributes and thus obtain 349 communities. We however concentrate on the first generated 100 attributes and their corresponding communities for simplicity. On average, each of these considered communities contains 28 users, and each user belongs to 38 communities.

Afterwards, we assign values to each user in G for these 100 attributes. For an attribute a_x, we find the corresponding community $\mathcal{C}_x$ and do the following. For each user in $\mathcal{C}_x$, we compute the weight sum of its incidental edges in $\mathcal{C}_x$; for each vertex outside $\mathcal{C}_x$, we compute the weight sum of its incident edges to the vertices in $\mathcal{C}_x$; then, we sort all the users in the decreasing order of their weight sums and assigned their values on a_x with $(78, 77, \cdots, 1)$. This assignment method is reasonable because a large weight sum indicates a large interest in communicating with users in $\mathcal{C}_x$ and thus a strong background in the aspect represented by a_x.

Our simulation spans $10,000$ time slots, each lasting 30 seconds, and focuses on a randomly selected attribute. Users can change their pseudonym at the beginning of each time slot. The pseudonym is *corrupted* in terms of k-anonymity (on the selected attribute)

if there are less than $k-1$ other users in the network that will obtain the same matching results in the same protocol settings. A user experiences an anonymity break (on the selected attribute) if it is using a *corrupted* pseudonym.

3.5.2 Simulation Results

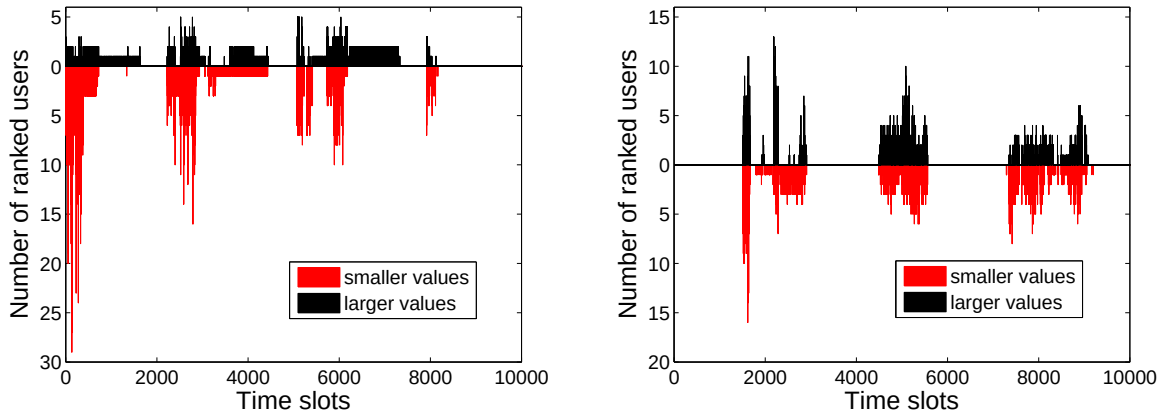


(a) $z = 1$ (b) $z = 20$

Figure 3.6: Anonymity break period under the constant strategy

Figure 3.6 shows the anonymity break period experienced by each user with the constant strategy being used. It can be seen that when $z = 1$, each user experiences the shortest anonymity break period at the cost of $10,000$ pseudonyms per user. Anonymity break is still possible in this extreme case because users may have multiple contacts within a single time slot while they are still using the same pseudonym. If a user has a more restrictive anonymity requirement (e.g., from 10-anonymity to 30-anonymity) or uses a larger pseudonym change interval (from 1 time slot to 20 time-slots), it will have more *corrupted* pseudonyms and thus suffer a longer period of anonymity break.

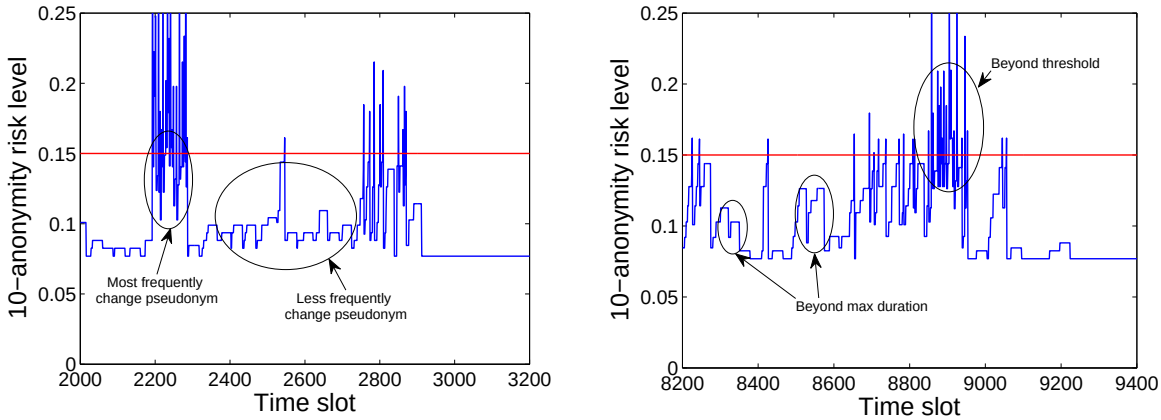
The neighborhood status of a user on a given attribute is characterized by the number of neighbors with larger values and the number of neighbors with smaller values. We investigate the regularity of neighborhood status of individual users over time and justify the effectiveness of pre-adaptive strategy. To do so, we randomly choose two users, ranked respectively the 7th and the 32nd. Figure 3.7 shows their neighborhood status. The 7th user's neighborhood status exhibits regular change, i.e., the number of neighbors with



(a) The 7th user (b) The 32nd user

Figure 3.7: Neighborhood status over time

larger values stays stable, and that of neighbors with smaller values decrease linearly over time. For the 32nd user, the number of users with larger values and the number of users with smaller values both decrease.



(a) Time period $(2000, 3200)$ (b) Time period $(8200, 9400)$

Figure 3.8: Anonymity risk level over time ($th = 0.15$)

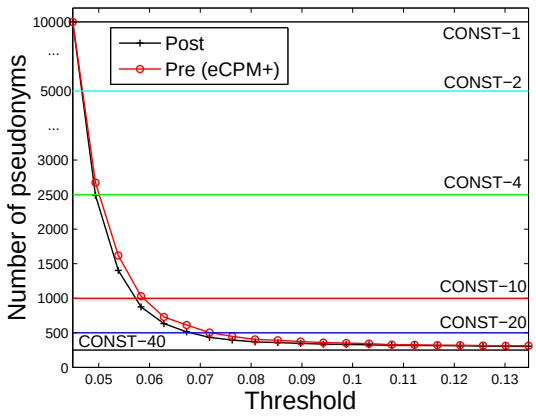
We choose the 32nd user, who in general has lower anonymity risk level than the 7th user, and show its 10-anonymity risk level in two consecutive time periods $(2000, 3200)$

and $(8200, 9400)$ with the post-adaptive strategy in Fig 3.8. The anonymity risk level threshold is $th = 0.15$. In the figure, the drop from a high risk level to a low risk level indicates a pseudonym change. Recall that a user changes its pseudonym not only when the anonymity risk level is beyond threshold th but also when its current pseudonym expires. This is reflected by the anonymity risk level drop happened below the threshold line in the figure. From Fig. 3.7, we can see that the pseudonym change frequency is high when the user encounters a large number of neighbors. This is reasonable as a large number of profile matching runs are executed in this case, and the user's anonymity risk level grows quickly. When the level is beyond a pre-defined threshold, the user changes its pseudonym.

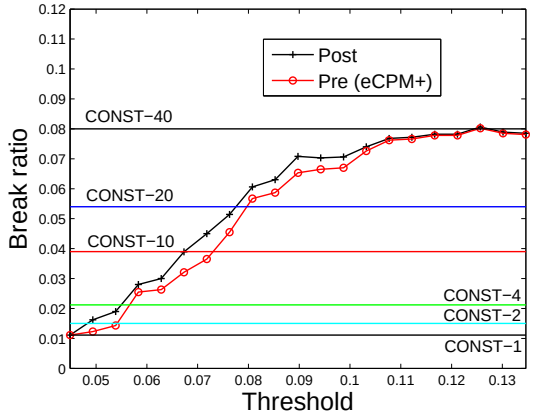
Figure 3.9 shows the performance of the constant, the post-adaptive and the pre-adaptive strategies respectively for 5-anonymity and 10-anonymity, in relation with threshold th. The results are obtained with respect to the 32nd user. For the constant strategy, multiple lines are plotted, respectively corresponding to $z = \{1, 2, 4, 10, 20, 40\}$. As z goes up, the user consumes a decreasingly number of pseudonyms and has an increasingly break ratio (the ratio of the number of time slots that the k-anonymity of the 32nd user is broken to 10,000). It can be seen that the number of pseudonyms consumed by the post-adaptive and pre-adaptive strategies are much smaller than those of the constant strategy. For example, in the case of 5-anonymity and $th = 0.0763$, the post-adaptive strategy spends 369 pseudonyms and results in a 514 time slot anonymity break period. The constant strategy consumes $500(> 369)$ pseudonyms and has a $0.0540(> 0.0514)$ break ratio. The post-adaptive strategy outperforms the constant strategy in anonymity protection by using fewer pseudonyms to achieve smaller break ratio. Similar phenomena are observed for other th values and 10-anonymity scenario as well. In particular, we find that as expected, the pre-adaptive strategy leads to yet better anonymity performance than the post-adaptive one. Fig. 3.9 shows that in case of 5-anonymity and $th = 0.0763$, the pre-adaptive strategy consumes $449(> 369)$ pseudonyms and results in a $0.0445(< 0.0514)$ break ratio. The pre-adaptive strategy consumes slightly more pseudonyms, but achieves significantly shorter anonymity break period.

3.6 Related Work

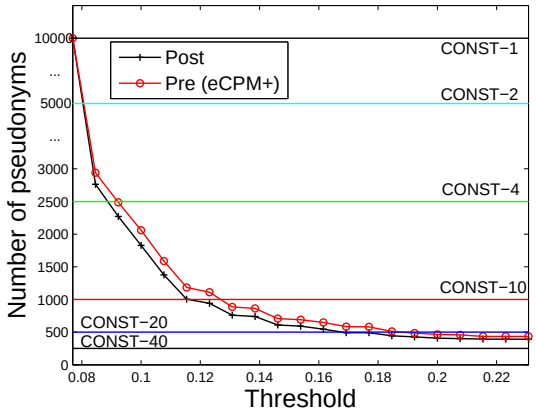
In general, the profile matching can be categorized based on the formats of profiles and the types of matching operations. A well-known profile matching is the FNP scheme [62], where a client and a server compute their intersection set such that the client gets the result while the server learns nothing. Later, Kissner et al. [91] implemented profile matching with more operations including set intersection, union, cardinality and over-threshold operations. On



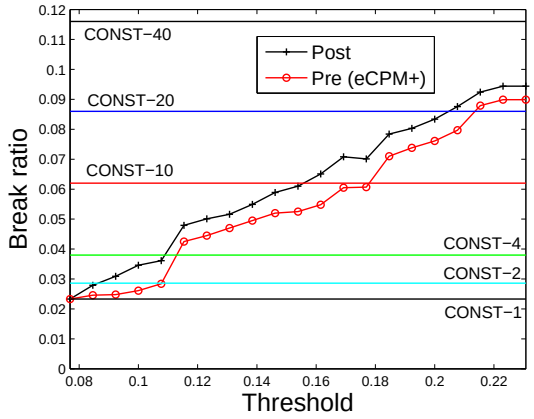
(a) # of pseudonyms for 5-anonymity



(b) 5-anonymity break period



(c) # of pseudonyms for 10-anonymity



(d) 10-anonymity break period

Figure 3.9: Pseudonyms and break ratio (the 32nd user)

the other hand, Ye et al. [92] further extended the FNP scheme to a distributed private matching scheme and Dachman-Soled et al. [93] aimed at reducing the protocol complexity. All the above solutions to the set intersection rely on homomorphic encryption operation. In the meantime, other works [94, 95] employed an oblivious pseudo random function to build their profile matching protocols, where communication and computational efficiency is improved. Li et al. [28] implemented profile matching according to three increasing privacy levels: i) revealing the common attribute set of the two users; ii) revealing the size of the common attribute set; and iii) revealing the size rank of the common attribute sets between a user and its neighbors. They considered an honest-but-curious (HBC) adversary model, which assumes that users try to learn more information than allowed by inferring from the profile matching results, but honestly following the protocol. They applied secure multiparty computation, the Shamir secret sharing scheme, and the homomorphic encryption scheme to achieve the confidentiality of user profiles.

In another category of profile matching [26,31,96], profiles can be represented as vectors, and matching operation can be inner product or distance. Such profile matching is a special instance of the secure two-party computation, which was initially introduced by Yao [97] and later generalized to the secure multi-party computation by Goldreich et al. [98]. Specifically, we introduce two recent works in this category. Dong et al. [26] considered user profile consisting of attribute values and measured the proximity of two user profiles using dot product $f_{dot}(u, v)$. An existing dot product protocol [99] is improved to enable verifiable secure computation. The improved protocol only reveals whether the dot product is above or below a given threshold. The threshold value is selected by the user who initiates the profile matching. They pointed out the potential anonymity risk of their protocols; an adversary may adaptively adjust the threshold value to quickly narrow down the value range of the victim profile. Thus, it is required that the threshold value must be larger than a pre-defined lower bound (a system parameter) to guarantee user anonymity. The same problem exists in other works [28, 31]. Furthermore, Dong et al. [26] required users to make a commitment about their profiles to ensure the profile consistency, but profile forgery attack may still take place during the commitment phase. In the same category, Zhang et al. [31] set the matching operation $f_{dis}(u, v)$ of two d-dimension user profiles u and v as the calculation of the following distances: i) Manhattan distance, i.e., $f_{dis}(u, v) = l_\alpha(u, v) = (\sum_1^d |v_i - u_i|^\alpha)^{\frac{1}{\alpha}}$; or ii) Max distance, i.e., $f_{dis}(u, v) = l_{max}(u, v) = \max\{|v_1 - u_1|, \cdots, |v_d - u_d|\}$. The distance is compared with a pre-defined threshold τ to determine whether u and v match. Then, three increasing privacy levels are defined as: i) one of u and v learns $f_{dis}(u, v)$, and the other only learns f_{dis}; ii) one of them learns $f_{dis}(u, v)$, and the other learns nothing; and iii) one of them learns whether $f_{dis}(u, v) < \tau$, and the other learns nothing.

3.7 Summary

We have investigated the privacy-preserving profile matching problem, and introduced three comparison-based profile matching protocols, the explicit comparison-based profile matching protocol (eCPM), the implicit comparison-based profile matching protocol (iCPM), and the implicit predicate-based profile matching protocol (iPPM). We have shown that the eCPM achieves *conditional anonymity* and both the iCPM and the iPPM achieves *full anonymity*. We have further introduced an enhanced version of the eCPM, i.e., eCPM+, by exploiting the prediction method and the pre-adaptive pseudonym change. The effectiveness of the eCPM+ is validated through extensive simulations using real-trace data.

Chapter 4

Cooperative Data Forwarding Strategy with Privacy Preservation

4.1 Introduction

In the MSN, users rely on the opportunistic contacts for cooperative data forwarding. Unlike conventional wireless relay networks assuming end-device to be insensate, users have specific social features, e.g., privacy concerns and selfishness, and they will choose a data forwarding strategy under the impacts of these features. For example, when privacy preservation of users is applied, users become unrecognizable to each other and the social ties and interactions are no longer traceable. In this case, there is no obvious incentives for users to be cooperative on data forwarding. Thus, due to the selfish behavior, the cooperative data forwarding could be severely interrupted or even disabled.

In this chapter, we address the privacy preservation problem and the data forwarding problem in the MSN. Our goal is to resolve the two problems in one framework by proposing a privacy preserving social-based cooperative data forwarding protocol. We exploit the social morality for cooperative data forwarding design. The morality of human beings is a common social phenomenon which provides the rules for people to act upon and grounds the moral imperatives. It is the fundament of a cooperative and mutually beneficial social life in the real-world society. Specifically, we will address the problem according to three steps.

First, we identify the conflicting nature between privacy preservation and cooperative data forwarding in the MSN. We leverage social morality to model the user cooperation and accordingly promote the communication efficiency.

Second, we introduce a three-step protocol suite to attain the privacy-preserving data forwarding. In step one, we introduce a privacy-preserving route-based authentication scheme. It enables users to expose the mobility information to each other for cooperation, yet with location privacy preserving. In step two, based on the mobility of users, we evaluate the forwarding capability of individual users on a given packet. In step three, a game-theoretic approach taking account of both the morality and forwarding capability is designed to adaptively determine the optimal data forwarding strategy for individual users.

Third, we evaluate the performance of the protocols through extensive trace-based simulations. The simulation results validate the efficiency of the data forwarding protocols and the location privacy preservation.

The remainder of this chapter is organized as follows: In Section 4.2, we present the network model and design goal. Then, we introduce the three-step protocol suite in Section 4.3. We evaluate the protocol in a trace-based simulation environment in Section 4.4. Lastly, we review the related work and draw our summary respectively in Section 4.5 and Section 4.6.

4.2 Models and Design Goal

4.2.1 Network Model and Social Behavior Model

We consider an MSN composed of a set $\mathcal{V} = \{u_1, \cdots, u_N\}$ of mobile users with the network size $|\mathcal{V}| = N$. Users have equal communication range, denoted by R_t. The communication between any two users u_i and u_j, is bidirectional, i.e., u_i can communicate to user u_j if and only if user u_j can also communicate to u_i. Users follow the same behavior model: they are selfish, tending to maximize their individual utilities during data forwarding, and do not perform irrational attacks. A trusted authority is available at the initialization phase for generating pseudonyms and secret keys for MSN users, but it will not be involved in the data forwarding (Section 2.1). Users continuously change their pseudonyms to preserve their identity and location privacy. The pseudonym change breaks any relation previously established between two users and as a result they can no longer recognize each other.

User Location Privacy: We assume that there exists a set $\mathcal{A} = \{a_1, \cdots, a_l\}$ of social hotspots in the network. They are located in regions such as supermarkets, restaurants, office buildings and residential blocks with high population density as shown in Fig. 1.1. Different users have different sets of favored hotspots that they frequently visit. The

hotspots that a user visited in the past indicate the personal preference of the user and thus may relate to the user's future locations [100]. In addition, the hotspots can be categorized into sensitive hotspots, e.g., office buildings, residential blocks, and non-sensitive hotspots, e.g., supermarkets, restaurants. Sensitive hotspots are tightly related to users' personal lives. The access to sensitive hotspots needs to be protected according to users' privacy needs. In this work, users are able to anonymize their sensitive hotspots, and thus the hotspots can be used to assist data forwarding with the location privacy preservation.

User-to-Spot Data Forwarding: We introduce a user-to-spot data forwarding protocol to achieve privacy preservation and user cooperative data forwarding. Specifically, each hotspot is equipped with a non-compromised and communicable storage device which buffers the packets for receivers to fetch. A data sender/forwarder leaves packets at selected hotspots, and receivers can fetch the packets upon their later access to the same hotspots. Compared with the contact-based data forwarding protocols where users swap

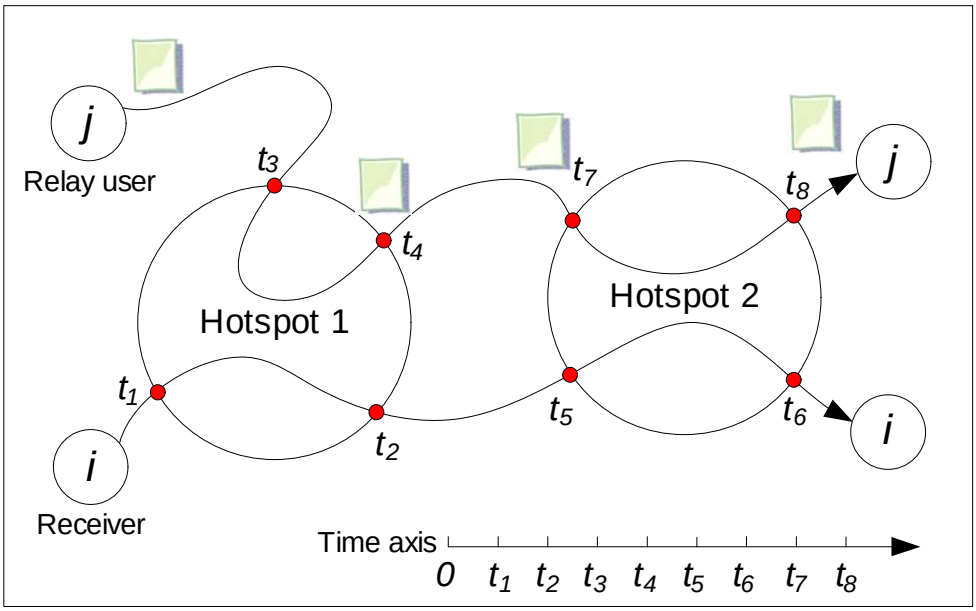


Figure 4.1: An illustration of effective data forwarding

data upon their contacts, the user-to-spot data forwarding protocol would have more successful deliveries in special cases as shown in Fig. 4.1. In this figure, relay user u_j has no contact with receiver u_i but they enter the common hotspots during different time periods. By making use of this property, the user-to-spot data forwarding protocol enables u_j to deliver the packet to u_i. This user-to-spot data forwarding protocol is practical due to the

following facts:

- Social users often have specific preferences on common social hotspots, such as supermarkets, office buildings, etc. They are likely to choose part of these hotspots and visit them frequently.
- In the MSN, data sender often has certain social relationship with receiver. The sender is likely to be partially aware of the social behaviors and frequently-visited hotspots of the receiver.
- Hotspot buffers are low-cost and can be pervasively available data storage resources [101]. They are not interconnected and will not be involved in cooperative data forwarding. They act as static receivers to temporarily store user data and allow authorized wireless access of the data when users come into their wireless communication range.

In this work, the identity of the receiver is implicitly contained (thus protected) in the packet, and the receiver can fetch the packet from the hotspot buffer after a simple authentication operation, e.g., using the scheme in [102].

Observing the unique social features in the MSN, we exploit the morality factor of the MSN by mimicking the morality-centric human society. We emphasize that the morality factor should be counted into the calculation of users' utility. To this end, we instantiate two forms of social morality, i.e., guilt and high-mindedness, in the context of MSN-based data forwarding where cooperation is highly desirable: users feel *guilty* when they defect (i.e., refuse to forward a packet), and they feel *high-minded* when choosing to cooperate (i.e., help to forward a packet). Guilt creates a feeling of indebtedness, which directs them to cooperate, while high-mindedness alleviates the guilty feeling of users.

A self-regulated morality factor g, internalized for each user that quantitatively depicts the internal moral force, is based on two elements:

- *Morality state* x: The morality state reflects the behavior history of a user. It increases by one level for a single cooperation behavior and decreases by one level due to a single defection conduct.
- *Sociality strength* st: The sociality strength st is related to a user's personal experience, such as education and habitation. It is stabilized and less independent with short-term behavior changes. If the sociality strength of a user is significant, the

user feels a correspondingly significant increment of guilt towards a single defection behavior and a correspondingly significant increment of high-mindedness towards a single cooperation behavior.

Each u_i has a sociality strength denoted by st_i, and a varying morality state x_i. Following social theory [41, 42], we depict the morality state x_i by a Markov chain model with the state space and non-null transitions shown in Fig. 4.2. Let $P_i(j, j+1)$ and $P_i(j, j-1)$ denote the transition probabilities from the u_j-th state to the $(j+1)$-th and the $(j-1)$-th states, respectively. The state $j = 0$ is the initial neutral state (neither guilty nor high-minded). The states with a positive index are high-minded states, and those with a negative index are guilty states. Being in a high-minded state implies frequent cooperation behavior in the past; being in a guilty state indicates overwhelming defection conduct in the past. The morality factor g_i of u_i is evaluated by a function $f(x_i, st_i)$ that increases as x_i decreases or st_i increases. Later, in Section 4.4 when we present our performance evaluation, we will define a specific $f()$.

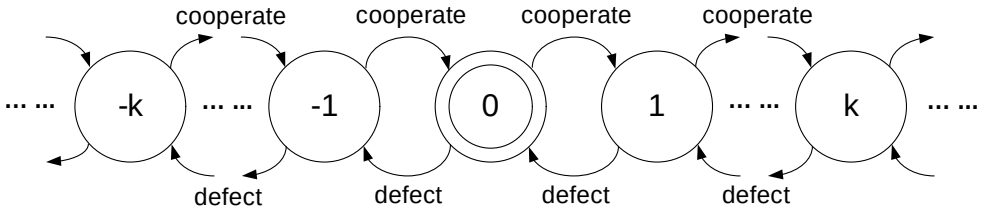


Figure 4.2: Markov chain model for morality state

4.2.2 Design Goal

We address a fundamental tradeoff between the privacy preservation and the data forwarding efficiency in the MSN. Specifically, with the *multiple pseudonym* technique applied for privacy preservation, an unpleasant accompanying side-effect is that users are unable to identify their social friends because of the anonymity of users. This directly impedes the cooperative data forwarding as social ties among users are interrupted. Since users are anonymous, the malicious behaviors (e.g., selfish and free-riding) can no longer be tracked and punished on time using traditional mechanisms.

This may discourage user cooperations and deteriorate the data forwarding efficiency. Therefore, privacy preservation protects and hides the identities of users to the public,

which, however, hinders the social-based cooperative data forwarding. Our goal is *to resolve the two conflicting goals in one framework by proposing a privacy preserving social-based cooperative data forwarding protocol*. We exploit the social morality for cooperative data forwarding design. Specifically, the morality of human beings is a common social phenomenon in real-world which provides the rules for people to act upon and grounds the moral imperatives.

4.3 PDF Solutions

4.3.1 Overview of the Protocol

With the user-to-spot data forwarding protocol deployed, in the following sections, we concentrate on how to forward packets to the hotspots for effective and efficient data forwarding with privacy preservation. This delivery is enabled in three steps:

1. Privacy-preserving route-based authentication,
2. Proximity measurement,
3. Morality-driven data forwarding.

In the first step, the privacy-preserving route-based authentication enables two encountered users to exchange partial route information. The route information can be constructed in a privacy-preserving structure determined by users themselves. The use of an authentication scheme is to resist user manipulation attacks, i.e., users have to honestly tell about their hotspots. In the second step, each user measures a proximity score between the destination and the route information provided by the relay user. The proximity score reflects the forwarding capability of a relay node with respect to a specific destination. The larger a proximity score is, the more effective a relay's forwarding is. In addition, the proximity score also affects the morality factor of the relay node. The rationale is that a user would feel more guilty if he/she demonstrates more capability to deliver a packet (with a large proximity score), and yet, drops the packet. In the third step, the morality factor is incorporated into the utility calculation of a data forwarding game in which users act selfishly and preserve their privacy. We elaborate these three steps in the subsequent sections. Note that, we do not consider irrational attacks here. Users tend to be rational and selfish to maximize their own utility.

4.3.2 Step1: Privacy-Preserving Route-Based Authentication

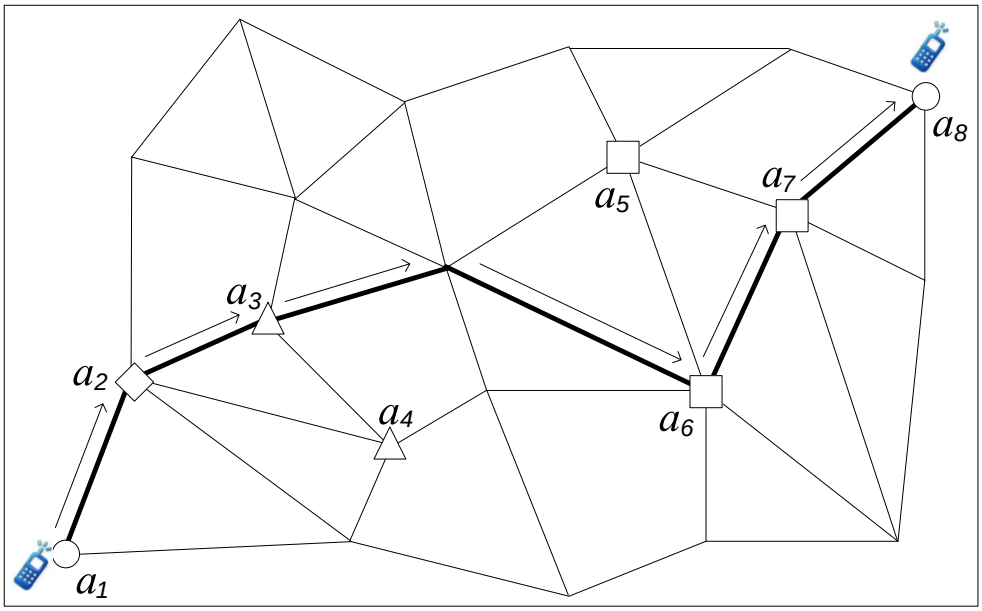


Figure 4.3: Geographical view of u_i's route

We first show how to construct a privacy-preserving *routing tree* which describes the route of u_i between hotspots. At an initial stage, the TA associates u_i to a subset of hotspots $\mathcal{A}_i = \{a_y | y = (2, 3, 6, 7)\} \subseteq \mathcal{A}$, which represents the hotspots frequently visited by u_i. We consider that u_i is located at hotspot a_1 and moving towards a_8, as shown in Fig. 4.3. Suppose that u_i moves along the route $a_1 \rightarrow a_2 \rightarrow a_3 \rightarrow a_6 \rightarrow a_7 \rightarrow a_8$. Users neighboring u_i have already known u_i's current location a_1. But u_i has no intention to reveal a_8 to them for privacy reason. In addition, it is unwilling to authenticate the entire hotspot set $\{a_y | y = (2, 3, 6, 7)\}$, which contains privacy-sensitive hotspots $\{a_3, a_6, a_7\}$. Then u_i creates a tree for its mobility route $\mathcal{T}_i$ as "a_2 AND (a_3 OR a_4) AND (2 of (a_5, a_6, a_7))" and only authenticates this tree to others. The authentication reveals the following fuzzy information instead of the precise route: u_i will visit a_2, one of (a_3, a_4), and at least two hotspots from (a_5, a_6, a_7).

We present the routing tree structure $\mathcal{T}$ as shown in Fig. 4.4, where each non-leaf node represents a threshold gate and each leaf node represents a hotspot in $\mathcal{A}_u$. We use $\mathcal{A}_\mathcal{T} = \{a_{z_1}, a_{z_2}, \cdots, a_{z_\tau}\} \subseteq \mathcal{A}_u$ to denote the hotspot set corresponding to all leaf nodes in $\mathcal{T}$. Note that, if we assign 0 or 1 to the hotspots $(a_{z_1}, a_{z_2}, \cdots, a_{z_\tau})$ of leaf nodes in $\mathcal{T}$, $\mathcal{T}$

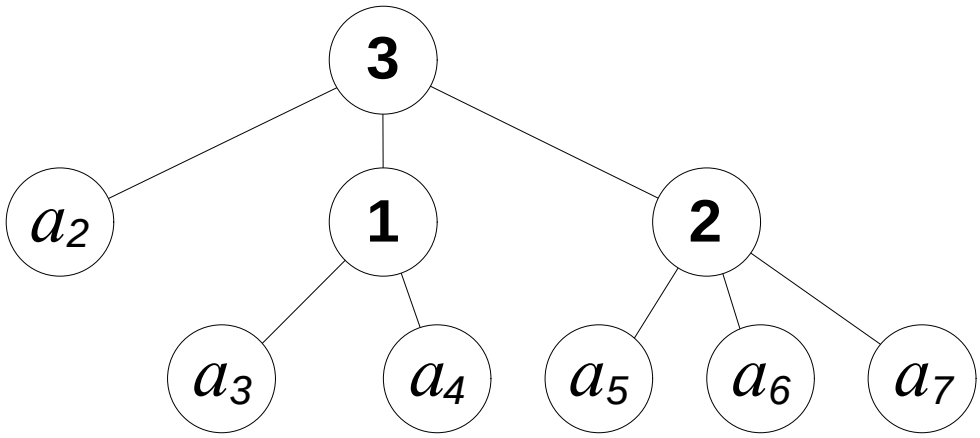


Figure 4.4: Tree structure of u_i's route

will be transformed into a Boolean function $F(a_{z_1}, a_{z_2}, \cdots, a_{z_\tau})$. For example, in Fig. 4.4, $F(a_1, a_2, \cdots, a_7) = a_2(a_3 + a_4)(a_5a_6 + a_5a_7 + a_6a_7)$. We say that a hotspot set $\mathcal{A}_i$ satisfies both $\mathcal{T}$ and function $F(a_{z_1}, a_{z_2}, \cdots, a_{z_\tau})$ if and only if $F(a_{z_1}, a_{z_2}, \cdots, a_{z_\tau}) = 1$, where for each a_y, $y \in \{z_1, z_2, \cdots, z_\tau\}$,

$$a_y = \begin{cases} 1, & \text{if } a_y \in \mathcal{A}_i, \\ 0, & \text{if } a_y \notin \mathcal{A}_i. \end{cases} \tag{4.1}$$

The routing tree preserves user privacy by making sensitive hotspots anonymous, and at the same time it provides certain information of the mobility route that can be used to evaluate the user's forwarding capability. We are now ready to present our privacy-preserving route-based authentication scheme which supports a single threshold gate (maximum threshold value d) for a routing tree. A multiple-threshold tree can be semantically converted to multiple single-threshold trees. The authentication scheme is built on the bilinear pairing technique [64, 65].

INITIALIZATION: Let $\mathbb{G}$ and $\mathbb{G}_T$ be two finite cyclic groups of the same composite order n, where $n = pq$ is a product of two large primes p and q (Section 2.4.2). Suppose $\mathbb{G}$ and $\mathbb{G}_T$ are equipped with a pairing, i.e., a non-degenerated and efficiently computable bilinear map $e : \mathbb{G} \times \mathbb{G} \to \mathbb{G}_T$ such that i) $\forall g, h \in \mathbb{G}$, $\forall a, b \in \mathbb{Z}_n$, $e(g^a, h^b) = e(g, h)^{ab}$; and ii) $\exists g \in \mathbb{G}$, $e(g, g)$ has order n in $\mathbb{G}_T$.

TA chooses a redundant hotspot set $\mathcal{A}_r = \{a_{l+1}, a_{l+d-1}\}$, two generators (g, u) of $\mathbb{G}$, a generator h of $\mathbb{G}_q$ ($\mathbb{G}_q$ is a subgroup of $\mathbb{G}$ with order q), a secure cryptographic hash function $H : \{0,1\}^* \to \mathbb{Z}_n^*$, and random number $\delta \in \mathbb{Z}_n^*$. For all $1 \leq y \leq l + d - 1$, TA chooses random numbers $t_y \in \mathbb{Z}_n^*$ and computes $T_y = g^{t_y}$. TA also computes $\Delta = e(g, u)^\delta$.

With these settings, TA keeps the master key $(\delta, (t_y)_{1\leq y\leq l+d-1})$ secretly, and publishes the public parameter $\mathsf{pub} = (n, g, u, h, \mathbb{G}, \mathbb{G}_T, e, H, \Delta, T_y(1 \leq y \leq l+d-1), \mathcal{A} \cup \mathcal{A}_r)$.

User Registration: TA chooses a unique random number $t \in \mathbb{Z}_n^*$ and a random polynomial $q(x) = \kappa_{d-1}x^{d-1} + \kappa_{d-2}x^{d-2} + \cdots + \kappa_1 x + \delta$, and generates $E_i = \langle k_d, (d_y)_{a_y \in \mathcal{A}_i \cup \mathcal{A}_r} \rangle$, where $k_d = t$ and $d_y = u^{\frac{q(y)}{t+t_y}}$. It informs the registering u_i about the secret key E_i.

Let users u_i and u_j denote the signer and verifier respectively. Denote u_i's routing tree (with a single threshold) by $\mathcal{T}_i$. Let k be the threshold value of the root of $\mathcal{T}_i$ and Θ_i a hotspot set corresponding to $\mathcal{T}_i$'s leaf nodes. $\Phi_i \subseteq \mathcal{A}_i \cap \Theta_i$ is a hotspot set of size k.

Signing by u_i: u_i first chooses a subset $\mathcal{A}_{r'} \subseteq \mathcal{A}_r$ ($|\mathcal{A}_{r'}| = d - k$). Let $\mathcal{A}_{r'}$ be $\{a_{l+1}, \cdots, a_{l+d-k}\}$. Then, for each hotspot $a_y \in \Psi = \Phi_i \cup \mathcal{A}_{r'}$, u_i computes the Lagrange coefficient $\omega_y = \sum_{w|a_w \in \Psi, w \neq y} \frac{0-w}{y-w}$. It randomly selects $r_t, r_p, r_y \in \mathbb{Z}_n^*$ for $a_y \in \Theta_i \cup \mathcal{A}_{r'}$ and computes S_y for $a_y \in \Theta_i \cup \mathcal{A}_{r'}$ as

$$S_y = \begin{cases} d_y^{\omega_y} \cdot h^{r_y}, \text{ if } a_y \in \Psi \\ h^{r_y}, \text{ if } a_y \in \Theta_i \setminus \Phi_i \end{cases} \tag{4.2}$$

It outputs the signature

$$\sigma_i = \langle \mathcal{T}_i, S_t, S_p, (S_y)_{a_y \in \Theta_i \cup \mathcal{A}_{r'}}, \pi_1, \pi_2 \rangle, \tag{4.3}$$

where $S_t = g^{k_d} \cdot h^{r_t}$, $S_p = g^{\frac{1}{k_d + H(pid_i)}} \cdot h^{r_p}$,

$$\pi_1 = S_p^{r_t}(g^{H(pid_i)} g^{k_d})^{r_p}, \tag{4.4}$$

$$\text{and } \pi_2 = \prod_{a_y \in \Psi} (d_y^{\omega_y})^{r_t} \prod_{a_y \in \Theta_i \cup \mathcal{A}_{r'}} (S_t T_y)^{r_y}. \tag{4.5}$$

Verification by u_j: u_j receives σ_i and checks

$$\begin{cases} e(S_t g^{H(pid_i)}, S_p) \stackrel{?}{=} e(g, g) \cdot e(h, \pi_1) \\ \prod\limits_{a_y \in \Theta_i \cup \mathcal{A}_{r'}} e(S_y, S_t T_y) \stackrel{?}{=} \Delta \cdot e(h, \pi_2), \end{cases} \tag{4.6}$$

If the above equations hold, u_j confirms that u_i has pseudonym pid_i and a hotspot set satisfying $\mathcal{T}_i$. The correctness of the verification is from the following mathematical manipulation:

$$\begin{aligned} & e(S_t g^{H(pid_i)}, S_p) = e(g^t h^{r_t} \cdot g^{H(pid_i)}, g^{\frac{1}{t+H(pid_i)}} h^{r_p}) \\ =& e(g, g) \cdot e(h, (g^{\frac{1}{t+H(pid_i)}} h^{r_p})^{r_t} \cdot (g^t g^{H(pid_i)})^{r_p}) \\ =& e(g, g) \cdot e(h, S_p^{r_t}(g^{H(pid_i)} g^t)^{r_p}) = e(g, g) \cdot e(h, \pi_1) \end{aligned} \tag{4.7}$$

$$
\begin{aligned}
&\prod_{a_y \in \Theta_i \cup \mathcal{A}_{r'}} e(S_y, S_t T_y) \\
=&\prod_{a_y \in \Psi} e(d_y^{\omega_y}, S_t T_y) \cdot \prod_{a_y \in \Theta_i \cup \mathcal{A}_{r'}} e(h^{r_y}, S_t T_y) \\
=&\prod_{a_y \in \Psi} e(u^{\frac{\omega_y q(y)}{k_d + t_y}}, g^{k_d} h^{r_t} g^{t_y}) \cdot \prod_{a_y \in \Theta_i \cup \mathcal{A}_{r'}} e(h^{r_y}, S_t T_y) \\
=&e(g,u)^{\delta} \prod_{a_y \in \Psi} e(u^{\frac{r_t \omega_y q(y)}{k_d + t_y}}, h) \cdot \prod_{a_y \in \Theta_i \cup \mathcal{A}_{r'}} e(h^{r_y}, S_t T_y) \\
=&\Delta \cdot e(h, \prod_{a_y \in \Psi} (d_y^{\omega_y})^{r_t} \prod_{a_y \in \Theta_i \cup \mathcal{A}_{r'}} (S_t T_y)^{r_y}) = \Delta \cdot e(h, \pi_2)
\end{aligned}
\tag{4.8}
$$

Privacy discussion: For user privacy preservation, the route-based authentication scheme mixes the hotspot $a_y \in \Psi$ that u_i has with the hotspot $a_y \notin \Psi$ that u_i does not have from the equation (4.2) by multiplying a subgroup element h. This achieves full-anonymity, i.e., any other user cannot trace the hotspots which are used to generate the signature, because the element h cannot be distinguished from either $\mathbb{G}_p$ or $\mathbb{G}_q$ without p or q known as a priori. The theoretical proof can be found in [64, 65]. Consider that an adversarial user may use the authenticated route information to identify the signer's trace. Without precaution, such misbehavior may violate location privacy. An effective defense mechanism against this privacy violation is to let each user change the routing tree structures of their route information as frequently as the change of their pseudonyms, and also include redundant hotspots into their routing tree. As a result, different users may generate the same routing tree, and the signature cannot be used to link the past/future locations and behaviors of any specific user.

4.3.3 Step2: Proximity Measurement

In this section, we develop a novel proximity measurement for implementing the user-to-spot data forwarding protocol. Consider a packet originated from u_j and destined to $\mathcal{D}_j$, which is a hotspot that its intended receiver frequently visits. When u_j meets a u_i, it computes a forwarding score $e_{j,i}$. This score implies u_i's forwarding capability of bringing the packet to $\mathcal{D}_j$. It is subject to multiple factors such as the time-to-live period of the packet, the probability that u_i drops the packet due to limited storage buffer, how close that u_i can be to $\mathcal{D}_j$, when the closest distance will occur, and so on. However, the more factors used, the more personal information revealed, and the less privacy preserved.

To avoid any additional privacy leakage, we define that $e_{j,i} = \psi(r_{j,i})$, where $r_{j,i}$ is the smallest distance between $\mathcal{D}_j$ and the hotspots that u_i will visit and $\psi()$ is a monotonically decreasing function of $r_{j,i}$. The smaller $r_{j,i}$, the more closely u_i can deliver the packet to $\mathcal{D}_j$, the larger $e_{j,i}$ by this definition. A particular case is shown in Fig. 4.5. Even if user h appears to move away from $\mathcal{D}_j$, its forwarding, when used, will still be effective since it is going to encounter u_i who will visit $\mathcal{D}_j$ afterwards. Given that no global knowledge is available and any user can be an effective forwarder, $\psi()$ always returns a positive value.

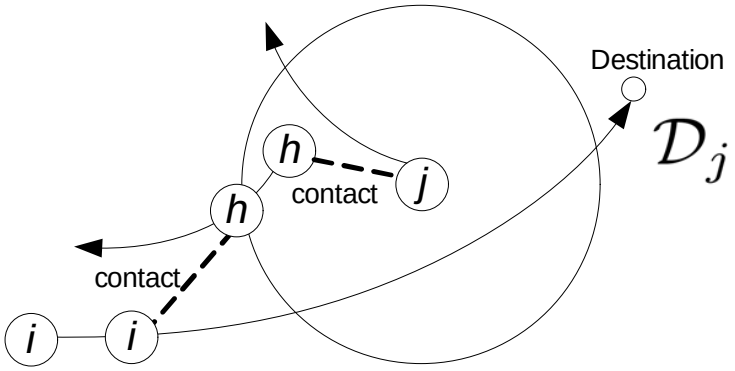


Figure 4.5: A user moving towards opposite direction of the destination can still provide effective forwarding

Algorithm 1 Smallest radius calculation by u_j

Input: $\mathcal{T}_i$ and $\mathcal{D}_j$.
Transform $\mathcal{T}_i$ to $F_i(a_{z_1}, a_{z_2}, \cdots, a_{z_\tau})$.
Calculate $\tilde{F}_i(a_{z_1}, a_{z_2}, \cdots, a_{z_\tau}) = \overline{F_i(\overline{a_{z_1}}, \overline{a_{z_2}}, \cdots, \overline{a_{z_\tau}})}$.
Calculate $D_s = \{d_{z_1}, d_{z_2}, \cdots, d_{z_i}\}$, where d_y is the distance between $\mathcal{D}_j$ and a_y for $y \in \{z_1, z_2, \cdots, z_\tau\}$.
Sort D_s in an ascending order $\{d_{z_1^*}, d_{z_2^*}, \cdots, d_{z_\tau^*}\}$ corresponding to spots $\{a_{z_1^*}, a_{z_2^*}, \cdots, a_{z_i^*}\}$.
Initialize $\tilde{\mathcal{A}} = \{a_{z_1^*}\}$, $\mu = 1$.
while ($\tilde{\mathcal{A}}$ does not satisfy $\tilde{F}_i(a_{z_1}, a_{z_2}, \cdots, a_{z_\tau})$) **do**
    $\mu = \mu + 1$,
    $\tilde{\mathcal{A}} = \tilde{\mathcal{A}} \cup \{a_{z_\mu^*}\}$.
end while
Let $r^*_{j,i} = d_{z_\mu^*}$ and $\mathcal{A}_{\mathcal{D}_j, r^*_{j,i}} = \tilde{\mathcal{A}}$.
Output $r^*_{j,i}$.

Since u_i only exposes partial information $\mathcal{T}_i$ of its mobility route to u_j during route-based authentication, u_j cannot compute $r_{j,i}$ accurately. We devise an approximation algorithm for u_j to obtain an approximate value $r^*_{j,i}$ with the inputs $\mathcal{T}_i$ and $\mathcal{D}_j$. In this

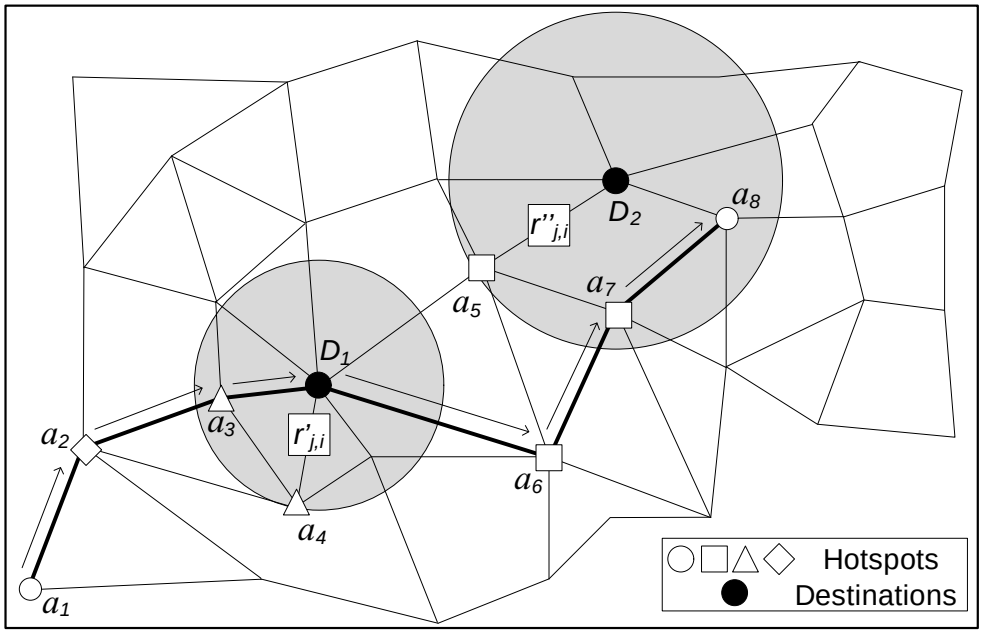


Figure 4.6: An example of the smallest radius calculation

algorithm, we first transform $\mathcal{T}_i$ to a Boolean function $F_i(a_{z_1}, a_{z_2}, \cdots, a_{z_\tau})$. We denote a self-dual function of F_i as $\tilde{F}_i(a_{z_1}, a_{z_2}, \cdots, a_{z_\tau}) = \overline{F_i(\overline{a_{z_1}}, \overline{a_{z_2}}, \cdots, \overline{a_{z_\tau}})}$. Let $\mathcal{A}_{\mathcal{D}_j,r}$ denote a set of hotspots located in a circular area centered at the destination $\mathcal{D}_j$ with radius r. For a u_i neighboring u_j, we can find the smallest radius $r^*_{j,i}$ such that $\mathcal{A}_{\mathcal{D}_j,r^*_{j,i}}$ satisfies function $\tilde{F}_i(a_{z_1}, a_{z_2}, \cdots, a_{z_i})$. The algorithm finally outputs an approximate value $r^*_{j,i}$. The algorithmic detail is given in Algorithm 1. u_j will then use this value $r^*_{j,i}$ to calculate the forwarding score of u_i.

We use an example to illustrate how proximity score is computed, in accordance with the scenario given in Fig. 4.6. u_i encounters u_j. u_i generates a routing tree $\mathcal{T}_i$ and the corresponding Boolean function $F_i(a_2, a_3, \cdots, a_7)$ ="a_2 AND (a_3 OR a_4) AND (2 of (a_5, a_6, a_7))". u_j has two packets with destinations $\mathcal{D}_1$ and $\mathcal{D}_2$, respectively. We have $\tilde{F}_i(a_2, a_3, \cdots, a_7)$ ="a_2 OR (a_3 AND a_4) OR (2 of (a_5, a_6, a_7))". According to the Algorithm 1, with $\mathcal{T}_i$ and $\mathcal{D}_1$ as inputs, $\tilde{\mathcal{A}}$ is initialized to $\{a_3\}$ since a_3 is the hotspot closest to $\mathcal{D}_1$. Then, $\{a_4\}$ will be added into $\tilde{\mathcal{A}}$ since $\{a_3\}$ does not satisfy $\tilde{F}_i(a_2, a_3, \cdots, a_7)$ and a_4 is the second closest to $\mathcal{D}_1$. $\tilde{\mathcal{A}} = \{a_3, a_4\}$ now satisfies $\tilde{F}_i(a_2, a_3, \cdots, a_7)$. The algorithm finally outputs the distance $r'_{j,i}$ between a_4 and $\mathcal{D}_1$. Similarly, with $\mathcal{T}_i$ and $\mathcal{D}_2$ as inputs, the algorithm outputs the distance $r''_{j,i}$ between a_5 and $\mathcal{D}_2$, where $\tilde{\mathcal{A}} = \{a_5, a_7\}$ satisfying $\mathcal{T}_i$.

4.3.4 Step3: Morality-Driven Data Forwarding

After finishing the first two steps, users can perform morality-driven data forwarding. Note that the mobile social users are autonomous and intelligent individuals. It is reasonable to assume that they are rational and their behaviors are driven by personal profit and morality. On one hand, they tend to act defection in order to reduce their forwarding costs. On the other hand, they offer cooperation from time to time so as to counteract the guilty feelings brought by the past selfish deeds. During MSN-based data forwarding, social users implement the best strategy to balance cost and payoff. In this section, we apply game theory to model individual user behavior and obtain the optimal data forwarding strategy.

Consider a scenario where users move along independently and randomly determined mobility routes. Upon the contact with another user, a user would either cooperate or defect for data forwarding. We assume that, for two users that both have packets to send, cooperation is reciprocal. Due to the random mobility and privacy preservation, users' future contacts are unpredictable. A user thus derives the optimal data forwarding strategy based on its self-related information, including its own mobility route, destination of its own packet, and morality factor, as well as the opponent information, including the morality factor, mobility route and packet destination of the encountered user.

From a user's perspective, among a series of cooperations with different encountered opponents, due to the privacy preservation, the opponent information of current contact is always independent from that of previous contacts, and thus the decision on cooperation or defection depends only on the self-related information and the opponent information of the current contact. We thus model the interplay upon each contact, namely cooperation game, as a nonzero sum two-player game.

Basic/Extended Cooperation Games

We first define a basic cooperation game, called B-game (B stands for Basic), as a 3-tuple $(\mathcal{N}, \mathcal{S}, \mathcal{P})$, where $\mathcal{N}$ is a pair of users, $\mathcal{S}$ is a set of strategies and $\mathcal{P}$ is a set of payoff functions. According to Section 2.1, users continuously change their pseudonyms to preserve their privacy. Pseudonym change breaks any relation previously established between two users and as a result they no longer recognize each other. Therefore, B-game is a non-repeated game which can be described as follows:

- **Players:** Two users u_i and u_j belong to the universal user set $\mathcal{V}$. u_j can also be

Table 4.1: User payoff matrix in PDF

(a) Payoff matrix of B-game

$i \setminus j$	Cooperate (C)	Defect (D)
Cooperate (C)	$(b-c, b-c)$	$(-c, b)$
Defect (D)	$(b, -c)$	$(0, 0)$

(b) Payoff matrix of E-game

$i \setminus j$	C	D
C	$(b-c, b-c)$	$(-c, b-g_j)$
D	$(b-g_i, -c)$	$(-g_i, -g_j)$

(c) Payoff matrix of S-game

$i \setminus j$	C	D
C	$(e_{i,j}b-c, e_{j,i}b-c)$	$(-c, e_{j,i}b-e_{i,j}g_j)$
D	$(e_{i,j}b-e_{j,i}g_i, -c)$	$(-g_i, -g_j)$

denoted as $-i$. The two users are within the transmission range of each other, and they decide to cooperate or defect, aiming at maximizing their individual payoff.

- **Strategy:** Upon the forwarding request of the opponent user, each user has two strategies: Cooperate (C) and Defect (D). Denote u_i's strategy by s_i. Then $s_i = C$ means that u_i forwards u_j's packet, and $s_i = D$ that u_i drops u_j's packet.

- **Payoffs:** The cost c of forwarding on one packet is a value, the same for both users. If u_i's data is forwarded by u_j, the profit acquired by u_i is b, which is also a constant. We set $b \geq c > 0$ since the profit acquired from each forwarding should be at least equal to the incurred cost. The user payoffs under different strategies are shown in Table 4.1(a).

From the payoff matrix in Table 4.1(a), it is observed that the B-game is a typical prisoner-dilemma game, where the only Nash Equilibrium (NE) is (D, D) for non-repeated version. In other words, no matter what the opponent's strategy is, the best strategy for a user is to defect. This is because that $b > b-c, 0 > -c$.

Next, we introduce an E-game (E stands for Extended), where the payoff matrix is shown in Table 4.1(b). This game considers users u_i and u_j's behaviors affected by morality factors g_i and g_j. The morality factors are introduced as the costs of defection behaviors into the payoff functions. The best strategy of the E-game for u_i is: cooperate if $g_i > c$;

defect if $g_i \leq c$. Based on the Markov chain model given in Section 4.2.1, there exists a morality state $x^* < 0$ such that $f(st_i, x^* + 1) < c < f(st_i, x^*)$. After a finite series of defections, u_i will reach state x^*, and then alternatively chooses to cooperate.

Social Cooperation Game

In the following, we extend the E-game to a complex S-game (S stands for Social), which is also denoted by a 3-tuple $(\mathcal{N}, \mathcal{S}, \mathcal{P})$. S-game further incorporates the forwarding scores $e_{i,j}$ and $e_{j,i}$ into the payoff function.

- **Players:** Two users u_i and u_j with different sociality strength st_i, st_j and current morality factors g_i, g_j.
- **Strategy:** The strategy is the same as that of the B-game. u_i's strategy is denoted by s_i.
- **Payoffs:** The payoff of u_i is evaluated by

$$p_i^s = \begin{cases} e_{i,j}b - c, & \text{if } s_i = C,\ s_j = C, \\ -c, & \text{if } s_i = C,\ s_j = D, \\ e_{i,j}b - e_{j,i}g_i, & \text{if } s_i = D,\ s_j = C, \\ -g_i, & \text{if } s_i = D,\ s_j = D. \end{cases} \tag{4.9}$$

In payoff formula (4.9), the forwarding scores $e_{i,j}$ and $e_{j,i}$ are used to measure u_i's profit and morality factor. If u_j forwards u_i's data, the profit that u_i acquires is $e_{i,j}b$ instead of b. If u_i drops u_j's data, depending on u_j's strategy, u_i acquires different morality factors, $e_{j,i}g_i$ or g_i. Note that, when users u_i and u_j both drop each other's packets, the morality factor on u_i's payoff is independent of the forwarding score $e_{j,i}$. This is because users u_i and u_j treat each other equally and do not further consider their forwarding capability.

S-game with complete information

We first analyze the S-game in the case that two players have complete information including the sociality strength and morality state of each other. Each player can calculate the morality factor by $\psi()$ as defined in Section 4.2.1 and determine the payoff before deciding whether to cooperate or defect, according to Table 4.1(c). We use *Theorem* 4 to identify the NE strategies of the S-game.

Theorem 4 *When the two players have complete information of each other in the* S*-game, there are multiple pure-strategy NE in different cases and one mixed-strategy NE* (x_i, x_j)*, where* $x_i = \frac{c-g_{-\theta}}{e_{\theta,-\theta}g_{-\theta}-g_{-\theta}}$ *is the probability that user* n_θ *chooses to cooperate, as shown in Fig. 4.7(b).*

Proof 4 *For* $\theta = i$ *or* j*, we have the following three cases to consider.*

• $g_\theta < \frac{c}{e_{-\theta,\theta}}$*: We have* $e_{\theta,-\theta}b - e_{-\theta,\theta}g_\theta > e_{\theta,-\theta}b - c$ *and* $-g_\theta > -\frac{c}{e_{-\theta,\theta}} \geq -c$ *due to* $e_{-\theta,\theta} \geq 1$*. As a result, when* $g_{-\theta} < c$*,* $(s_\theta = D, s_{-\theta} = D)$ *is a NE; and when* $g_{-\theta} > c$*,* $(s_\theta = D, s_{-\theta} = C)$ *is a NE.*

• $g_\theta > c$*: We have* $-g_\theta < -c$ *and* $e_{\theta,-\theta}b - e_{-\theta,\theta}g_\theta < e_{\theta,-\theta}b - c$ *due to* $e_{-\theta,\theta} \geq 1$*. As a result, when* $g_{-\theta} > \frac{c}{e_{\theta,-\theta}}$*,* $(s_\theta = C, s_{-\theta} = C)$ *is a NE; when* $g_{-\theta} < \frac{c}{e_{\theta,-\theta}}$*,* $(s_\theta = C, s_{-\theta} = D)$ *is a NE.*

• $\frac{c}{e_{-\theta,\theta}} < g_\theta < c$*: Let* x_θ *denote the forwarding probability of user* n_θ*. For* $s_{-\theta} = C$ *or* $s_{-\theta} = D$*, we separately calculate the payoff for* $n_{-\theta}$ *as follows:*

$$p^s_{-\theta}|C = x_\theta \times (e_{-\theta,\theta}b - c) + (1 - x_\theta) \times (-c) \tag{4.10}$$

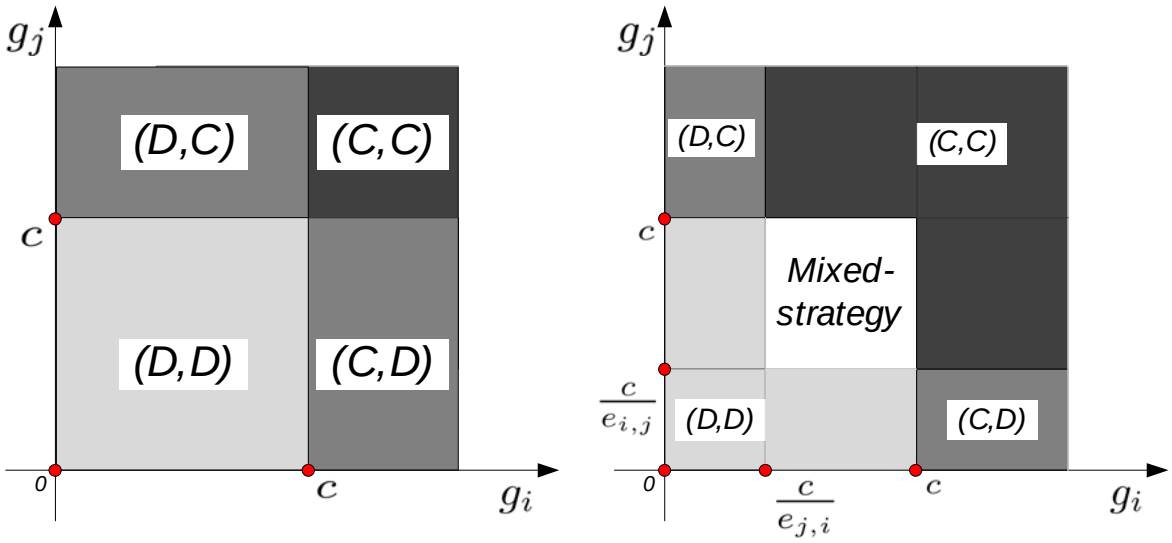
$$p^s_{-\theta}|D = x_\theta \times (e_{-\theta,\theta}b - e_{\theta,-\theta}g_{-\theta}) + (1 - x_\theta) \times (-g_{-\theta}) \tag{4.11}$$

If x_θ *is the best strategy of* n_θ*, we have* $p^s_{-\theta}|C = p^s_{-\theta}|D$ *which gives* $x_\theta = \frac{c-g_{-\theta}}{e_{\theta,-\theta}g_{-\theta}-g_{-\theta}}$.

S-game with incomplete information

We consider the case that the two players have incomplete information of each other. Specifically, u_i obtains sociality strength st_i, morality state g_i, forwarding scores $e_{i,j}$ and $e_{j,i}$, but it does not obtain the sociality strength st_j and morality factor g_j of u_j. As a supplementary information, we assume that u_i obtains the probability distribution ϱ of the morality factor of all users. Based on this, u_i can estimate the morality factor g_j of u_j. Then, u_i follows the following steps according to the best strategy shown in Fig. 4.7(b):

- If $0 \leq g_i < \frac{c}{e_{j,i}}$, then u_i chooses to defect regardless of u_j's strategy.
- If $c \leq g_i$, then u_i chooses to cooperate regardless of u_j's strategy.



(a) The best strategy of E-game

(b) The best strategy of S-game

Figure 4.7: The best strategy for different games

- If $\frac{c}{e_{j,i}} \leq g_i < c$, then there exists a pure-strategy NE (D, D) for $g_j < \frac{c}{e_{i,j}}$, a pure-strategy NE (C, C) for $g_j > c$, and a mixed-strategy NE for $\frac{c}{e_{i,j}} < g_j < c$. For the pure strategy NE, we calculate the defection probability $\Pr_1$ and cooperation probability $\Pr_2$:

$$\Pr_1 = \Pr(0 \leq g_j < \frac{c}{e_{i,j}}) = \int_0^{\frac{c}{e_{i,j}}} \varrho(\alpha) d\alpha,$$
$$\Pr_2 = \Pr(c \leq g_j) = \int_c^{+\infty} \varrho(\alpha) d\alpha.$$

  In addition, u_i makes a mixed-strategy NE with probability $\Pr_3$, which is given by

$$\Pr_3 = \Pr(\frac{c}{e_{j,i}} \leq g_i < c) = \int_{\frac{c}{e_{j,i}}}^{c} \varrho(\alpha) d\alpha. \tag{4.12}$$

  For the mixed-strategy NE with probability $\Pr_3$, *Theorem* 4 indicates the best strategy of u_i is to forward the data with probability $\frac{c-g_j}{e_{i,j}g_j - g_j}$ if g_j is known by u_i. In this case, the probability that u_i chooses to cooperate is

$$\Pr_4 = \int_{\frac{c}{e_{j,i}}}^{c} (\frac{c-\alpha}{e_{i,j}\alpha - \alpha}) \varrho(\alpha) d\alpha. \tag{4.13}$$

Overall, u_i decides to cooperate with probability $\Pr_F = \Pr_2 + \Pr_4$ and to defect with probability $\Pr_D = 1 - \Pr_F$.

4.3.5 Summary of Data Forwarding Strategy

Notice that the S-game with incomplete information emulates the MSN environments in reality, where the opponent's morality factor cannot be directly obtained. We use the optimal strategy of this game in our protocol for users to make the optimal data forwarding strategies. As we defined in Section 4.2.1, user morality factor would vary with both sociality strength and morality state. However, revealing such information violates user privacy since other adversarial users can utilize the information to track user behavior. In this case, we do not require an accurate calculation of morality factor in the S-game. Instead, we examine the strategy by using a probability distribution function ϱ of morality factor. This function ϱ can be either observed by a trusted authority or reported by individual users. Further analysis is presented in Section 4.3.4.

A user who has packets to forward starts the data forwarding protocol with a randomly selected neighbor. Consider two neighboring users u_i and u_j that are running the protocol, i.e., they are both able to provide cooperative data forwarding to each other and any forwarding/defection decision in the two-user game will impact their social morality. Let $S_i = \{p_{i_1}, p_{i_2}, \cdots, p_{i_\alpha}\}$ and $S_j = \{p_{j_1}, p_{j_2}, \cdots, p_{j_\beta}\}$ be the packet sets held by u_i and u_j, respectively. We summarize the protocol as follows. u_i first randomly selects a packet p_x (destined to $\mathcal{D}_i$) from its local repository. It then calculates the digest of the packet $d_i = H(p_x)$, where H is the cryptographic hash function. Lastly, it sends d_i to u_j. In the meantime, u_j executes a similar procedure locally and sends u_i the digest d_j of a packet of p_y (destined to $\mathcal{D}_j$). According to d_i (d_j), if u_j (resp., u_i) finds that it already has p_x (resp., p_y), it will inform u_i (resp., u_j) to re-select p_x (resp., p_y). Through exhaustive packet re-selection, if they cannot find any exclusively owned packet, the protocol will terminate. Otherwise, they proceed to exchange $(p_x, \mathcal{D}_i)$ and $(p_y, \mathcal{D}_j)$, together with their own routing trees $\mathcal{T}_i$ and $\mathcal{T}_j$. Then, they validate each other's routing trees (see Section 4.3.2). After that, they evaluate each other's forwarding scores (see Section 4.3.3), and finally make the forwarding strategy for each other (see Section 4.3.4).

4.4 Performance Evaluation

4.4.1 Simulation Settings

User Mobility, Hotspots, and Packet Generation

We generate user mobility model according to the real-world trace of pedestrian runners provided in [79]. In the real trace set, $N = 100$ mobile users are randomly deployed in a 1000×1000 m^2 square region with the velocity randomly distributed with a mean value of 1 m/s. The communication range R_t of users is set to 50 m. The log contains the user locations in successive $T = 900$ time slots.

We divide the network field into 10×10 grids, where each grid is a square with side length 100 m. We create a circle of radius R_t around each grid point, and there are totally 121 circles. The areas enclosed by these circles are called spots and denoted by $(a_1, a_2, \cdots, a_{121})$ as shown in Fig. 4.8; no any two spots overlap.

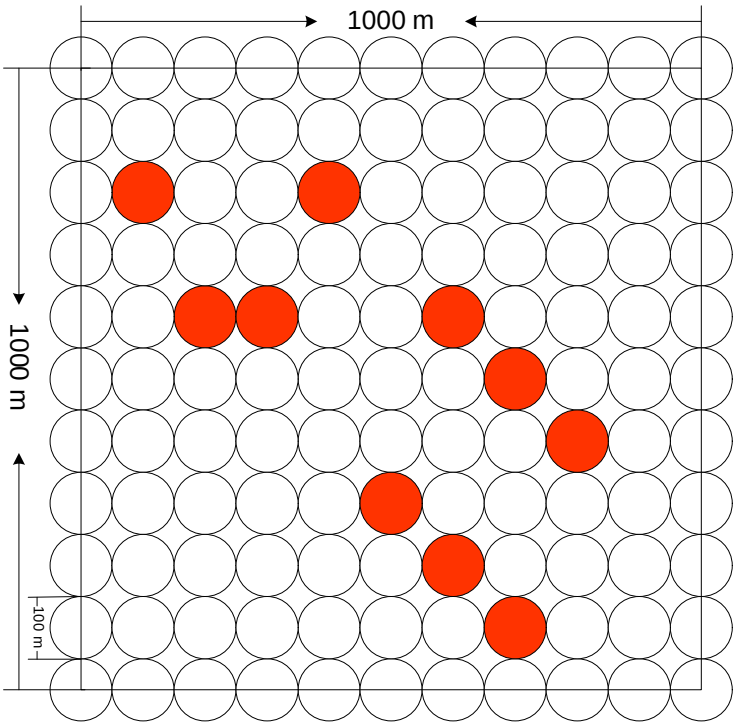


Figure 4.8: Hotspots

We aggregate user route information to determine the most popular spots as follows. Let $d_{m,n}$ denote the number of users in hotspot a_m at time slot n, where integers $m \in [1, 121]$ and $n \in [1, 900]$. We sort the spots in an descending order according to $d_m = \sum_{n=1}^{T} d_{m,n}$, and choose the top-ten spots as hotspots (i.e., $l = 10$). At the middle of each hotspot, we place a wireless storage device which has a communication range equal to R_t. Once a user enters a hotspot, it can access the storage device of the hotspot via wireless communication.

For each simulation run, there are totally 1000 packets generated for transmissions, 100 packets per each user, with uniformly selected hotspots as the packet destinations. In each time slot, a u_i randomly selects a neighboring u_j to play a two-player cooperation game. In the cooperation game, we consider the communication cost of data forwarding to be much greater than the computational cost of the associated authentication. As such, the authentication scheme imposes negligible influence on user behavior. Upon each contact, users uniformly select one available packet from their buffers to transmit. In order to focus on the impact of cooperation on the data forwarding effectiveness, we consider packets do not expire during the simulations and hotspot buffers and user device buffers are not limited in size.

Sociality Strength and Morality Function

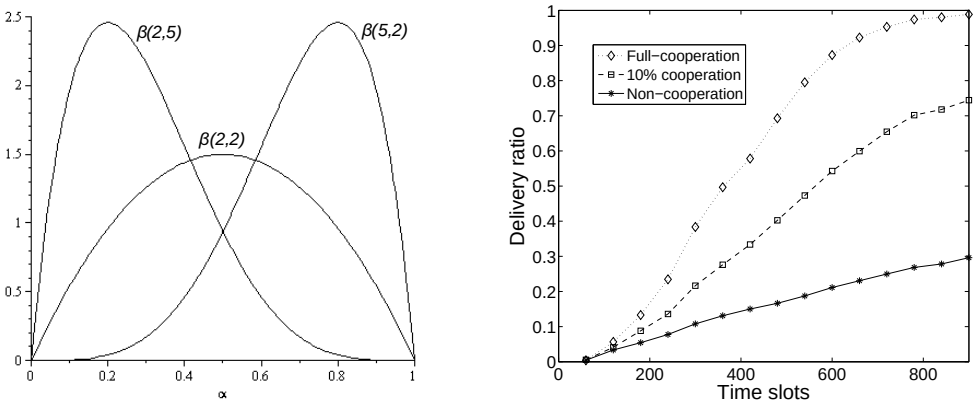
The sociality strength st_i of u_i $(1 \leq i \leq 100)$ is selected from the range of $[0, 1]$. The greater st_i is, the more intense social morality impact on u_i's cooperation. In this section, we adopt different models of sociality strength represented by three beta distributions $\beta(2, 5), \beta(2, 2), \beta(5, 2)$ shown in Fig.4.9(a), respectively, to evaluate the performance of the protocol in the cases of low, medium and high users' sociality strength, respectively.

The morality function f is used to calculate the morality factor of each u_i using the user's sociality strength st_i and current morality state x. From Section 4.2.1, we define three morality functions: *linear* function f_1, *natural logarithm* function f_e and *common logarithm* function f_{10}. They output 0 if $x \geq 0$, and otherwise,

$$\begin{aligned} f_1(st_i, x) &= k \cdot st_i \cdot (-x) \\ f_e(st_i, x) &= k \cdot \ln(1 + st_i \cdot (-x)) \\ f_{10}(st_i, x) &= k \cdot \log_{10}(1 + st_i \cdot (-x)) \end{aligned} \tag{4.14}$$

where k is a tunable coefficient in the range of $(0, +\infty)$. For simplicity, we fix $k = 1$ in our simulation.

The three morality functions represent three different levels of morality force affecting user cooperation behavior, respectively. They always output a non-negative value. The



(a) Sociality strength

(b) Cooperation effect

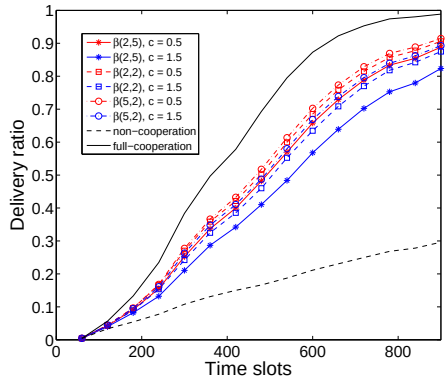
Figure 4.9: Preliminary results

common logarithm function f_{10} generates a smaller morality factor, compared with the other two functions. If it is adopted, we can expect to see more defection behaviors.

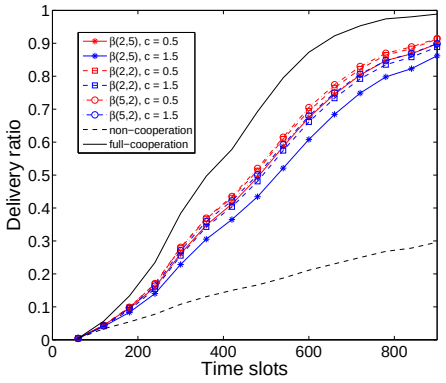
Routing Tree and Forwarding Capability

Recall that a user's routing tree preserves user privacy by making the sensitive hotspots anonymous, and in the meantime provides partial information of user mobility route in order to facilitate cooperative data forwarding. With 10 hotspots in simulations, each u_i may have at most 10 hotspots and at least 0 hotspot in $\mathcal{A}_i$. We generate a simplified routing tree structure $\mathcal{T}$ in the following way: if $|\mathcal{A}_i| = 0$, the tree cannot be created; if $0 < |\mathcal{A}_i| < 5$, we set the threshold as $|\mathcal{A}_i|$, and the leaf nodes as all the hotspots of $\mathcal{A}_i$ and other $5 - |\mathcal{A}_i|$ ones from $\mathcal{A}_u \setminus \mathcal{A}_i$; if $|\mathcal{A}_i| \geq 5$, we set the threshold as 4, and the leaf nodes as four randomly selected hotspots from $\mathcal{A}_i$ and another different hotspot. In short, for every user, the tree structure can be written as "t of 5", where $1 \leq t \leq 4$.

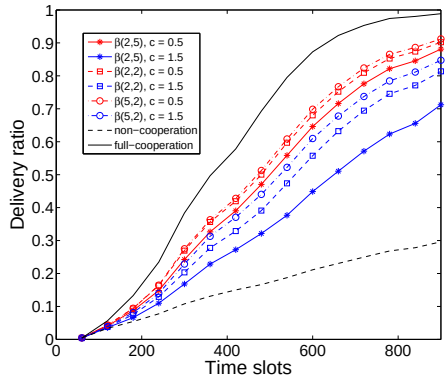
In Section 4.3.3, a function ψ is used to compute the forwarding capability of a given u_i for a packet with a specific destination. We set the lower bound of ψ as 1. In the network grid, $r^*_{i,j}$ can be $1000 \times \sqrt{2} = 1415$ meters at most and 0 at least. Intuitively, if $r^*_{i,j} = 1415$, the forwarding capability $e_{i,j}$ reaches the minimum value; and if $r^*_{i,j} = 0$, $e_{i,j}$ reaches the maximum value. We define $\psi(r^*_{i,j}) = e^{k' - k' r^*_{i,j}/1415}$ and set $k' = 3$ as an example to illustrate the effect of forwarding capability.



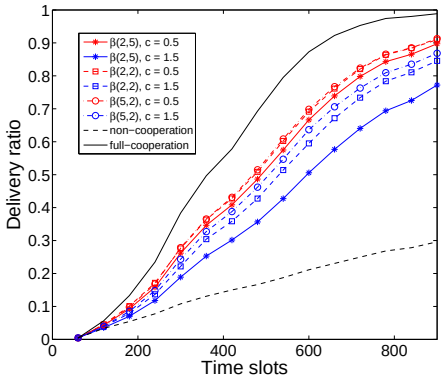
(a) E-game with f_1



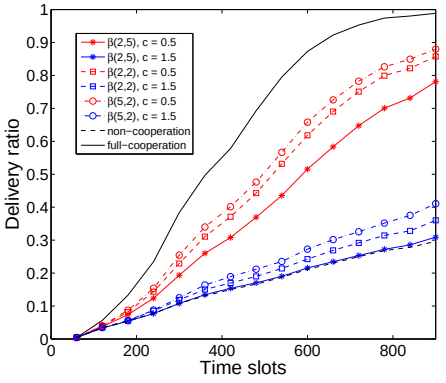
(b) S-game with f_1



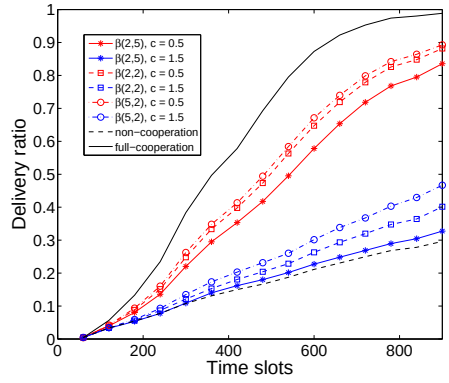
(c) E-game with f_e



(d) S-game with f_e



(e) E-game with f_{10}



(f) S-game with f_{10}

Figure 4.10: Delivery ratio in E-game and S-game with complete information

4.4.2 Simulation Results

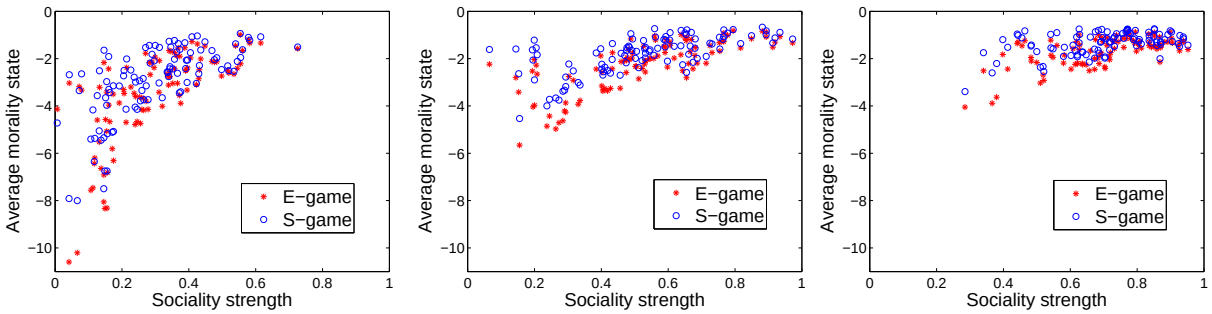
The performance metrics used in the simulation are: i) the delivery ratio, which is the fraction of packets that are correctly delivered to the hotspots as their destinations; and ii) the average morality state, which reflects the intention of users to cooperate over time. The delivery ratio examines the overall cooperation of users in the MSN, while the average morality state denotes the long-term cooperation strategies for a single user. For each simulation, we conduct 50 simulation runs and report the average results.

B-game

We first examine the B-game, where users always choose defection as the best strategy as discussed in Section 4.3.4. Fig. 4.9(b) shows three delivery ratios in the following three cases: a) users do not cooperate (i.e., B-game); b) users stochastically cooperate to forward packet with the probability of 10%; and c) users fully cooperate. It can be seen that at time slot 900, the full-cooperation strategy achieves 99% delivery ratio while the non-cooperation strategy achieves only 30%. Furthermore, Fig. 4.9(b) indicates that the probabilistic cooperation strategy provides a significant improvement to the delivery ratio up to 74%. However, without effective incentive and appropriate exploration of their social feature, users will not take cooperation due to the selfishness. Successful delivery happens only when the data senders arrive at their selected hotspots. This inevitably results in a low delivery ratio in the B-game.

E-game and S-game

The E-game extends the B-game by embedding the morality factor into the payoff function as shown in Table 4.1(b), while the S-game further considers the forwarding capability into the payoff of the E-game. Fig. 4.10 shows the delivery ratio of both the E-game and the S-game with complete information, with red lines representing the performance of forwarding cost $c = 0.5$, blue lines representing that of $c = 1.5$, and black lines depicting those of full-cooperation and non-cooperation as the best and worst case. It is clearly observed that the strategies with $c = 0.5$ can achieve higher delivery ratio than the strategies with $c = 1.5$. The rationale is that a large forwarding cost $c = 1.5$ hinders the cooperation performed by users who have limited resources and thus limits guilty incentive. In particular, when f_{10} is adopted, the cooperation condition in case of $c = 1.5$ approaches to the worst case. This is because that the guilty function f_{10} returns the smallest morality factor resulting in the least incentive to cooperate, compared to the function f_e and f_1. Fig. 4.10 shows that the

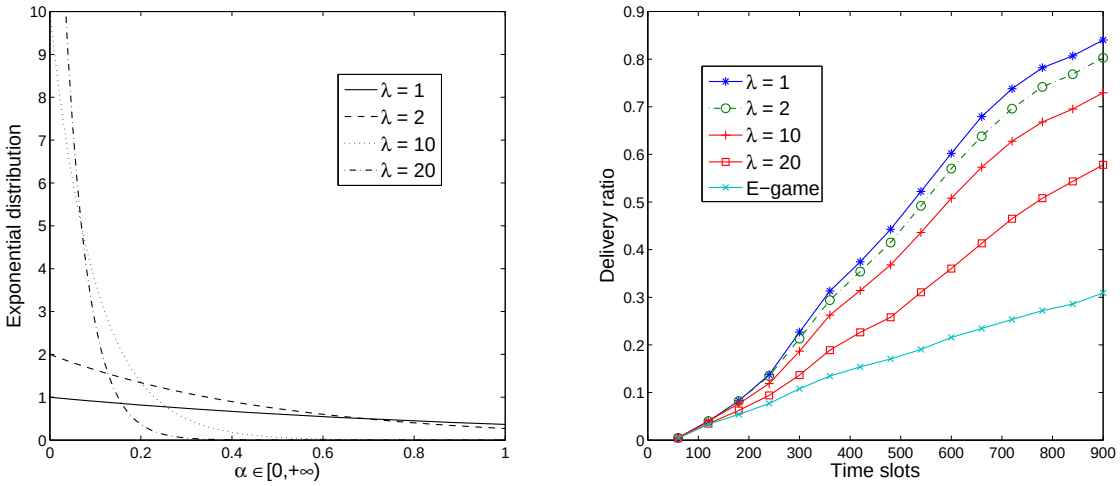


(a) Sociality strength $\beta(2,5)$ (b) Sociality strength $\beta(2,2)$ (c) Sociality strength $\beta(5,2)$

Figure 4.11: Average morality states of all users in E-game and S-game with complete information, $c = 0.8$, and common logarithm

strategies with the sociality strength $\beta(5,2)$ perform much better than those with $\beta(2,2)$ and $\beta(2,5)$ in terms of delivery ratio. This is because that, compared to cases $\beta(2,2)$ and $\beta(2,5)$, users will be initialized with larger sociality strength in case $\beta(5,2)$ as shown in Fig. 4.9(a), and as discussed in Section 4.2.1, more users feel intense guilt towards their defection and choose to cooperate, which leads to a better performance.

Fig. 4.10 shows the performance comparisons between the E-game and the S-game under the same parameters. It can be seen that the delivery ratio can be further improved by enabling privacy-preserving route-based authentication. But since the route information is limited due to the privacy preservation, the improvements are not significant, e.g., when choosing $\beta(2,5)$ and $c = 1.5$, the delivery ratio increases from 0.309 as shown in Fig. 4.10(e) to 0.327 as shown in Fig. 4.10(f). To further investigate the impact of the route information on the data forwarding cooperation, we randomly select 100 users in the network and examine their average morality states. Fig. 4.11 shows the average morality state of each selected user in terms of the user sociality strength in three settings of social strength $\beta(2,5), \beta(2,2)$, and $\beta(5,2)$, respectively. The blue circle represents a user which adopts the best strategy from the S-game, and the red star represents a user which adopts the best strategy from the E-game. It can be seen that with the same sociality strength, the users represented by the red star have smaller morality states than users represented by the blue circle. This is to say, the incentive to defect in the cooperation game can be further reduced by enabling privacy-preserving route-based authentication.



(a) Morality factor

(b) Delivery ratio, f_{10}, $c = 1.5$, $st_i \sim \beta(2, 5)$

Figure 4.12: S-game with incomplete information

S-game with Incomplete Information

For the S-game with incomplete information, the morality factor cannot be obtained directly in our morality model due to the lack of sociality strength and morality state information about the opponent user. As such, the morality factor will be estimated by a probability distribution function ϱ. In our simulation, we use exponential distribution with parameter $\lambda = \{1, 2, 10, 20\}$ to generate the morality factors for all users. The probability distribution function ϱ is shown in Fig. 4.12(a).

Fig. 4.12(a) shows that most users in case of $\lambda = 1$ may have relatively large morality factor. As we make $st_i \sim \beta(2, 5)$, most users would have the weak sociality strength. Thus, the large morality factors of users indicate that they have already adopted a large amount of defections. Accordingly, they would have intense guilty feeling so that their following behaviors are probably cooperative. Besides that, it can be seen that when $\lambda = 20$ most users with the weak sociality strength have smaller morality factors, and without enough guilt as cooperation incentives their future behaviors would likely be defections. The performance results from Fig. 4.12(b) validate the above analysis, where the delivery ratio largely decreases if λ changes from 1 to 20. By investigating the strategy, it can be seen that when $\lambda = 20$, from u_i's perspective, the opponent u_j has a morality factor $g_j < \frac{c}{e_{i,j}}$ with a large probability. In this case, u_i chooses to cooperate if $g_i \geq c$ and defect if $g_i < c$.

The best strategy of the S-game with incomplete information is thus almost equal to that of the E-game; both games indicate users to cooperate or defect mostly based on user self morality factors. However, the S-game with incomplete information outperforms the E-game since it has an additional mixed-strategy space shown in Fig. 4.7(b) to encourage user cooperation.

4.5 Related Work

Data forwarding protocols have been extensively investigated in delay-tolerant networks. Due to the sparse and dynamic nature of delay-tolerant networks, user-to-user data forwarding often relies on the mobility and random contacts of users. For example, Lindgren et al. [103] evaluated the forwarding capability of a user by the historic contact information. Under the similar framework, [20, 48, 100, 104, 105] used social metrics calculated from the contact information to evaluate the forwarding capability of a user. Hui et al. [105] demonstrated that community and centrality social metrics can be effectively used in data forwarding protocol. Li et al. [20] introduced the social-selfish effect into user behavior, i.e., a user gives preference to packets received from other users with stronger social relations. Yuan et al. [100] proposed a data forwarding protocol enabling two users to share their historical mobility information. Based on the opponent's past mobility information, a user is able to predict the future location that the opponent will visit.

Though significantly improving the data forwarding effectiveness, most contact-based data forwarding protocols require a contact calculation phase in which each user must have a unique identity and reveal it to others. In this phase, user behaviors are very easy to be linked together and user's identity privacy and location privacy are completely compromised. In the contact-based data forwarding protocol, a sender must exchange the contact and unique identity with a relay user. In [20, 48, 103], to improve the forwarding effectiveness, a sender can evaluate the forwarding capability of a relay user based on both the relay user's contact probability and forwarding willingness. However, the required contact probability and unique identity information are privacy-sensitive to the relay user and not available in a privacy-preserving environment. The conventional contact-based data forwarding protocols do not provide effective privacy preservation and can hardly be accepted by the privacy-aware mobile users. We aim to solve the privacy preservation and security issues of cooperative data forwarding in the MSN.

Recently a rich body of literature [106–111] addressed the cooperation stimulation issue from a game-theoretic perspective. Yu and Liu [106] proposed a game-based approach to stimulate cooperation in mobile ad hoc networks, where two participating users set a

threshold on the number of forwarded packets in each forwarding round and they alternatively forward each other's packets. The setting of the threshold can stimulate cooperation and also limit the possible damage caused by the opponent's defection. If the opponent defects, a user immediately terminates the interaction and his maximum damage is bounded by the threshold setting in the previous round. Li and Shen [111] proposed an integrated system over an individual reputation system and a price-based system which demonstrates a superiority in terms of the effectiveness of cooperation incentives and selfish node detection. However, their works do not address user privacy and are not applicable in the privacy-sensitive the MSN.

The studies in the MSN mainly focus on exploring the human factors and behaviors for communications in a distributed and autonomous environment. Privacy preservation as a fundamental user requirement is however neglected in previous research. Recent proposals [112] indicated that one or a few snapshots of a user's location over time might assist an adversary to identify the user's trace, and an effective attack was presented to identify victims with high probability. As a defense technique, the *multiple-pseudonym* technique providing both identity and location privacy is widely applied in literatures [74, 113, 114]. Freudiger et al. [74] developed a user-centric location privacy model to measure the evolution of location privacy over time, and they derive the equilibrium strategies on changing pseudonyms for each user from the game-theoretic perspective. With the *multiple-pseudonym* technique applied, conventional cooperation stimulation mechanisms without privacy preservation [72, 106, 115, 116] are no longer applicable in the considered environment.

4.6 Summary

We have studied two fundamental problems in the MSN, i.e., privacy preservation and cooperative data forwarding. We have indicated the difficulties to solve both problems at the same time. This is because that concealing and protecting user information may prohibit tracking the social behavior of users, which impedes the cooperative data forwarding and effective incentive mechanism. We have attained the two conflicting design goals in one framework. Specifically, we have introduced a novel user-to-spot data forwarding protocol where each packet is destined to a hotspot associated with the receiver and then retrieved by the receiver upon its access to the hotspot. With this protocol, not only can receiver location privacy be preserved, but the packet delivery ratio is also enhanced. Game-theoretic approaches have been adopted to derive the best data forwarding strategy for users, with respect to user morality factor and forwarding capability. Through extensive trace-based

simulations, we have demonstrated the data forwarding effectiveness of the protocol in terms of packet delivery ratio. Particularly, the embedded privacy-preserving route-based authentication scheme makes important contribution to the protocol performance.

Chapter 5

Recommendation-based Trustworthy Service Evaluation

5.1 Introduction

In this chapter, we introduce another research topic, called trustworthy service evaluation (TSE). We envision the MSN as business streets as shown in Fig. 5.1 where local service providers (vendors) are densely distributed. Users in the MSN not only want to talk to other users, but also expect to well communicate with the nearby vendors. In the meantime, the vendors will try possible advertising methods to attract the potential customers.

The TSE is a distributed system involving both users and vendors. The intuition of designing the TSE is from the successful business solutions, as shown in Fig. 5.2. When we visit the business stores, especially restaurants, we often see some photos on the walls showing the famous people had a very pleasure time with the restaurant owners. This is a simple but very effective recommendation mechanism; people believe they would have the same experience as the famous people had. The behavior of the famous people with positive reputation would largely impact the customers' choices. In the TSE, we aim to change the format of the recommendations, i.e., convert the photos to non-forgeable digital review comments. The review comments can be collected and disseminated not only inside of the stores but also over the streets. However, the efficiency, security and privacy issues would be more challenging.

We introduce a basic trustworthy service evaluation (bTSE) system and an extended Sybil-resisted TSE (SrTSE) system for the MSN. In both systems, no third trusted authorities are involved, and the vendor locally maintains reviews left by the users. The vendor

Figure 5.1: Mobile social networks with vendors

Figure 5.2: Restaurants with the reviews from famous people

initializes a number of tokens, which are then circulated among the users to synchronize their review submission behaviors. After being serviced by a vendor, a user generates and submits a non-forgeable review to the vendor. The user cannot proceed with the review submission until it receives a token from the vendor. If the review submission succeeds, the user will forward the token to a nearby user who is wishing to submit a review to the same vendor; otherwise, the user will forward both the token and its own review to the receiver, expecting that receiver-user will cooperate and submit their reviews together. During token circulation, a hierarchical signature technique [64, 65] is adopted to specify and record each forwarding step in the token, and a modified aggregate signature technique [82] is employed to reduce token size. Both signature techniques are also used during cooperative review submission for reducing communication overhead and improving review integrity. Specifically, we identify three unique review attacks, i.e., review linkability attack, review rejection attack, and review modification attack in the bTSE. We also introduce two typical sybil attacks which cause huge damage to the bTSE. Under the sybil attacks, the bTSE system cannot work as expected because a single user can abuse the pseudonyms to generate multiple unlinkable false reviews in a short time. To resist such attacks, in the SrTSE, the pseudonyms are embedded with a trapdoor; if any user leaves multiple false reviews toward a vendor in a pre-defined time slot, its real identity will be revealed to the public. Through the security analysis and numerical results, we show that both the bTSE and the extended SrTSE are secure against the possible attacks. We further evaluate the performance of the bTSE in comparison with a non-cooperative system that does not engage cooperative review submission. Simulation results indicate that the bTSE achieves significantly (up to 100%) higher submission rates in the presence of the review rejection attacks, and (up to 75%) lower submission delays in general than the non-cooperative system, at the cost of reasonable cooperation overhead.

The remainder of this chapter is organized as follows: In Section 5.2, we present the system model and design goal. Then, we introduce the TSE systems in Section 5.3 where the above challenges can be resolved. We provide the security analysis and the simulation-based performance evaluation in Section 5.4 and Section 5.5, respectively. We also review the related works in Section 5.6. Lastly, we draw our summary in Section 5.7.

5.2 System Model and Design Goal

5.2.1 System Model

As mentioned in previous chapter, an MSN may contain multiple vendors offering different or similar services to users. Without loss of generality we consider a singe-vendor MSN. There is no central trusted authority in the network. The vendor is assumed to offer a single service. The vendor is equipped with a wireless communication device that has a large storage space. Each user has a handheld device such as cell phone; the transmission range of the device is the same for all users, and smaller than the vendor's transmission range. There are two types of communication in the network: vendor-to-user communication and user-to-vendor communication. The former may take place directly if users are in the vendor's transmission range, or indirectly through other users' message relay otherwise. It aims to disseminate up-to-date service information including service description and reviews to users. The later enables users to submit reviews to the vendor. Similar to vendor-to-user communication, it occurs directly if the vendor is in the transmission range of users, or indirectly otherwise.

We consider an MSN composed of a set $\mathcal{V} = \{u_1, \cdots, u_N\}$ of mobile users with the network size $|\mathcal{V}| = N$. Users have equal communication range, denoted by R_t. From a social perspective [117], users spontaneously form different social groups based on their common interests, termed as "attributes". Suppose that there are p social groups $\{g_1, \cdots, g_p\}$. Let $\mathcal{A}_u$ be the universal attribute set. Denote a social group g_h's attribute set by $\mathcal{A}_h$ ($\mathcal{A}_h \subseteq \mathcal{A}_u$) for $1 \leq h \leq p$. Every user u_j belongs to at least one social group. It inherits the attributes of the social groups that it belongs to. Thus, the attribute set of u_j is $\mathcal{P}_j = \bigcup_{h \in \mathcal{H}} \mathcal{A}_h$, where u_j is a member of g_h. The vendor (precisely, its service) is also tagged by an attribute set $\mathcal{V} \subseteq \mathcal{A}_u$. It periodically disseminates its up-to-date service information including service description and reviews to users. The integrity and non-forgeability of such service information will be achieved by using a public/private key pair of the vendor.

Each group g_h relies on a group authority c_h for membership management. c_h has a public/private key pair (pk_h, sk_h), and publishes the public key to all users. A multi-authority identity based signature scheme [82] is used to implement group membership. Note that c_h is not a part of the network, and the management of group membership is performed offline. Every user u_j has a private unique identity id_j. When it joins g_h, c_h verifies the validity of u_j's identity id_j and assigns u_j a number of randomly generated verifiable pseudonyms $pid_{j,h,1}, pid_{j,h,2}, \cdots$. It also allocates u_j a number of secret keys $psk_{j,h,*}$, each corresponding to $pid_{j,h,*}$. Thus, u_j has a set of pseudonyms $pid_{j,*,*}$ allocated

by the group authorities of the social groups that it belongs to. It interacts with the vendor and other users using these pseudonyms alternatively, instead of its unique identity id_j, for privacy preservation. Reviews are associated with pseudonyms, which in turn belong to social groups, such that the vendor and other users are able to check the authenticity of the reviews and the group authorities are able to trace the reviews generated by their group members.

5.2.2 Design Goal

Due to the lack of centralized control, the MSN is vulnerable to various security threats. It is worthy noting that with third trusted authorities in the network, the security problems can be easily solved. We consider that the group authorities are trusted but not a part of the network. The vendor and compromised users can manipulate reviews for malicious competition. In the following, we describe several malicious attacks that aim particularly at the TSE. They are called *review attacks* and *sybil attacks*, where the review attacks includes review linkability, rejection and modification attacks and the sybil attacks have two categories. Without protection, they may take place easily, paralyzing the entire system.

Review attack 1: Review linkability attack is executed by malicious users. who claim to be members of a specific group, but disables the group authority to trace the review back to its unique identity, thus breaking review linkability.

Review attack 2: Review rejection attack is launched by the vendor when a user submits a negative review to it. In the attack, the vendor drops the review silently without responding to the submission request from the user. The vendor may intend to perform review rejection attacks so as to hide public opinions and mislead users.

Review attack 3: Review modification attack is performed by the vendor toward locally recorded review collections. The vendor inserts forged complimentary reviews, or modifies/deletes negative reviews in a review collection. Such attacks aim at false advertising by breaking review integrity and influencing user behavior.

In addition, we consider attacks where legitimate users generate false reviews. As reviews are subjective in nature, it is difficult to determine whether the content of an authentic review is false or not. However, the TSE must prevent the sybil attacks which subvert the system by creating a large number of pseudonymous entities, using them to gain a disproportionately large influence. Since the TSE assigns multiple pseudonyms to a registered user, the sybil attacks can easily happen in the TSE as follows:

Sybil attack 1: Such an attack is launched by malicious users: Registered users leave multiple reviews toward a vendor in a time slot where reviews are false and negative to the service.

Sybil attack 2: Such an attack is launched by malicious vendors with colluded users: A malicious vendor asks registered users to leave multiple reviews toward itself in a time slot where reviews are positive to the service.

The above two sybil attacks produce inaccurate information, which is unfair to either vendors or users, and disrupt the effectiveness of the TSE. In previous requirement, to prevent review linkability attacks, reviews are needed to be linked to real identities by the group authorities. However, the group authorities are not part of the network, and the detection of the sybil attacks by the group authorities is inefficient and probably with huge delay. To this end, we introduce another security mechanism to effectively resist the sybil attacks by restricting each user to generate only one review toward a vendor in a pre-defined time slot. If any user generates two or more than two reviews with different pseudonyms toward a vendor in a time slot, its real identity will be exposed to the public and such malicious behavior will be caught. The above two sybil attacks can thus be resisted.

Note that, restricting the number of reviews per each user in one time slot effectively limits the sybil attacks. However, any user can still generate false reviews using multiple pseudonyms for different time slots, and the reviews cannot be linked immediately. Since users are grouped based on their interests and reviews are linked to the social groups, false reviews will damage group reputation in a long run. Group reputation can therefore be taken as a weighting factor for the reviews generated by the group members. To further mitigate the effect by the false reviews, users may also make their service selection decisions based on reviews from familiar groups with high reputation rather than strange groups with low reputation.

5.3 TSE Solutions

We present the bTSE based on the above defined models. In the bTSE, a user, after being serviced by the vendor, submits a review to the vendor, which then records the review in its local repository. The review consists of two parts: (α, σ), where α is the review content and σ is the signature proving the authenticity of the content. Review submission may need cooperations from other users when the vendor is not in the transmission range of the user, or when direct submission fails due to communication failure. The logic is: the user

forwards its review to a nearby user who wants to submit a review to the same vendor and expects that user to submit their reviews together. User cooperation increases submission rate and reduces submission delay at the cost of additional transmission efforts. To have a clear idea about the cost of user cooperation, we analyze the communication overhead with or without user cooperation being engaged.

Without cooperation, users submit only their own reviews, and the total communication overhead of l users (one review per user) is $l \cdot f(|\alpha|+|\sigma|)$, where $f(x)$ is the communication cost on transmitting x bits. With cooperations, in an extreme case, user u_{k_i} requires user $u_{k_{i+1}}$ to submit a review for it, $u_{k_{i+1}}$ further requires $u_{i_{i+2}}$, and so on, and $u_{k_{i+l-1}}$ finally submits the reviews of the l users altogether. The communication overhead is $(\sum_{j=1}^{l} j) \cdot f(|\alpha| + |\sigma|)$. If we further adopt the aggregate signature scheme [82], multiple signatures σ can be aggregated into a single batch signature σ^*, where σ^* has the same size as σ, and the communication overhead can be reduced to $(\sum_{j=1}^{l} j) \cdot f(|\alpha|) + l \cdot f(|\sigma|)$.

During review submission, data confidentiality and access control are not necessary because review information is open to the public, and data integrity, authenticity and non-repudiation can be obtained by directly applying traditional cryptography techniques such as hashing and digital signature on review content. As these techniques are very classic, we do not detail them here. While the basic security features are easy to achieve, it is challenging to resist the three review attacks and the two sybil attacks. To overcome this challenge, we first introduce the bTSE which uses tokens to synchronize review submission and organize reviews into certain structures. The integrity of the review structure is protected through hierarchical and aggregate signature techniques so that the review modification can be detected. User cooperation is further exploited to deal with the review rejection. Below, we elaborate on review structure, token usage, and the review generation and submission processes.

5.3.1 Step 1 of bTSE: Structured Reviews

In the bTSE, reviews are structured to reflect their adjacency (i.e. submission order) through user cooperation. As such, vendors simply rejecting or modifying reviews will break the integrity of the review structure, thus being detected by the public. Consider a collection of n reviews received by a vendor v. We define four basic review structures (as illustrated in Fig. 5.3) and indicate vendors' review modification capabilities corresponding to them.

In Fig. 5.3(a), reviews appear as discrete points, meaning that they are submitted separately and independent of each other. This independence gives the vendor maximum

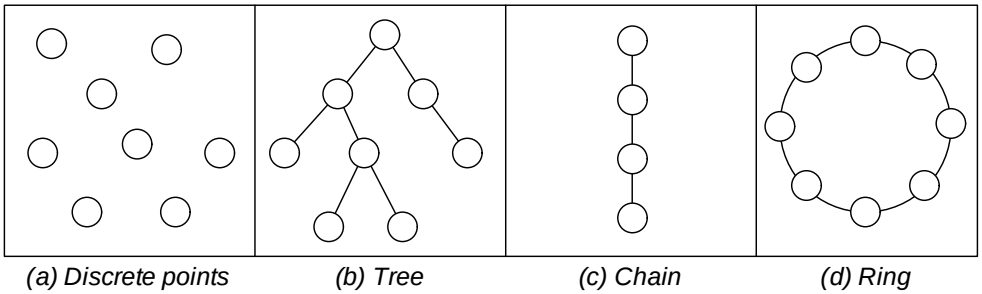


Figure 5.3: Basic review structures

capability of manipulating the n reviews, and its modification capability is therefore $O(n)$. A logarithm modification capability is shown in Fig. 5.3(b), where the reviews are presented in a tree-like structure. In this scenario, v is able to delete any single review corresponding to the leaf node, and the number of such reviews is $O(\log n)$. Figures 5.3(c) and 5.3(d) exhibit a chain structure and a ring structure. They respectively lead to constant $O(1)$ and zero modification capabilities. Clearly, the strength of the modification capabilities follows the order of $O(n) > O(\log n) > O(1) > 0$.

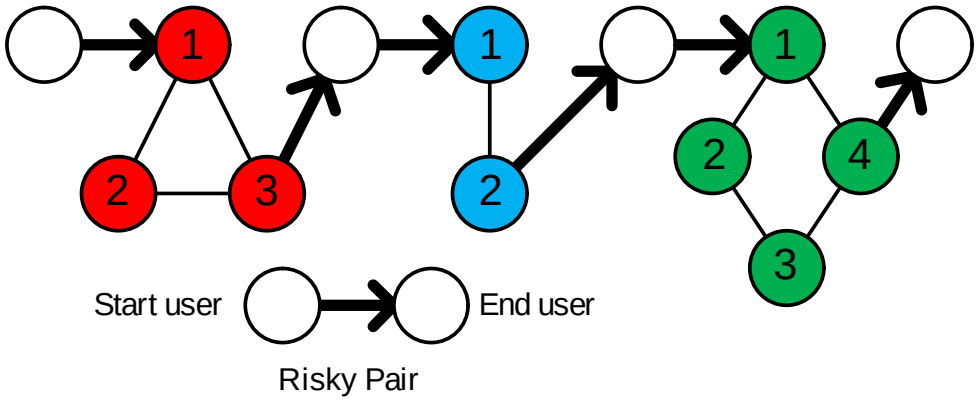


Figure 5.4: A hybrid review structure

In order to restrict the vendor's review modification capability, reviews need to be structured. Pure use of the strongest ring structure requires extensive cooperation efforts from users, i.e., the first user that submitted a review must be aware of the pseudonyms of the users who are going to submit reviews subsequently. Considering the decentralized nature of the S-MSN, the assumption of having such pre-knowledge is unrealistic. Therefore, in the bTSE, separately submitted individual reviews and collectively submitted review

clusters are linked into a chain according to their submission order, and within each review cluster, reviews are organized to form a ring. This hybrid structure, as shown in Fig. 5.4, limits the modification capability of the vendor below $O(1)$. Because this structure has a chain as its skeleton, in the sequel we refer to it as "chain" for ease of our presentation.

5.3.2 Step 2 of bTSE: Synchronization Tokens

The chain structure requires reviews to be submitted sequentially. The bTSE uses a token technique to synchronize review submission. The vendor spontaneously initializes a number of tokens and issues them to distinct users, one per user. The tokens will then be circulated among users according to their local decision on token forwarding. A user cannot submit a review unless it currently holds one of the tokens. A token may be lost due to user mobility or malicious dropping. The vendor considers a token lost if it has not received any review submission associated to the token for a pre-defined maximum time duration θ_{exp}. It replaces lost tokens with new ones so as to maintain a constant number of active tokens and stable system performance.

Each token leads to an independent review chain. The vendor's review modification capability is proportional to the number of review chains. The more review chains, the less trustworthy the reviews from users' viewpoint. Thus, the vendor has the motivation to keep the token number as small as possible. On the other hand, there should be sufficient tokens in order to avoid token starvation problem, where some user never obtains a token to leave its review. In the performance evaluation, we will study the impact of token number on the system performance.

A user, when having a review to submit, transmits a token request message. After receiving the request, a nearby user currently holding a token or the vendor (if having a spare token) may send the token to the requesting user. The requesting user accepts the first arrived valid token and replies with an ACK message. For other received tokens, it replies with a RETURN message, indicating that it no longer needs a token. The token request, ACK and RETURN messages are signed by senders using (pseudonym) secret keys which are non-forgeable. Token forwarding happens toward one user at a time; successfully forwarded tokens (replied with ACKs) are no longer passed to any other user. Transmission retrials may be made up to a maximum number of times to tolerate communication failure.

The vendor maintains a token-pseudonym (TP) list. In this list, each token is linked to a pseudonym that belongs to a user who most recently submitted a review using the token. The list is updated whenever the vendor receives a new review, and is periodically broadcasted to all users in the vendor's transmission range. Once a token's information

is published, the vendor cannot simply remove the token from the TP list because any modification to the list will cause inconsistency with previously published information and be noticed by the public. A user having a token will forward the token, after using it, to a randomly selected neighboring user who is wishing to submit a review. Below, we explain token structure and how a token is forwarded among users.

Consider three users u_1, u_2 and u_3, with u_1 neighboring u_2, and u_2 neighboring u_3. They are respectively members of groups g_1, g_2, g_3 and have obtained pseudonyms $pid_{1,1,*}$, $pid_{2,2,*}$, and $pid_{3,3,*}$ from the corresponding group authorities. The vendor initializes a token with an identifier tok. It generates a public/private key pair (pk_t, sk_t) for tok and publishes the public key pk_t. Suppose that it intends to issue the token to u_1. Then, the token initially is a signature $\sigma_1 = Sign_{sk_t}(g_1||pid_{1,1,*}||T)$, where T is current time stamp. We denote this initial version σ_1 by tok_1. It implies that u_1 is the first user who can submit a review and must submit the review using pseudonym $pid_{1,1,*}$. The pseudonym $pid_{1,1,*}$ is exposed to the vendor by u_i.

After submitting a review using tok_1 and $pid_{1,1,*}$, u_1 updates tok_1 to tok_2 and passes tok_2 to u_2 as a response to u_2's token request. The updated version tok_2 is $(PF_1, \sigma_2 = Sign_{psk_{1,1,*}}(g_2||pid_{2,2,*}||T_1))$, where $PF_1 = (g_1, pid_{1,1,*}, \sigma_1)$ is the token forwarding proof of u_1. Note that, $(pk_t, tok, pid_{1,1,*})$ is currently included in the TP list. Suppose that tok_2 is the first token received by u_2. u_2 does the following: validate tok_2 by checking the authenticity of PF_1 using signatures σ_1 and σ_2, check if the user with $pid_{1,1,*}$ is the one that lastly forwards tok (by looking at the TP list), send an ACK to u_1, submit its review using tok_2 and $pid_{2,2,*}$, and update tok_2 to $tok_3 = (PF_1, PF_2, \sigma_3 = Sign_{psk_{2,2,*}}(g_3||pid_{3,3,*}||T_2))$ where $PF_2 = (g_2, pid_{2,2,*}, \sigma_2)$, and send tok_3 to u_3.

The token forwarding process is repeated among users until tok expires or is brought out of the network. tok is always in the form of $(\{PF_x = (pid_{x,*,*}, \sigma_x)\}_{x \in \mathcal{X}}, \sigma_y)$ where u_x has forwarded the token and u_y the receiver user. It includes the hierarchical signatures that define the order of review submission and organizes submitted reviews in a chain structure. Note that malicious token drop is handled by the vendor through token replacement, as discussed previously.

Reducing token size by signature aggregation: We introduce an aggregate signature technique within multiple-authority settings, which is a variant of the scheme presented in [82]. This technique aggregates the signatures of different users from different social groups, and the signatures can be on different messages. By this technique, the signatures in a token can be aggregated, and the token size, thus the communication cost can be reduced. The aggregate signature technique will also be used for review aggregation in the next sub-section, and the associated $Sign$ and $Verify$ functions will be instantiated

as explained below.

Let $\mathbb{G}$ and $\mathbb{G}_T$ be two cyclic additive groups with the same prime order q, and $e : \mathbb{G} \times \mathbb{G} \rightarrow \mathbb{G}_T$ be a bilinear pairing (Section 2.4.1). P is a generator of $\mathbb{G}$. A group authority c_h picks a random $s_h \in \mathbb{Z}/q\mathbb{Z}$ and sets $Q_h = s_h P$. It also chooses two cryptographic hash functions $H_1 : \{0,1\}^* \rightarrow \mathbb{G}$, and $H_2 : \{0,1\}^* \rightarrow \mathbb{Z}/q\mathbb{Z}$.

Key generation: A user u_j if registering to a group authority c_{h_j} will receive a bunch of pseudonym secret keys corresponding to randomly generated pseudonyms $pid_{j,h_j,*}$. Within a social group, the pseudonyms are never repeatedly assigned to users. The pseudonym secret keys $psk_{j,h_j,*} = (k_{j,0}, k_{j,1})$, where $k_{j,0} = s_{h_j} P_{j,0} = s_{h_j} H_1(pid_{j,h_j,*}||0)$ and $k_{j,1} = s_{h_j} P_{j,1} = s_{h_j} H_1(pid_{j,h_j,*}||1)$.

Signing: u_j generates a string as $str =$ "v", where v represents the identity of the vendor. Note that, all tokens are toward a specific vendor at a time period t. Therefore, the string can be obtained by other similar users. The signature on m_j will be $\sigma_j = Sign_{psk_{j,h_j,*}}(m_j) = (str, S_j, T_j)$.

$$S_j = r_j P_s + k_{j,0} + \beta_j k_{j,1} \text{ and } T_j = r_j P \tag{5.1}$$

where $P_s = H_1(str)$, $\beta_j = H_2(m_j, pid_{j,h_j,*}, str)$ and r_j is randomly chosen from $\mathbb{Z}/q\mathbb{Z}$.

Aggregation: Multiple signatures with the common str can be aggregated. Consider $\sigma_j = (str, S_j, T_j)$ for $1 \leq j \leq n$ are the signatures with common string str. The aggregated signature $\sigma_{agg} = (str, S_{agg}, T_{agg})$ can be obtained, where $S_{agg} = \Sigma_{j=1}^{n} S_j$ and $T_{agg} = \Sigma_{j=1}^{n} T_j$.

Verification: Consider $\sigma_{agg} = (str, S_{agg}, T_{agg})$ is the aggregated signature for $\{(str, S_j, T_j)_{1 \leq j \leq n}\}$. The function $Verify(pid_{1,h_1,*}|| \cdots ||pid_{n,h_n,*}, m_1|| \cdots ||m_n, \sigma_{agg})$ outputs 1 if the following condition holds; 0 otherwise.

$$\begin{aligned} &e(S_{agg}, P) \stackrel{?}{=} e(T_{agg}, P_s) \cdot \\ &\Sigma_{j=1}^{n} e(H_1(pid_{j,h_j,*}||0) + \beta_j H_1(pid_{j,h_j,*}||1), Q_{h_j}) \end{aligned} \tag{5.2}$$

where $\beta_j = H_2(m_j, pid_{j,h_j,*}, str)$. A user will only use $pid_{j,h_j,*}$ to generate a review on m_j for v only once to resist existential forgery attack [63].

5.3.3 Step 3 of bTSE: Review Generation and Submission

Review generation and submission involve multiple steps as shown in Fig. 5.5. Review generation does not rely on tokens which gives users flexibility to generate review. Consider

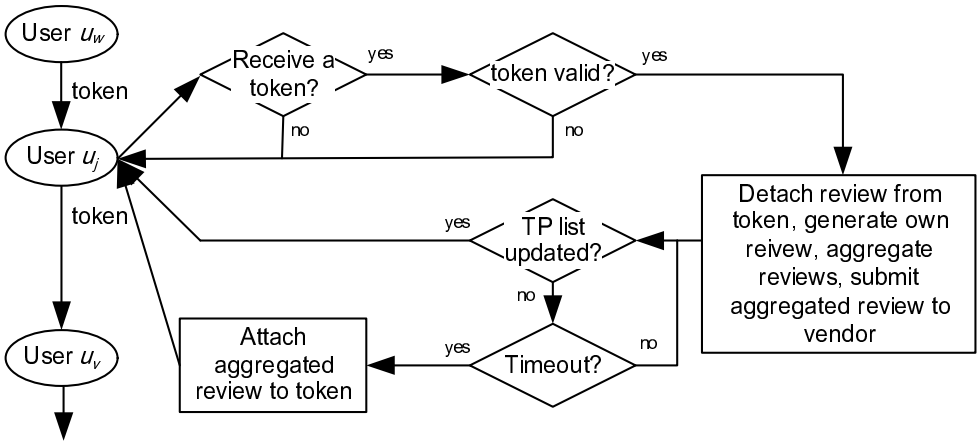


Figure 5.5: Review generation and submission

a user u_j who just received a token tok from a nearby user u_w with pseudonym $pid_{w,*,*}$. It checks if the received tok is valid. This validation step has two perspectives: i) to ensure that tok is indeed originated from the vendor and has been properly forwarded in the past; ii) to ensure that tok is sent by the user who lastly used it. The first goal can be realized by using the public key pk_t of the vendor and the forwarder information (including secrets, pseudonyms, and time stamps) embedded in tok. The second one can be achieved by checking if the association $(tok, pid_{w,*,*})$ exists in the latest TP list provided by the vendor.

During token forwarding, a token is supposed to be passed to only one user that is wishing to submit a review to the same vendor. When multiple such users are present, a random selection can be made. In case that the token is passed to multiple users, whether accidentally (due to the failure in transmitting ACK message) or intentionally, the vendor will only accept the first subsequently submitted review using the token. With the second check on the TP list during token validation, the other users holding the token will find that the token is no longer valid and then try to find a new token to submit their reviews.

After confirming that tok is valid, u_j separates the attached review REV_w from tok. It checks the authenticity of REV_w. It is able to do so because u_w's pseudonym $pid_{w,*,*}$ is included in tok. If REV_w is invalid, u_j will discard it. After the review authenticity check, u_j generates its own review rev_j. Denote the review content by α_j. Suppose that u_j will use the pseudonym $pid_{j,h,*}$ from social group g_h for the review generation, and set T_j to

current time which is larger than all the time stamps embedded in tok. It computes

$$\begin{aligned} \sigma_j &= Sign_{psk_{j,h,*}}(\alpha_j||v||T_j) \\ rev_j &= \langle g_h, pid_{j,h,*}, \alpha_j, v, T_j, \sigma_j \rangle. \end{aligned} \tag{5.3}$$

The signature σ_j can be verified by checking $Verify(pid_{j,h,*}, \alpha_j||v||T_j, \sigma_j) \stackrel{?}{=} 1$ (see the previous sub-section for the details of functions $Sign$ and $Verify$). The receiver then knows that rev_j is indeed generated by a user from g_h at time T_j, not forged by the vendor or a user from a different group. Having generated rev_j, u_j aggregates it with REV_w (by the signature aggregation technique in Section 5.3.2) and submits the aggregated reviews REV_j ($REV_j = rev_j$ if $REV_w = null$) together with tok to the vendor. The vendor checks the validity of REV_j and tok, and broadcast the updated TP list. Review aggregation is the same process as signature aggregation during token forwarding presented in the previous section. Review aggregation has two advantages: i) it effectively resists the review attacks; ii) it largely reduces the communication overhead.

Note that u_j is unable to forge a review of u_w because it cannot obtain any pseudonym secret key $psk_{w,*,*}$, and u_j is unable to replace the review with any other review received from u_w in the past because time stamp is used to prevent review replay. Direct replacement can be easily detected and rejected by the vendor. Further, u_j cannot forward the token without submitting REV_w and/or rev_j because the token records the forwarding history and the vendor will detect the review missing when it later receives the token as part of a review submission made by another user.

After submitting REV_j and tok to the vendor, u_j checks the updated TP list from the vendor. An unsuccessful submission can be due to communication failure or review rejection. To tolerate communication failure, a number of submission retrials can be made before drawing a submission failure conclusion. Upon receiving the updated TP list, u_j will check which pseudonym tok is related to in the list. If tok is related to $pid_{j,h,*}$, meaning that u_j have successfully submitted REV_j, u_j will forward tok to a nearby user as described in the previous section. If tok is still related to $pid_{w,*,*}$, meaning that u_j's submission failed, u_j will resort for cooperative submission by sending tok and REV_j together to a nearby user that is requesting for a token. If tok is related to a different pseudonym, implying that u_w must have sent the token to multiple users and u_j's submission failed, u_j will try to find a new token from nearby users and submit REV_j using it.

Comments: During service information dissemination, the vendor needs to broadcast its entire review collection together with the latest versions of the tokens. After receiving the service information, a user checks the authenticity of the reviews and compares the pseudonyms associated with reviews to those embedded in tokens. Because the token

contains its circulation history (implemented by hierarchical signatures and time stamps), the user may arrange the reviews according to the circulation history. Any missed review will be detected. If multiple reviews from the same user appear, it will use time stamp to differentiate them.

5.3.4 SrTSE

In previous sub-sections, we have introduced a bTSE where review linkability, rejection and modification attacks are considered. We further extend the bTSE to a Sybil-resisted TSE, named SrTSE, which effectively prevents the sybil attacks. In the following, we first describe the sybil attacks in the S-MSN, and then introduce our solutions to complete the design of the SrTSE.

Sybil Attacks: In Section 5.2.2, we define two types of sybil attacks: the sybil attack 1 is launched by a group of registered users. They aim at telling other users the bad service from a vendor while the service of the vendor is good. With the valid registration, these malicious users are able to leave false reviews toward a specific vendor. Even realizing the reviews are not in accord with the service, the vendor cannot simply delete or reject the reviews. If the vendor does, users will detect such behavior and regard the vendor as a dishonest vendor. Besides, the sybil attack 2 is launched by a vendor and a group of registered users. They aim at raising the reputation of the service from a vendor while the service of the vendor is not that good. The reviews generated by these malicious users cannot be distinguished from other reviews by well-behaving users. In the bTSE, every user receives multiple pseudonyms and the corresponding secret keys. For example, u_j has $pid_{j,h,1}, pid_{j,h,2}, \cdots$ in social group g_h. Since these pseudonyms are random numbers and cannot be linked by anyone except group authorities, u_j can use $pid_{j,h,1}, pid_{j,h,2}, \cdots$ to generate multiple reviews toward a vendor for a short time period. In addition, u_j can form the false reviews in chain structure or ring structure. Therefore, from the perspective of other users, they cannot tell if these reviews are from the same user or not.

Sybil-resisted TSE (SrTSE): In the SrTSE, we introduce a novel solution to prevent the two sybil attacks. In the S-MSN, we consider that a user has no need to generate multiple reviews toward a vendor in a short time period. The SrTSE allows a user to leave only one review toward a vendor for a pre-defined time slot. If a user generates multiple reviews with the same pseudonyms, the linkability of the reviews can be easily verified by the public; if a user generates multiple reviews with different pseudonyms toward a vendor in a time slot, its real identity will be exposed to the public. To achieve the above properties, we modify the pseudonym generation and the signature scheme of the bTSE.

Let $\mathbb{G}$ and $\mathbb{G}_T$ be two cyclic additive groups with the same order q, and $e : \mathbb{G} \times \mathbb{G} \to \mathbb{G}_T$ be a bilinear pairing [80]. P, Q are two generators of $\mathbb{G}$. A group authority c_h picks a random $s_h \in \mathbb{Z}/q\mathbb{Z}$ and sets $Q_h = s_h P$. It also chooses two cryptographic hash functions $H_1 : \{0,1\}^* \to \mathbb{G}$, and $H_2 : \{0,1\}^* \to \mathbb{Z}/q\mathbb{Z}$.

Consider a user u_j registers to the social group g_h in the SrTSE. Then, u_j obtains the following values:

- $pid_{j,h_j,*}$, a published random number.
- $a_{j,*} = \rho H_2(pid_{j,h_j,*}) + id_j$, where id_j is the real identity of u_j, and ρ is a coefficient in $\mathbb{Z}/q\mathbb{Z}$.
- $b_{j,*} = (r_* P, s_h Q + r_* H_1(a_{j,*} r_* P || pid_{j,h_j,*}))$, where r_* is a random number. This is a signature on $a_{j,*} r_* P$ by the group authority c_h.

For multiple random numbers $pid_{j,h_j,*}$, u_j obtains multiple tuples $(pid_{j,h_j,*}, a_{j,*}, b_{j,*})$ from c_h. Then, u_j regards $pid_{j,h_j,*}$ as the pseudonym and $psk_{j,h_j,*} = a_{j,*}$ as the secret key. In order to generate a signature on message m_j, u_j executes the following steps:

- u_j calculates $a_{j,*} H_1(m_j)$.
- u_j generates a random number $\bar{r} \in \mathbb{Z}/q\mathbb{Z}$, and outputs a signature

$$\sigma_j = (pid_{j,h_j,*}, \sigma_{j,1}, \sigma_{j,2}, \sigma_{j,3}, \sigma_{j,4}), \tag{5.4}$$

$$\begin{aligned} \text{where } \sigma_{j,1} &= a_{j,*} H_1(m_j), \\ \sigma_{j,2} &= a_{j,*} r_* P, \\ \sigma_{j,3} &= r_* P, \\ \sigma_{j,4} &= s_h Q + r_* H_1(a_{j,*} r_* P || r_* P || pid_{j,h_j,*}). \end{aligned} \tag{5.5}$$

If an entity receives σ_j, it runs the following verification steps.

- Step 1:

$$e(\sigma_{j,4}, P) = e(Q, Q_h) e(H_1(\sigma_{j,2} || \sigma_{j,3} || pid_{j,h_j,*}), \sigma_{j,3}) \tag{5.6}$$

- Step 2:

$$e(\sigma_{j,1}, \sigma_{j,3}) = e(H_1(m_j), \sigma_{j,2}) \tag{5.7}$$

It can be seen that $(\sigma_{j,3}, \sigma_{j,4})$ is a signature generated by the group authority c_h since s_h is the secret key only known to c_h. From Step 1, the authenticity of $\sigma_{j,2}$ and $pid_{j,h_j,*}$ can be guaranteed. In addition, from Step 2, if the equality holds, it is publicly verified that u_j knows the value $a_{j,*}$. In fact, we build our signature scheme based on identity-based signature [118] and short signature [119].

Sybil Attack Detection: For each review, we require users to sign on $m_j = v||t$ where v is the vendor's name and t is the time slot. If users do not output the signature on m_j, its review will not be accepted by the public. We consider a sybil attack launched by u_j who generate two reviews with two different pseudonyms $pid_{j,h_j,1}$ and $pid_{j,h_j,2}$. If both reviews are authentic, they must contain both $a_{j,1}H_1(m_j)$ and $a_{j,2}H_1(m_j)$ which can be accessed by the public. Thus, the public is able to calculate $Tr = id_jH_1(m_j)$ from

$$a_{j,1} = \rho H_2(pid_{j,h_j,1}) + id_j \tag{5.8}$$

and

$$a_{j,2} = \rho H_2(pid_{j,h_j,2}) + id_j, \tag{5.9}$$

since

$$id_j = \frac{a_{j,1}H_2(pid_{j,h_j,2}) - a_{j,2}H_2(pid_{j,h_j,1})}{H_2(pid_{j,h_j,2}) - H_2(pid_{j,h_j,1})}. \tag{5.10}$$

To recover the real identity of the sybil attacker, any entity calculates $Tr' = idH_1(m_j)$ for every possible id and tests if $Tr' \stackrel{?}{=} Tr$. The entity outputs the recovered identity id, upon satisfaction of the above equation.

Note that, similar to [64,65], the vendors or the users can pre-calculate values $idH_1(m_j)$ for every possible identity, and then, they just need to check the equality between Tr and these values. Within a constant time, the real identity of the sybil attacker can be revealed.

Aggregate Signature in the SrTSE: The signature aggregation plays an important role in the bTSE because it largely reduces the communication overhead. We will also explore the possible aggregation scheme for the newly developed signatures in the SrTSE. Observing the modified signature scheme, the pseudonyms and the corresponding secret keys have to be equipped with a trapdoor such that other entity (not group authority) is able to recover the real identity of the sybil attacker. Therefore, the aggregation on signatures becomes more difficult. From the verification Step 1 and Step 2, we can see that $\sigma_{j,1}, \sigma_{j,2}$ and $\sigma_{j,3}$ cannot be aggregated because $\sigma_{j,2}$ and $\sigma_{j,3}$ have to be individually input in the hash function and $\sigma_{j,1}$ is paired with different $\sigma_{j,3}$ every time. But $\sigma_{j,4}$ from different users can be aggregated in the form of $\prod_j \sigma_{j,4}$ because it is always paired with P. The verification on the aggregate signature is shown below.

$$e(\prod_j \sigma_{j,4}, P) = e(Q, Q_h) \prod_j e(H_1(\sigma_{j,2}||pid_{j,h_j,*}), \sigma_{j,3}) \tag{5.11}$$

In the SrTSE, we have modified the signatures of the review generation in order to resist the sybil attacks. Such modification makes the aggregation less efficient. If we have n signatures and each has 4 group elements in $\mathbb{G}$, these signatures can be aggregated into $3k + 1$ group elements. Though the size of aggregate signature decreases, it still linearly depends on k. We regard the size of such aggregate signature as $O(k)$. In comparison, the bTSE offers an aggregated signature sized at $O(1)$. Thus, we can still use the aggregate signature scheme of the bTSE for the token generation to achieve higher efficiency.

5.3.5 Summary of bTSE & SrTSE

We have introduced two trustworthy service evaluation systems: one considers the review attacks only and the other one considers both the review attacks and the sybil attacks. In the following, we summarize the efficiency and security properties of these two systems. We also consider the non-cooperative system where pseudonyms are employed and the reviews are individually submitted by users. Let "L_att" denote "review linkability attacks", "R_att" denote "review rejection attacks", "M_att" denote "review modification attacks", "S_att" denote "sybil attacks", "S_token_1" denote "the size of signature on tokens", "S_review_1" denote "the size of signature on reviews", "S_token_k" denote "the size of k-aggregated signatures on tokens", "S_review_k" denote "the size of k-aggregated signatures on reviews", "Y" denote "resist", and "N" denote "not resist".

Table 5.1: Security attacks in bTSE and SrTSE

	L_att	R_att	M_att	S_att
Non-Coop	Y	N	N	N
bTSE [4]	Y	Y	Y	N
SrTSE	Y	Y	Y	Y

Table 5.2: Communication overhead in bTSE and SrTSE

	S_token_1	S_token_k	S_review_1	S_review_k
bTSE [4]	$2\|\mathbb{G}\|$	$2\|\mathbb{G}\|$	$2\|\mathbb{G}\|$	$2\|\mathbb{G}\|$
SrTSE	$2\|\mathbb{G}\|$	$2\|\mathbb{G}\|$	$4\|\mathbb{G}\|$	$(3k+1)\|\mathbb{G}\|$

From the above the security comparisons in Table 5.3.5, it can be seen that both the bTSE and the SrTSE outperforms the non-cooperative system in terms of security. Moreover, the bTSE resists "L_att", "R_att", and "M_att" which are the possible attacks. The SrTSE additionally resists the two sybil attacks from malicious users, and thus the SrTSE is more reliable and trustworthy in the S-MSN.

In the above Table 5.3.5, we give the communication overhead of a token and a review in both bTSE and SrTSE. We do not count the sizes of messages and the common strings because their sizes are negligible compared to the signatures. From the Table 5.3.5, both bTSE and SrTSE have very efficient review and token generation due to the signature aggregation. To resist the sybil attacks, SrTSE employs a trapdoor in the pseudonym which leads to a linearly-increasing size in review generation of the SrTSE.

5.4 Security Analysis

Security analysis focuses on the system's resilience against review linkability attacks, review rejection attacks, review modification attacks, and sybil attacks.

5.4.1 Resilience to Review Linkability Attacks

In a review linkability attack, a user submits unlinkable reviews. If reviews without linkability enabled on the group authorities are allowed, malicious users may abuse their memberships and generate irresponsible reviews to undermine the system's performance. Recall the review generation process described in Section 5.3.3. A review rev_j is valid if and only if the following verification function can be checked by the public: $Verify(pid_{j,h,*}, \alpha_j||v||T_j, \sigma_j)$. By the verification function, $(g_h, pid_{j,h,*}, \alpha_j||v||T_j)$ are related by a non-forgeable signature. Anyone without the secret key sk_h or $psk_{j,h,*}$ is unable to forge a triple tuple in such relation. Furthermore, when generating $pid_{j,h,*}$ and the corresponding $psk_{j,h,*}$ for user u_j, the group authority c_h checks the unique identity id_j of u_j, and maintains an association $(pid_{j,h,*}, id_j)$ all the time. Therefore, invalid reviews are recognizable by the public and the group authorities, and the group authorities are able to link any valid review to the unique identity of its generator. Review linkability attacks thus can be effectively prevented.

5.4.2 Resilience to Review Rejection Attacks

In a review rejection attack, the vendor rejects unwelcome but authentic reviews from users. Recall the review submission process in Section 5.3.3. A user u_j tries to directly submit its review rev_j using token tok to the vendor for several times. If all the trials fail, whether due to communication failure or owing to a review rejection attack, it will pass both tok and rev_j to a nearby user u_k who also has a need in submitting its review rev_k to the same vendor, and expect u_k to submit rev_j and rev_k together. Then, u_k validates the received tok and rev_j, aggregates rev_j and rev_k to obtain REV_k, and submits REV_k as a whole, together with tok, to the vendor. The vendor either accepts REV_k (including the previously rejected rev_j) or rejects it (including the new one rev_k). Now, the vendor has a constraint on rejecting REV_k because it has to consider whether rev_k is complimentary or not. As reviews are aggregated, the vendor will have more and more constraints on launching review rejection attacks. If it finally decides to accept the aggregated reviews that are submitted as a whole piece, it will actually accept all the reviews that it previously rejected. The review aggregation and indirect review submission techniques mitigate such attacks.

5.4.3 Resilience to Review Modification Attacks

In a review modification attack, the vendor manipulates its locally recorded review collection by inserting forged complimentary reviews and modifying or deleting existing unwelcome authentic reviews. The integrity of the review content is guaranteed by the signature techniques (refer to Section 5.4.1). Reviews are generally linked in one or a few review chains, depending on the number of the used tokens, if they are directly submitted by users. The cooperation among users enables indirect review submission in case of direct-submission failure. Indirect submission causes the reviews from different users to be aggregated and formed in a ring structure. Figure 5.4 shows a single review chain as a result of direct and indirect submissions. In this figure, dots represent individual reviews, and without ambiguity they also refer to the users that submit the corresponding reviews.

Let the users whose reviews are aggregated in one signature form a cluster. In Fig. 5.4, there are three clusters of users as indicated by the colorful dots. We index the users in each cluster such that a smaller index indicates the user obtains the token earlier and the largest index implies the user successfully and directly submitted the aggregated reviews to the vendor. Thus, the users with the smallest index and the largest index are the interfaces of the cluster. Outside these clusters, arrowed lines indicate the token forwarding direction. We define a risky pair of users as two users that are interconnected by an arrowed line.

The one from which the line starts is called start user, and the other is referred to as end user. The following theorems indicate that review modification attack can be resisted.

Theorem 5 *The vendor is able to insert reviews into a review chain if and only if it has compromised a start user.*

Proof 5 *Suppose that the vendor has compromised a start user u_j and obtained its all keying materials. Let u_v be the end user corresponding to u_j. The token is in the form of $(\cdots, PF_j, PF_v, \cdots, \sigma_y)$. If the vendor wants to insert a false review via the pseudonym of user u_m, it has to change the token to $(\cdots, PF'_j, PF_m, PF_v, \cdots, \sigma_y)$, where*

$$\begin{aligned} PF'_j &= (pid_{j,h_j,*}, Sign_{psk_{j,h_j,*}}(g_{h_m}||pid_{m,h_m,*}||T_j), \\ PF_m &= (pid_{m,h_m,*}, Sign_{psk_{m,h_m,*}}(g_{h_v}||pid_{v,h_v,*}||T_m). \end{aligned} \tag{5.12}$$

The validity of the modified token can be easily verified. Note that in this case, the vendor has also compromised u_m because otherwise it would not have $psk_{m,h_m,*}$ and not be able to generate PF_m or forge the review.

We consider the case that the vendor has successfully inserted a forged review. In order for the forged review to be accepted by the public, the vendor must have inserted a fake token forwarding proof in the token, which in turn implies that it must have compromised a user who has used the token. Assume that the compromised user is not a start user. In this case, it must be a user in a cluster (see Fig. 5.4) that does not have the largest index. Because the user with largest index outputs a non-forgeable aggregated signature on the legitimate reviews in the cluster, the forged review will be detected, contradicting to the fact that the insertion is successful. This completes the proof.

Theorem 6 *The vendor without compromising any user can only delete a sub-chain of a review chain, starting with an end user and spanning all the users that receive the token later than the end user.*

Proof 6 *A cluster of aggregated reviews are treated as a single piece because the vendor is not able to separate them. They are either all kept or all deleted. By definition, an end user is also a start user unless it is within a user cluster (corresponding to a cluster of aggregated reviews). Thus, the vendor can only delete reviews from an end user. After deleting a review or some aggregated reviews, the review chain becomes broken. The breakage is detectable unless the subsequent reviews are also deleted. However, if the vendor compromises a start user (and obtains the user's keying materials), it will be able to delete an arbitrary number of successive reviews including review clusters from the start user, and fix the chain breakage, without being detected.*

5.4.4 Resilience to Sybil Attacks

To resist to the sybil attacks, we need to prove that the SrTSE satisfies the following two properties.

- **P1.** If a user leaves two or more false reviews with different pseudonyms toward a vendor in a time slot, its real identity can be derived by the vendor and other users.
- **P2.** If a user leaves only one review toward a vendor in a time slot, its real identity can be protected.

We first consider the property **P1** of the SrTSE. We consider a malicious user u_j generates two signatures on $m_j = v||t$. From the signature, $\sigma_{j,1}$ can be obtained. If both signatures are valid, the relation $\sigma_{j,1}$, $\sigma_{j,2}$ and $\sigma_{j,3}$ will be fixed by the eqn. (5.7). Since $\sigma_{j,2}$ and $\sigma_{j,3}$ are included in the message of $\sigma_{j,4}$, their authenticity can be verified. Therefore, $\sigma_{j,1} = a_{j,*}H_1(m_j)$ where $a_{j,1}$ is generated in the specific format by the group authority. The public can obtain $a_{j,1}H_1(m_j)$ and $a_{j,2}H_1(m_j)$, and then derive

$$id_j H_1(m_j) = \frac{H_2(pid_{j,h_j,2})a_{j,1} - H_2(pid_{j,h_j,1})a_{j,2}}{H_2(pid_{j,h_j,2}) - H_2(pid_{j,h_j,1})} \cdot H_1(m_j) \tag{5.13}$$

By executing the equality checks, the real identity id_j of u_j will be determined. Note that, ρ is determined by the group authorities. Different group generate different ρ. We consider the used two pseudonyms $pid_{j,h_j,1}$ and $pid_{j,h_j,2}$ are from the same social group in the above analysis. We can further require a trusted third authority to coordinate all the group authorities to generate the same ρ for one user, and then the sybil attacks using pseudonyms from different groups can be resisted.

We then consider the property **P2** of the SrTSE. From a signature σ_j, the real identity can be disclosed from $a_{j,*}$ which is contained in $\sigma_{j,1} = a_{j,*}H_1(m_j)$ and $\sigma_{j,2} = a_{j,*}r_*P$. Denote $H_1(m_j) = r'P$. Thus, we have two values

$$\sigma_{j,1} = (\rho H_2(pid_{j,h_j,*}) + id)r'P \tag{5.14}$$

and

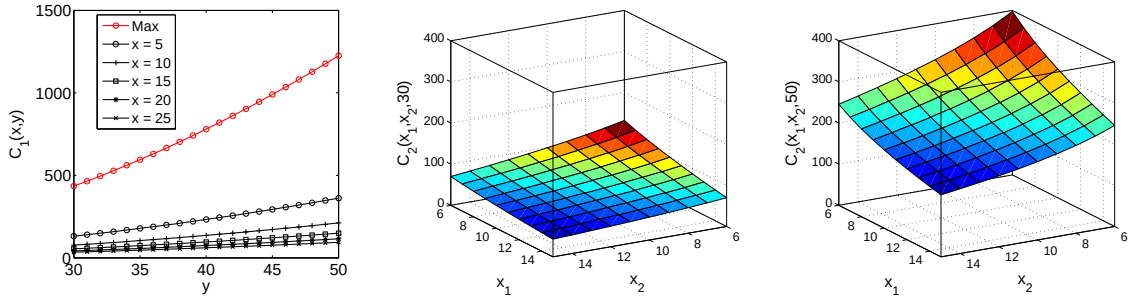
$$\sigma_{j,2} = (\rho H_2(pid_{j,h_j,*}) + id)r_*P. \tag{5.15}$$

If multiple signatures with different pseudonyms are generated toward different m_j by u_j, we can obtain the following values:

$$\begin{aligned}&(\rho H_2(pid_{j,h_j,1}) + id_j)r'_1P,\\&(\rho H_2(pid_{j,h_j,1}) + id_j)r_1P,\\&(\rho H_2(pid_{j,h_j,2}) + id_j)r'_2P,\\&(\rho H_2(pid_{j,h_j,2}) + id_j)r_2P, \cdots\end{aligned} \tag{5.16}$$

Since $(r'_1, r_1, r'_2, r_2, \cdots)$ are independent and unknown to the public. The random number ρ cannot be removed by the linear combination of these values. Therefore, the real identity id_j is always anonymized by ρ, and thus id_j is protected.

5.4.5 Numerical Results of Detecting Sybil Attack



(a) 1 malicious user (b) 2 malicious users, 30 reviews (c) 2 malicious users, 50 reviews

Figure 5.6: Number of calculation on detecting the sybil attack

The SrTSE can resist the sybil attack, i.e., the sybil attack can be detected without the involvement of the group authorities. In the following, we study the performance of the SrTSE under the sybil attack. We will evaluate how much computation costs needed to detect the false reviews by the sybil attack. We first consider the case of a single malicious user in the SrTSE. The sybil attacker generates x false reviews toward the vendor in time slot t using its x different pseudonyms. The vendor totally receives y reviews in time slot t ($y \geq x$). From eqn. (5.13), the vendor needs to do every calculation for any pair of the received reviews. That means, the maximum number of calculation is $\binom{y}{2}$. We denote the number of calculations needed to filter all the false reviews by $C_1(x, y)$ ($\leq \binom{y}{2}$). In fact, if two reviews have been identified to be associated with the attacker, all the rest false

reviews can be easily identified by comparing them with the detected false reviews. Thus, the expected value of $C_1(x, y)$ is calculated in eqn. (5.17).

$$\begin{aligned} C_1(x,y) &= \frac{y-x}{y}(y-1+C_1(x,y-1)) + \frac{x}{y}(y-1) \\ &= y-1+\frac{y-x}{y}C_1(x,y-1) \end{aligned} \tag{5.17}$$

In the above equation, $\frac{y-x}{y}$ and $\frac{x}{y}$ represent the probabilities of choosing a valid review and a false review, respectively. If a valid review is chosen, we need to do $y-1$ calculations between the chosen review with the rest $y-1$ reviews and $C_1(x, y-1)$ calculations among $y-1$ reviews. If a false review is chosen, we need to do the first $y-1$ calculations and then all the false reviews will be detected. Similarly, we further derive the number of calculations $C_2(x_1, x_2, y)$ in case of two malicious users, as shown in eqn. (5.18), where x_1 and x_2 represent the numbers of false reviews of two malicious users, respectively. We have $x_1 + x_2 \leq y$.

For the initial values, we have $C_1(x, x) = x - 1$, $C_2(0, x_2, y - x_1) = C_1(x_2, y - x_1)$ and $C_2(x_1, 0, y - x_2) = C_1(x_1, y - x_2)$. If $x_1 + x_2 = y$, $C_2(x_1, x_2, y) = y - 2 + \frac{2x_1x_2}{y}$.

$$\begin{aligned} C_2(x_1,x_2,y) =& \frac{y-x_1-x_2}{y}(y-1+C_1(x_1,x_2,y-1)) \\ &+ \frac{x_1}{y}(y-1+C_2(0,x_2,y-x_1)) + \frac{x_2}{y}(y-1+C_2(x_1,0,y-x_2)) \\ =& y-1+\frac{y-x_1-x_2}{y}C_1(x_1,x_2,y-1)+ \\ &+ \frac{x_1}{y}C_2(0,x_2,y-x_1) + \frac{x_2}{y}C_2(x_1,0,y-x_2) \end{aligned} \tag{5.18}$$

Then, we plot $C_1(x, y)$ and $C_2(x_1, x_2, y)$ and $C_2(x, y)$ in terms of x, y, x_1 and y_1, respectively, as shown in Fig. 5.6. From Fig. 5.6(a), in case of 1 malicious user, it can be seen that the number of calculations almost increases linearly as the number of received reviews increases. When more reviews received at the vendor, more calculation efforts are needed to find the false reviews. Moreover, when the number of false reviews increases, the calculation efforts can be reduced because the probability of finding a false review is larger. From Fig. 5.6(b) and Fig. 5.6(c), we can observe that when the number of false reviews decreases or the number of received reviews increases, the number of calculations

to detect all false reviews increases. Note that when $x_1 = x_2 = 15$ and $y = 30$, the number of calculations is 43. In this case, 30 reviews are all false reviews, and we still need 43 calculations on average to detect them. The reason is that the calculations cannot detect any false reviews when the two reviews are separately from two users.

5.5 Performance Evaluation

In this section, we evaluate the performance of the bTSE through trace-based custom simulations. We choose to compare the bTSE with a non-cooperative system, where each user directly submits its review to the vendor without any synchronization constraint (use of tokens). We use the following three performance metrics:

- *Submission rate*: It is defined as the ratio of the number of successfully submitted reviews to the total number of generated reviews in the network.
- *Submission delay*: It is defined as the average duration between the time when a review is generated and the time when it is successfully received by the vendor.
- *Cooperation overhead*: It is defined as the total number of times that tokens are forwarded among users.

Because the non-cooperative system involves only direct review submission, the last metric is not applicable to it. As we will see, the bTSE achieves significantly (up to 100%) higher submission rate under a defined review rejection attack, and greatly (up to 75%) lower submission delay in general than the non-cooperative system, at the cost of reasonable cooperation overhead. The SrTSE performs exactly the same as the bTSE in the review submission.

5.5.1 Simulation Setup

In the simulation, we use the real trace log [79] which has been used in previous chapters. In the previous chapter, we have shown that how to obtain the top 10 hotspots in Fig. 4.8. In this chapter, we also choose these 10 hotspots and consider the chosen hotspot as the place of the vendor.

We define a universal attribute set of 50 elements. The set is known by all users. Users are organized into 10 social groups, each being tagged with 5 random attributes. Each user

has a membership with $1 \sim 5$ random social groups, that is, it may have $5 \sim 25$ attributes, inherited from the belonged social groups. The vendor (precisely, its service) has 3 random attributes. If a user shares a common attribute with the vendor, it will be interested in the vendor (service). For simplicity, we do not implement users random state transition from 'not interested' to 'interested' caused by the recommendation from its friends. Each user has a transmission range of $80m$. The vendor has a transmission range equal to its service range (SR). A user interested in the vendor wishes to submit a review to the vendor when it enters the vendor's service range for the first time. Direct review submission is possible only when the vendor is within the user's transmission range. As the trace log covers a small region and a small period time, we do not implement the token timeout interval θ_{exp} (see Section 5.3.2).

We conduct two sets of simulations under the situations with/without review attacks. We vary SR between $150m$ and $300m$, and token number TN between 1 and 10. As analyzed in Section 5.4, the bTSE resists the review linkability and modification attacks through cryptography techniques and specially-designed review structure, and mitigates review rejection attack through cooperative review submission. The first two attacks have no influence on review submission. In our simulation study, we are therefore interested only in the impact of review rejection attack on the system performance. Each review is a value ranged in $[0, 1]$. A review is negative if its value is lower than 0.5. The vendor performs review rejection action by rejecting all negative reviews. When multiple reviews are aggregated and submitted together, the vendor accepts them all if their average value is no less than 0.5, or rejects them all otherwise. We place the vendor at the centers of the 10 hotspots in turn and conduct 50 simulation runs for each placement. Using the total 500 simulation runs, we obtain the average results to be analyzed in the next sub-section.

5.5.2 Simulation Results

Under no Review Rejection Attack: We first study the system performance in relation with SR. Let us observe Fig. 5.7. When SR goes up, the number of users who enter the service range and thus generate reviews increases. Recall that each user has a transmission range much smaller than SR. In the non-cooperative system, users have to move close enough to the vendor in order to submit their reviews. Hence, the system shows a decreasing submission rate and increasing submission delay with SR. In the bTSE, review submission is constrained by token possession in addition to user-to-vendor distance on one hand. On the other hand, cooperative review submission is triggered when direct submission is not possible. The interplay of the two factors renders the bTSE exhibiting a performance trend similar to the non-cooperative system's in submission rate and submission delay as

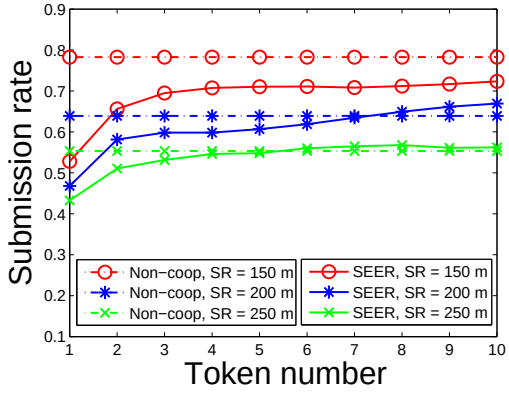
SR varies. From Fig. 5.7(c), the bTSE has greatly lower submission delay than the non-cooperative system, up to 75% lower. Fig. 5.7(e) depicts the cooperation overhead of the bTSE. As expected, the larger the vendor's service range, the more cooperation efforts from users involved.

We then look at how TN impacts the system performance. Intuitively, when TN goes up, users have increased opportunity to submit reviews, leading to raised system performance. This intuition is confirmed by the results in Figures 5.7(a) and 5.7(c). We observe an arguable phenomenon: submission rate and delay both stabilize after TN is beyond certain value. In the case of SR = 150, it occurs after TN = 20 and is however not shown here. The reason for this phenomenon is as follows. When there are more tokens circulating in the network, initially users can easily get tokens and submit their reviews. Recall that users no longer participate in the review system once their reviews are submitted to the vendor or forwarded to others. Over time, the network of participating users becomes sparse and sparse, and these users have less and less chance to receive a token due to decreased network density. This can be cross verified by the cooperation

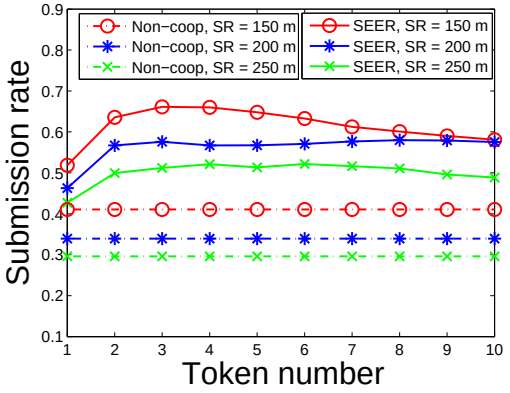
Under Review Rejection Attack: Figures 5.7(b) and 5.7(d) show the performance comparison of the bTSE and the non-cooperative system when the vendor launches the review rejection attack. We observe that the non-cooperative system has a performance drop ($> 25\%$) in submission rate. Indeed, it is not equipped with any security mechanism against the attack and suffers performance degradation. Submission delay does not show any noticeable change since only direct submission is engaged in the non-cooperative system and only successfully submitted reviews are considered during delay calculation. Compared with the case of no review rejection attack, the bTSE only has slightly reduced ($< 10\%$ smaller) submission rate and nearly unchanged submission delay thanks to the user cooperation and review aggregation mechanisms. The bTSE achieves significantly higher submission rate than the non-cooperative system, up to 100%. These simulation results indicate that the bTSE can effectively resist the review rejection attack.

5.6 Related Work

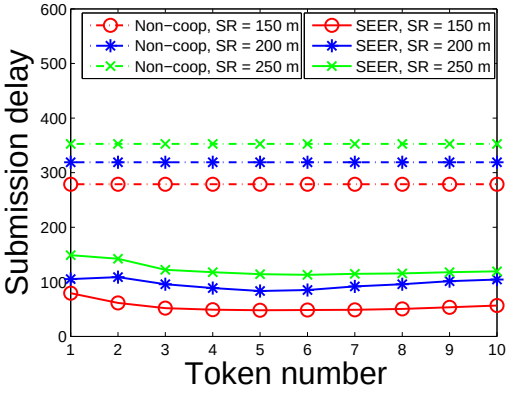
Trust evaluation of service providers is a key component to the success of location based services in a distributed and autonomous network. Location-based services require a unique and efficient way to impress the local users and earn their trust so that the service providers can obtain profits [120, 121]. Rajan and Hosamani [122] used an extra monitor deployed at the untrusted vendor's site to guarantee the integrity of the evaluation results. Wang and Li [123] proposed a two-dimensional trust rating aggregation approach to enable a small set of



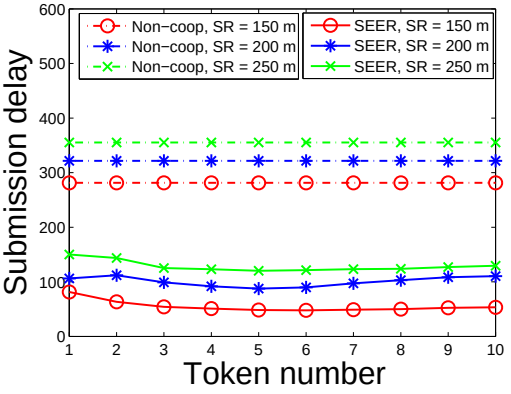
(a) Submission rate with no attack



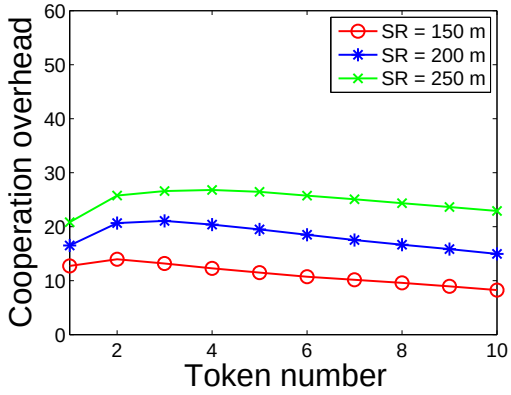
(b) Submission rate with attack



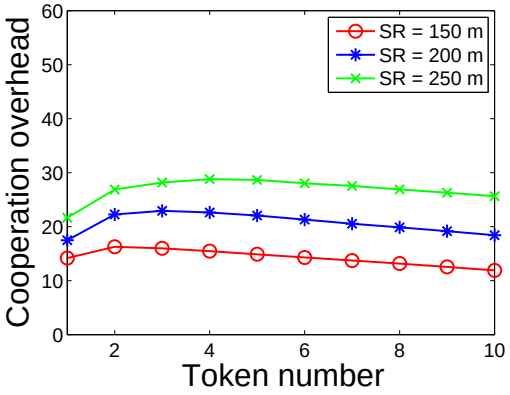
(c) Submission delay with no attack



(d) Submission delay with attack



(e) Cooperation overhead with no attack



(f) Cooperation overhead with attack

Figure 5.7: Performance with/without review rejection attack

trust vectors to represent a large set of trust ratings. Aydey and Fekri [124] approached the trust management as an inference problem and proposed a belief propagation algorithm to efficiently compute the marginal probability distribution functions representing reputation values. Das and Islam [125] introduced a dynamic trust computation model to cope with the strategically altering behavior of malicious agents.

Distributed systems are vulnerable to *sybil attacks* where an adversary manipulates bogus identities or abuse pseudonyms to compromise the effectiveness of the systems. For example, in the peer-to-peer networks, Douceur [126] indicated that the sybil attacks can compromise the redundancy of distributed storage systems. In the sensor networks, Karlof and Wagner [127] showed that the sybil attacks can damage the routing efficiency. Newsome *et al.* [128] proposed many defense mechanisms, such as, radio resource testing, key validation for random key pre-distribution, and position verification. In vehicular ad hoc networks, Lu *et al.* [129] proposed an efficient detection mechanism on double-registration which can be conducted to mitigate the possible sybil attacks. The sybil attacks in social networks have attracted great attention recently [66–68]. In social networks, Wei *et al.* [68] mentioned the existence of a trusted authority can mitigate the effect of the sybil attacks, but they considered that such requirements impose additional burdens on users which is not acceptable.

5.7 Summary

We have introduced a trustworthy service evaluation (TSE) system for service-oriented mobile social networks (S-MSN). The TSE enables a vendor to receive, record the reviews from its customers and disseminate the reviews to other nearby users. It helps build the user-to-vendor trust from the user-to-user trust. Specifically, the TSE engages hierarchical signature and aggregate signature techniques to transform independent reviews into structured review chains. This transformation involves distributed user cooperation, which improves review integrity and greatly reduces vendors' modification capability. We have presented three review attacks and shown that the bTSE can effectively resist the review attacks without relying on a trusted authority. We have also considered the notorious sybil attacks and demonstrated that such attacks cause huge damage to the bTSE. We have subsequently modified the construction of pseudonyms and the corresponding secret keys in the bTSE, and obtained a sybil-resist TSE (SrTSE) system. The SrTSE allows users to leave only one review toward a vendor in a pre-defined time slot. If multiple reviews with different pseudonyms from one user are generated, the real identity will be disclosed to the public. The sybil attack is thus prevented in the SrTSE. Numerical results show

the effectiveness of the SrTSE to resist the sybil attacks. Further trace-based simulation results demonstrate that the bTSE significantly outperforms a non-cooperative review system in terms of submission rate and delay, especially in the presence of the review rejection attacks.

Chapter 6

Secure and Efficient Routing Protocol for Body Area Networks

6.1 Introduction

In previous chapters, we discussed the mobile applications in the two-user, user-chain, and user-star domains. Besides, the MSN includes the single-user domain where multiple body sensors and the smartphone interact for collecting body physiological signals of an individual user. In this chapter, we will study some critical research problems in this domain.

Although WBANs are deployed in a compact spatial region (along the human body), multi-hop communication rather than single-hop is their main communication pattern. Previous research [130–132] indicate that, due to the energy absorption of the human body, the physical channels of WBANs have much higher path loss than those in free space propagation especially when the communication is non-line of sight (NLOS); this communication, for example, occurs when the sender is placed on the back and the receiver on the chest. Alternatively, high power radio frequency (RF) enforced throughout a large coverage area cannot be used in WBANs because RF energy waves may heat and damage body tissue by energy absorption. This consideration implies that in WBANs, multi-hop communication has advantages and sometimes is an absolute requirement. The experimental study in [133] further confirms that multi-hop communication is most reliable in WBANs.

It is rather straightforward to perform multi-hop routing in a small-scale static WSN environment. WBANs are small in size, but they are composed of nodes that move along

body gestures. Node mobility leads to dynamically changing network topology and significantly varying RF energy absorption (thus link quality), rendering routing a challenging task. The openness of the wireless media makes it easy for a malicious adversary to launch various security attacks and violate the basic security requirements, i.e., data confidentiality, authenticity, integrity and non-repudiation. This problem exists in any wireless network, but it is more serious in WBANs because the network traffic is health-related, highly personal and user-sensitive [11,25,134]. Pure cryptographic security solutions are often computation-intensive and vulnerable to *data injection attacks* given that body sensors have restricted resources.

A data injection attack aims to consume the resources of a target network node by sending false data to it. For example, the attacker may eavesdrop the communication transactions of the target node, retrieve useful authentication information and use it to send false packets to the target node. Without precaution, the target node will put intensive efforts to respond to the false packets; even worse, it may retransmit them to other nodes. In energy-constrained WBANs, data injection attacks can exhaust sensor battery power quickly and reduce network lifetime. Sensors should be intelligent enough to recognize and reject false data at minimal cost. Cryptography alone is not sufficient to solve this security problem.

To ensure secure and reliable routing (toward the data sink) in WBANs, the following two requirements must be satisfied, in addition to the aforementioned basic security requirements:

- Localized reliable data forwarding: A node should be able to select an incidental link to forward data packets, which is likely to have high quality in the immediate future.
- Resilience against data injection attacks: A node should be able to avoid processing false and/or irrelevant data injected into the network during a short period of time.

We address the above requirements by proposing a novel distributed Prediction-based Secure and Reliable routing framework (PSR). Persistent data injection attacks, regarded as notorious Denial-of-Service (DoS) attacks, and other robust and exhaustive adversaries are beyond our scope.

It is observed that body sensors may exhibit regular mobility when a user's physical activity (e.g., swimming and jogging) contains repeated motions, and as a result, the link quality and the neighbor sensor set often present periodic changes. This observation serves as the foundation of the PSR routing framework, which can be combined with any specific WBAN routing protocol to increase the latter's security and reliability performance. By

employing PSR, each node maintains an autoregressive (AR) model [79] for every neighbor, based on the link quality measurements (characterized by the received signal power at the other side of the links) between them. Using this model, it predicts the quality of its incidental links as well as the change of its neighbor set.

By the underlaying routing protocol, a node selects a subset of incidental links that can be used to forward packets to the data sink; among these links, it chooses the one that has the highest predicted quality as routing next hop. Each node is equipped with two novel authentication mechanisms specifically devised for source authentication and data authentication. It performs lightweight hash-based data authentication for every received data packet; it disables relatively computation-intensive source authentication if its neighbor set is not changing according to the prediction results in order to save computational resources, or enable source authentication otherwise. The logic is that, if the neighbor set is not changing, source authentication will not be necessary since the existing neighbors have already been authenticated.

The remainder of this chapter is organized as follows: In Section 6.2, we present the frequently-used notations, the network model, and the security model. Then, we propose the PSR routing framework in Section 6.3, followed by the security analysis in Section 6.4 and the performance evaluation in Section 6.5. Lastly, we review the related work and draw our summary respectively in Section 6.6 and Section 6.7.

6.2 Notation and Models

Table 6.1: Frequently used notations in PSR

S	a set of s body sensor nodes $\{n_1, n_2, \cdots, n_s\}$
T_c	current time slot
λ	the length of a single time slot
$\mathcal{H}$	$\{(i, h_i)_{1 \leq i \leq s}\}$ represent (index i, hop count h_i)
(i, k_i)	node index and the corresponding secret key
$S_{i,j}$	a secret key shared by nodes n_i and n_j
$\mathcal{M}_i$	a matrix containing link quality measurements
H_1, H_2, H_a, H_b	four cryptographic secure hash functions
(d, m)	a hash seed and a positive even integer
$\mathcal{N}_j^c$	a real neighbor set at the end of T_c
$\hat{\mathcal{N}}_j^c$	a predicted neighbor set at the beginning of T_c

Before proceeding further, we define the network model and the security model that PSR is to be developed upon. A non-exhaustive list of notations to be used throughout the rest of the chapter can be found in Table 6.1.

6.2.1 Network model

Consider a WBAN composed of s body sensors. We denote by $\mathcal{S} = \{n_1, n_2, \cdots, n_s\}$ the sensor set and n_0 the sink. Every sensor is associated with a unique identifier or index such as MAC address or manufacturer serial number by which it can be distinguished from others. Two nodes are neighbors if they are within each other's communication range. Each node has some fixed neighbors to which it has a constant distance along the surface of human body in spite of body gestures. For example, a node placed on a wrist may be a fixed neighbor of a node placed on the elbow of the same arm, and vice versa. A communication link between two fixed neighbors is called *backbone link*. The backbone links alone connect all the nodes together. Considering the critical nature of WBAN applications, these backbone links are necessary in order to guarantee connectivity. Also, it is feasible to establish these links since a WBAN is usually deployed manually.

A shortest path tree rooted at the data sink n_0 is constructed using backbone links, as shown in Fig. 6.1. Along this tree, the hop count information $\mathcal{H} = \{(i, h_i)_{1 \leq i \leq s}\}$ is obtained, where i is node index and h_i the hop count from n_i to n_0, and distributed to each sensor node. Although any existing WBAN routing protocol may be applied on individual nodes for identifying routing next hop candidates, for simplicity we use a greedy routing protocol based on the established hop count information to present and evaluate PSR. We do not use real-time hop count information for two reasons: i) maintaining such information is costly when the network topology is changing, and ii) delay induced by using non-shortest paths is not a major concern in such a small-scale network. The logic of greedy forwarding is to move a packet to a node closer to n_0 than the node currently holding it.

Time is locally slotted by nodes with equal length λ, which is a positive real number, the same for all the nodes. At the beginning of each time slot, n_i chooses appropriate routing next hop and authentication policies to follow for the current time slot; at the end of each time slot, it adjusts a few system parameters for better decision making in the next time slot.

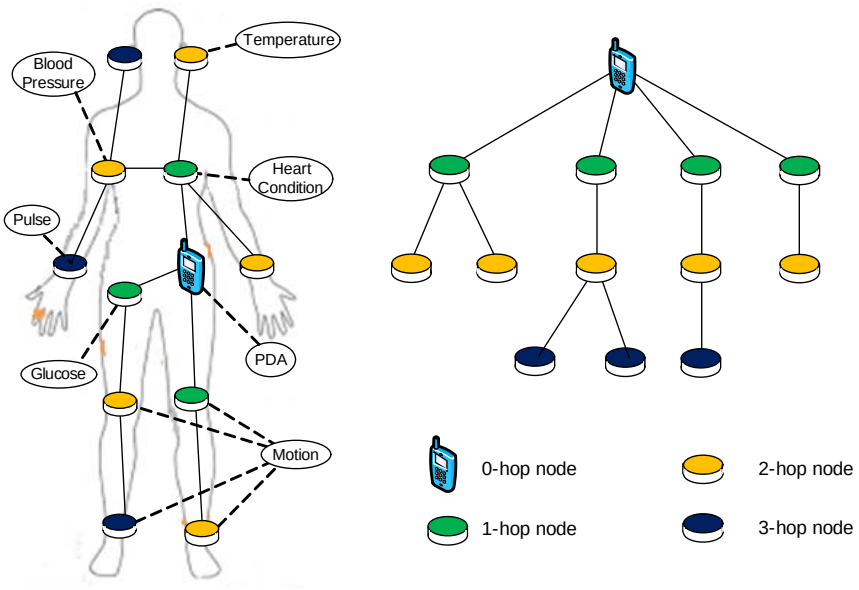


Figure 6.1: Shortest path tree based on backbone links

6.2.2 Security model

WBANs are subject to both internal attacks and external attacks. Here we consider only external attacks, which are launched by adversaries outside the network. DoS attacks are out of the scope of this work. We do not consider lower-layer jamming attacks that block the traffic between two neighboring nodes. Encryption (e.g. symmetric approaches) and hashing prevent eavesdropping attacks and data modification attacks at low cost. Signature approaches realize authenticity and non-repudiation, but with large computation overhead.

Thus we focus on network-layer data injection attacks that make use of the weakness of signature-based authentication to exhaust sensors' computational resources including CPU cycle and battery power. If nodes are unable to resist such attacks, the network will be paralyzed, and the network lifetime will be shortened. Data injection attacks can be launched in the following three forms:

- Exhaustive source authentication attacks, where the attacker repeatedly sends false authentication requests;
- Exhaustive data authentication attacks, where the attacher continuously sends false data packets to a node;

- Data replay attacks, where the attacker uses eavesdropped security materials to inject forged data packets.

6.3 PSR Solutions

6.3.1 Security initialization

Initially, system parameters are configured and embedded in every node as follows. At the first step, given a security parameter $k \in \mathbb{Z}^+$, the administrator runs a bilinear pairing generator (Section 2.4.1) on input k to generate a prime q, two groups $\mathbb{G}_1, \mathbb{G}_2$ of order q, and an admissible bilinear map $e : \mathbb{G}_1 \times \mathbb{G}_1 \rightarrow \mathbb{G}_2$. The administrator then chooses a random generator $P \in \mathbb{G}_1$, a random $s \in \mathbb{Z}_q^*$, and four cryptographic hash function $H_1 : \{0,1\}^* \rightarrow \mathbb{G}_1^*$, $H_2 : \{0,1\}^* \rightarrow \mathbb{Z}_q^*$, and $H_a, H_b : \{0,1\}^* \rightarrow \{0,1\}^*$. The administrator computes $P_{pub} = sP$ and sends $\text{PP} = \langle q, \mathbb{G}_1, \mathbb{G}_2, e, P, P_{pub}, H_1 \rangle$ to the nodes and the sink. At the second step, for n_i, the administrator computes $Q_i = H_1(n_i) \in \mathbb{G}_1^*$, and sets its private key $k_i = sQ_i$. For the sink node n_0, it also computes $Q_0 = H_1(n_0)$ and a private key $k_0 = sQ_0$. All the nodes keep their private keys secretly. At the third step, the administrator sends hop count information $\mathcal{H}$ to every node.

The session key $S_{i,j}$ between nodes n_i and n_j can be non-interactively calculated as $S_{i,j} = e(H_1(n_i), H_1(n_j))^s = e(k_i, H_1(n_j)) = e(H_1(n_i), k_j)$ by using bilinear pairing property. Then, if n_i uses a symmetric key encryption scheme E to encrypt data with $S_{i,j}$ and sends the ciphertext $C = E(S_{i,j}, data)$ to n_j, n_j can decrypt C by a symmetric key decryption scheme D and obtains $data = D(S_{i,j}, C)$. Since $S_{i,j}$ is known only to nodes n_i and n_j, n_j is able to secretly obtain $data$ and check if the ciphertext C is generated by n_i. Note that we do not adopt a simple setting in which all the nodes share the same key. The reason is as follows. Nodes could be compromised (such situation is not considered here though) and reveal the key to attackers, putting the entire network at risk [135].

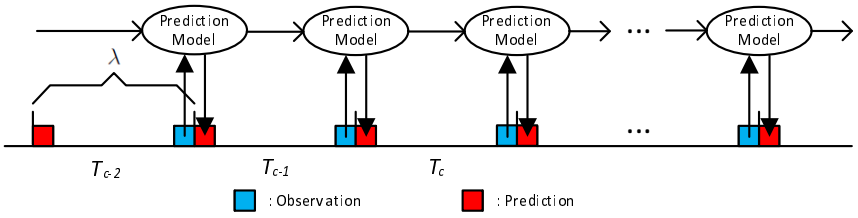


Figure 6.2: Prediction model update along time axis

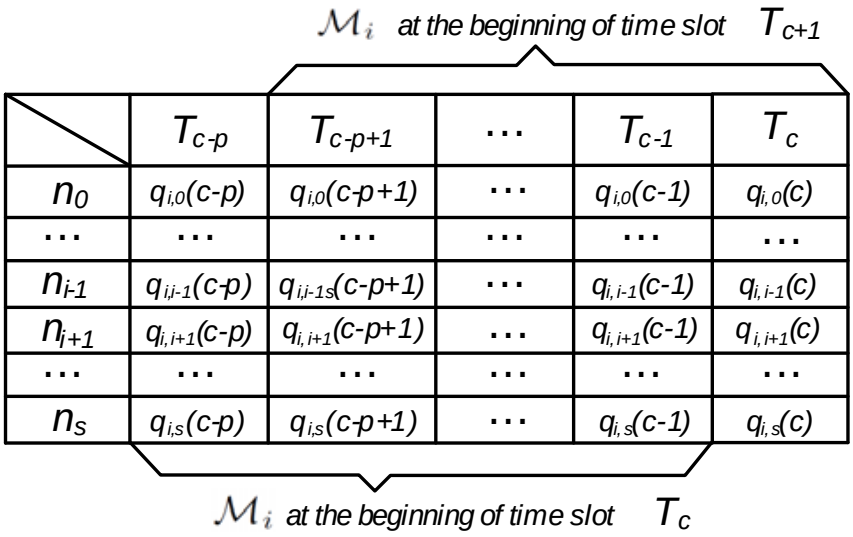


Figure 6.3: Link quality matrix $\mathcal{M}_i$ of node n_i

In this section, we propose a novel distributed Prediction-based Secure and Reliable routing framework (PSR) for WBANs. PSR can be integrated with any routing protocol to improve the latter's reliability and security performance. It is composed of two sub-algorithms *Next-hop selection* and *Data transmission*, both of which employ prediction-based techniques to help nodes make decisions on routing and data processing. As shown in Fig. 6.2, at the beginning of each time slot, nodes use the link quality measurements collected in the past time slots to predict neighborhood conditions (link quality and neighbor set) in the current time slot and run the two algorithms with respect to the prediction results, and at the end of each time slot, they use real conditions measured during the time slot to update the prediction model.

Here, we present PSR with autoregressive model [79] being used for prediction due to its simplicity. But nevertheless, it can be replaced with any other prediction model as needed. Below we elaborate the two sub-algorithms with respect to an arbitrary sensor node n_i and an arbitrary time slot T_c.

6.3.2 Next Hop Selection

Node n_i maintains matrix $\mathcal{M}_i(s \times p)$ that stores the link quality measurements between itself and every other node in the network for the immediate past p time slots. Here p is a

pre-defined system parameter. Link quality is characterized by the received signal power at the receiver side. In this matrix, each row corresponds to a unique node; the k-th column indicates the link quality between n_i and the other s nodes in $T_{c-p+k-1}$ (the current time slot is T_c). The matrix is initially empty. It is possible that some rows remain to have only 0 values since the corresponding node may have never been neighboring with n_i during the p time slots. Because a WBAN is a small-scale network of only a few nodes, it is feasible that each node maintains such a link quality matrix. Figure 6.3 comparatively shows $\mathcal{M}_i$ at the beginning of T_c and T_{c+1}.

Based on this link quality matrix, n_i builds an order-p autoregressive model. At the beginning of T_c, using this model n_i predicts the link quality with every other node, and it chooses a neighbor that has the best predicted link quality among those closer to the sink than itself as next hop (greedy forwarding). If the prediction model is not established yet, the backbone-link based shortest path tree will be used conservatively for packet forwarding as the backbone links have relatively stable quality. In the sequel, n_i transmits every data packet with the selected next hop as a designated receiver.

All the neighbors hear the data transmission of n_i and measure the received signal power (i.e., link quality). They then reply n_i with an acknowledgement (ACK) carrying the measurements whether they are the intended receiver or not. A detailed description of data transmission and acknowledging is presented in the next subsection. By receiving ACKs from neighboring nodes, n_i knows the average quality of the incidental links to them during T_c and updates $\mathcal{M}_i$ with the average results at the end of T_c. Note that, if an expected ACK does not arrive from a node, n_i will consider the corresponding link quality measurement to be $-\infty$.

6.3.3 Data Transmission

Node n_i shares with another node n_j a set of secret tokens if they have successfully authenticated each other. For each data packet to be sent, n_i checks if it has a valid token with every n_j in the network. Having a valid token with n_j means being recognized by it. Thus, n_i starts the data authentication immediately if the check results are all positive. Otherwise, it has to first start source authentication with the n_js for which the check results are negative. To tolerate occasional transmission failure, n_i initiates source authentication up to the maximum number of times. After all the authentication retrials or after having a valid token with every other node, n_i proceeds with the data transmission.

The set of tokens shared between n_i and n_j are a sequence of hash values, such as $\langle H^m(d), H^{m-1}(d), \cdots, H(d)\rangle$, where H is a function defined as $H^{2k}(d) = H_a^k(d)$ and

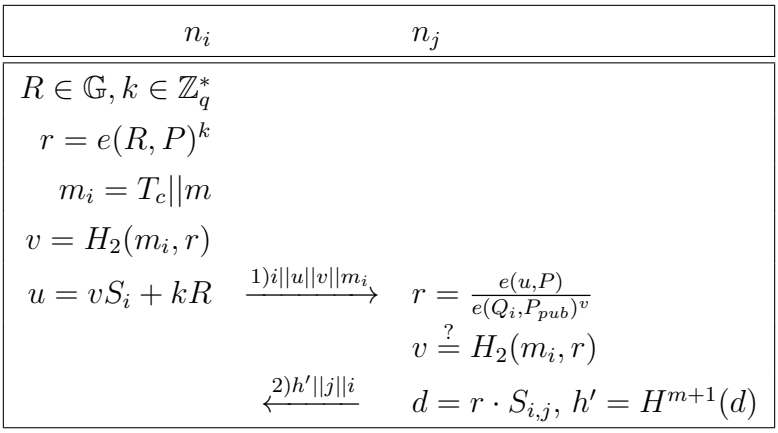


Figure 6.4: Source authentication

$H^{2k-1}(d) = H_b^k(d)$ for any integer $k \geq 1$ (refer to Section 6.3.1 for the definition of functions H_a and H_b). The token set is therefore partitioned evenly into two disjoint portions used respectively by n_i and n_j for authenticating packets. In each data transmission, n_i attaches a single token from its portion to the data packet. The token is placed at the beginning of the packet if n_j is the next hop, or at the end otherwise. Tokens are used one by one in a pre-defined order; once used, they are no longer secrets and become invalid for future use.

Every data packet sent by n_i contains a token for every neighbor n_j, which is therefore able to authenticate the packet. This is because that the valid tokens are secrets shared only between n_i and n_j, and outside attackers can obtain valid tokens only if data transmission failure happens (the analysis can be found in Section 6.3.3). For each authenticated data packet from n_i, n_j identifies whether or not it is the intended receiver (i.e., the next hop) and responsible for packet forwarding by checking the token's position in the packet, and it also replies n_i with an ACK packet, enabling n_i to measure the quality of the link between them. The ACK packet is authenticated similarly using a token from n_j's portion of the token set.

Source Authentication

The center of data transmission is obviously the processes of source authentication and data authentication. We first elaborate source authentication, which enables two neighboring nodes n_i and n_j to authenticate each other. Figure 6.4 shows a source authentication process between these two nodes in T_c. It consists of two steps. At the first step, n_i

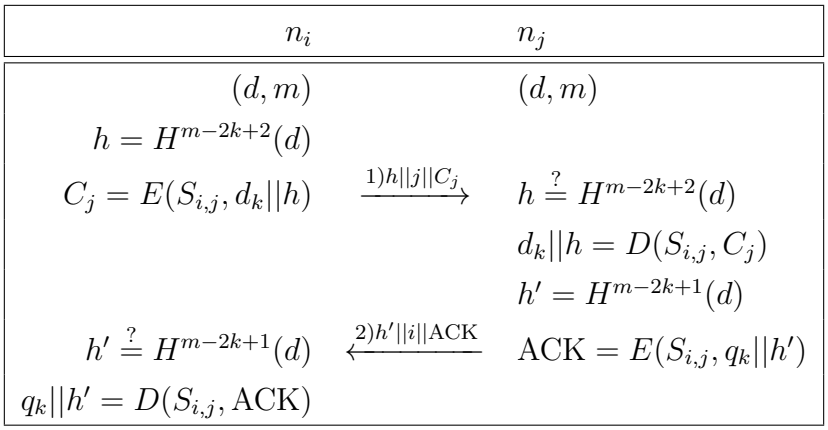


Figure 6.5: Data authentication

broadcasts $i||u||v||m_i$ as a source authentication request to all the neighboring nodes. Here, m_i contains the current time slot T_c and the number m of tokens to be generated, and the pair (u, v) is an identity based signature on message m_i using the signature scheme [81]. Each neighbor n_j then verifies the signature by computing $r = \frac{e(u,P)}{e(Q_i,P_{pub})^v}$ and checking if $v{=}H_2(m_i, r)$. If the equality holds, n_j accepts the signature and replies n_i with $h'||j||i$ at the second step; otherwise, it stops the authentication process. Here, $h' = H^{m+1}(d)$ is a hash value, where $d = r \cdot S_{i,j}$. From security initialization (see Section 6.3.1), since $S_{i,j}$ is only known by n_i and n_j, they are able to calculate d. In the source authentication request, if n_i receives h', n_i knows that n_j must have received the request and then reveals h' in T_c. Notably, r is a random value and d will be generated independently for different source authentications. They will not use d in data transmissions and therefore others will not be able to calculate $S_{i,j} = d/r$. After a successful source authentication, nodes n_i and n_j agree upon the use of (d, m) for data authentications.

Data Authentication

It is carried out for every packet and enables receiver n_j to ascertain that a packet is indeed from sender n_i as it claims to be. By source authentication, (d, m) are established and recorded by both nodes n_i and n_j. After the source authentication, it is required that n_i use token $H^{m-2k+2}(d)$ for sending the k-th data packet d_k to n_j and n_j then uses token $H^{m-2k+1}(d)$ for sending back the corresponding ACK to n_i. The sequence information k is contained in d_k. This data authentication process is illustrated in Fig. 6.5. It consists of two steps. At the first step, n_i sends $h||j||C_j$ to n_j, where $h = H^{m-2k+2}(d)$ is a valid token

and C_j is a ciphertext of the combination of d_k and h. At the second step, n_j checks whether the embedded token is used for the first time. It is able to do the check because it knows all the used tokens. If the token is indeed used for the first time, n_j proceeds to decrypt C_j. If the h obtained by the decryption equals to the one outside C_j, then n_j believes in the integrity of the data packet and replies n_i with $h'||i||\text{ACK}$, where $h' = H^{m-2k+1}(d)$ is a valid token and ACK indicates the successful recipient of d_k and reports the link quality q_k. If any of the above checks fails, n_j stops the process and ignores the packet. After receiving the ACK, n_i performs similar checks and retrieves q_k. Note that tokens h and h' can be only used for the k-th data packet of n_i after the last source authentication. If $m - 2k + 2 \leq 0$, n_i has to start a new source authentication process with n_j for a new tuple (d, m) in T_{c+1}. Further, if n_i does not receive any ACK with valid tokens from n_j within T_c, it marks all the unused tokens with n_j invalid, and a new source authentication is needed in T_{c+1}.

The data authentication process between n_i and n_j indicates that each data authentication consumes a token pair (h, h') in the shared token set between n_i and n_j. In fact, each data authentication has to consume a token pair between n_i and its every neighbor in order for n_i to be able to measure the link quality with them. Suppose that n_i has k neighbors $\{n_i^1, n_i^2, \cdots, n_i^k\}$ in addition to the next hop n_j. Let (h_l, h_l') be the token pair between n_i and neighbor $n_i^l, 1 \leq l \leq k$, which are respectively from the token sets that n_i shares with those neighbors. At the first step of data authentication, n_i attaches tokens $h_1, h_2, \cdots, h_k$ to the end of a data packet, i.e., $h||j||C_j||h_1||\cdots||h_k$; at the second step, neighbor $n_i^l, 1 \leq l \leq k$ responds with an ACK carrying h_l', i.e., $h_l'||i||\text{ACK}$. Note that n_i^l only verifies the tokens in the data packet without putting any effort on processing C_j, since its token does not appear at the beginning of the packet (i.e., it is not the intended receiver) and C_j can be decrypted only by the indented receiver.

6.3.4 Disabling Source Authentication

Source authentication is much more costly than data authentication as it requires decryption operations while data authentication only involves equality checks. If there are many false source authentication requests, as a receiver n_i will waste significant resources on processing them. To deal with this problem, n_i may adaptively enable or disable its source authentication function in T_c according to predicted neighborhood change and prediction accuracy.

Specifically, n_i chooses the set $\hat{\mathcal{N}}_i^c$ of possible neighbors at the beginning of T_c by checking the link quality prediction results (see Section 6.3.2): a node is a possible neighbor

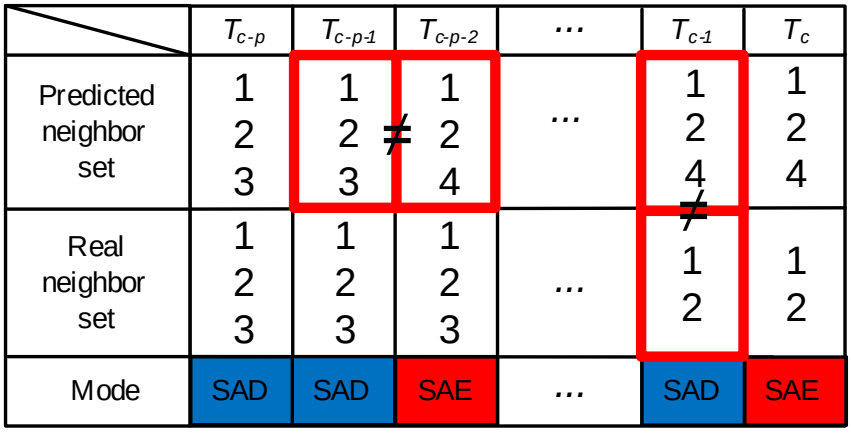


Figure 6.6: Neighbor set

if the corresponding link quality is predicted to have a value beyond certain threshold (a.k.a. receiver sensitivity). At the end of T_c, n_i computes the real neighbor set $\mathcal{N}_i^c$ in T_c based on the received ACKs during the time slot. Then it decides whether to disable source authentication for T_{c+1}, based on $\mathcal{N}_i^c$, $\hat{\mathcal{N}}_i^c$ and $\hat{\mathcal{N}}_i^{c-1}$. If $\mathcal{N}_i^c = \hat{\mathcal{N}}_i^c$ and $\hat{\mathcal{N}}_i^c = \hat{\mathcal{N}}_i^{c-1}$, n_i is in source authentication disabled mode (SAD) (or source authentication enabled (SAE) mode otherwise) as shown in Fig. 6.6. This condition implies that the prediction is accurate and the neighbor set is not expected to change; thus it is not necessary to perform source authentication. If the link quality prediction model is not established yet, $\hat{\mathcal{N}}_i^c$ is not available. In this case, source authentication has to be enabled by default. Source authentication is also periodically opened in order to accommodate unexpected legitimate neighbors.

6.4 Security Analysis

In this section, we analyze the security properties of the PSR framework. Specifically, following the security model discussed in Section 6.2.2, our analysis focuses on the resilience of PSR against data injection attacks including exhaustive source authentication attacks, exhaustive data authentication attacks and data replay attacks.

6.4.1 Resilience to Exhaustive Source Authentication Attacks

Fig. 6.4 shows the source authentication process. The sender node n_i computes an identity based signature (u, v) on message m_i and sends $u||v||m_i$ as authentication request to a node n_j at the first step. By checking $v{=}H_2(m_i, r)$ where $r = \frac{e(u,P)}{e(Q_i,P_{pub})^v}$, n_j knows whether the request is made by n_i or not. Specifically, if $r = e(R, P)^x$, n_j will be able to calculate $u = xR + vsQ_i$. Since $vsQ_i = vk_i$ can be only generated by n_i using its private key k_i, n_j is able to confirm that the signature (u, v) on m_i is indeed generated by n_i. This confirmation guarantees that n_j detects false source authentication requests. This signature-based approach consumes relatively intensive computational resources (compared with hash-based data authentication).

However, n_j does not always respond to source authentication requests. It records the real neighbor sets in the past and uses a prediction model to estimate the future neighbor sets (one time slot ahead). Such information assists it in making a wise decision: to disable the source authentication function when it is not necessary, i.e., when neighbor set is not changing and current neighbors have already been authenticated. In this way, most false source authentication requests can be directly ignored. Such an attack can still consume some computational resources of a receiver node when the node periodically enables source authentication for accepting new neighboring nodes. But the attack capability is significantly reduced.

6.4.2 Resilience to Exhaustive Data Authentication Attacks

A receiver node accepts only data packets that contain valid tokens. Recall that the tokens are created in a reverse order of hash values and initially known only to the sender and receiver nodes. Therefore, attackers cannot obtain the tokens in advance of the transmissions. Any false data packet will be rejected directly by the receiver node if attached the token is invalid (either unrecognized or already used).

6.4.3 Resilience to Data Replay Attacks

If a data transmission fails at the receiver node, a data replay attacker may use the intercepted tokens and inject forged information into the network. In this case, the receiver node has to consume additional computation power to detect these forged data packets by decryption operations. We show that such attack capability can be limited in terms of attacking period and numbers of valid tokens. By adopting the hash chain technique,

if $H^{m-2x+2}(d)$ is received and the x-th data packet is checked by the receiver node, the data packet with tokens $H^{m-2y+2}(d)$ for $1 \leq y \leq x$ will not be accepted anymore. This is because the y-th data packet cannot arrive later than the x-th data packet (packets are transmitted sequentially along a single hop). The possible attacking period is therefore largely reduced (see Theorem 1 below). Theorem 2 further indicates that the attacker can only obtain a limited number of valid tokens and thus attack the network a limited number of times. We denote the receive probability of n_j on a single transaction by ρ.

Theorem 7 *If n_i consumes k tokens from a token set for data authentication in every time slot, then a data replay attacker $\mathcal{A}$ has an average attacking period $P_A = \frac{(1-\rho)\cdot\lambda}{\rho\cdot k}$ available for each eavesdropped token h.*

Proof 7 *If $\mathcal{A}$ eavesdrops a token h from n_i's transaction in T_c, the token may be already received by n_j. Thus $\mathcal{A}$ can replay token h to exhaust n_j's computational resources with probability $1-\rho$ during time period λ/k. In addition, if the next transaction of n_i fails, $\mathcal{A}$ can use h to attack for an additional time period λ/k, totally $2\lambda/k$. Thus, we are able to obtain the average attacking period for token h as follows: $P_A = \Sigma_{x=1}^{+\infty}\rho(1-\rho)^x \cdot \frac{x\lambda}{k} = \frac{(1-\rho)\cdot\lambda}{\rho\cdot k}$.*

Theorem 8 *If n_i consumes k tokens from a token set for data authentication in every time slot, then a data replay attacker $\mathcal{A}$ can obtain $2k-1$ valid tokens at most.*

Proof 8 *If no less than $2k$ valid tokens are obtained by $\mathcal{A}$, the data authentications by n_i must fail in two or three successive time slots. However, this is impossible as we show below. If data authentications fail in two successive time slots, n_i will not receive any ACKs from n_j in the first time slot and stop using the rest of the tokens. In this case, $\mathcal{A}$ can obtain at most k tokens. If data authentication fail in three successive time slots, n_i will not receive any ACKs from n_j in the second time slot and stop using tokens in the third time slot. In this case, $\mathcal{A}$ can obtain at most $2k-1$ tokens. Thus, $\mathcal{A}$ obtains $2k-1$ valid tokens at most.*

6.5 Performance Evaluation

In this section, we evaluate PSR through an extensive set of simulations. In current literature, there are only a few multi-hop routing protocols designed for WBANs, none of which use link quality as routing metric. We choose to compare PSR (the version described in

Section 6.3) with a static tree-based routing protocol [136], referred to as Backbone, where sensors route data packets toward the data sink along a shortest path tree constructed using backbone links (see Section 6.2.1). The Backbone protocol is reliable compared with other existing protocols, because the tree is a fixed structure with relatively stable links in the presence of postural mobility. It can thus be a good benchmark algorithm. As we will see, PSR outperforms Backbone in reliability and has desired security performance.

6.5.1 Simulation Setup

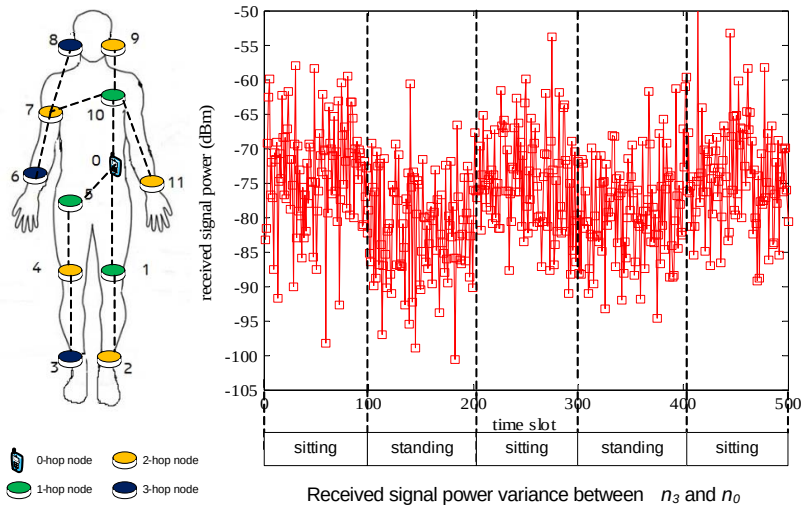


Figure 6.7: Link quality varying with body movements

We consider a WBAN deployed on the body of a person with height 1.7m. The network is composed of 12 nodes. As shown in Fig. 6.7, the data sink n_0 is placed on the waist; the others are placed on knees, ankles, shoulders, wrists and head. A shortest path tree rooted at n_0 is built using backbone links (see Section 6.2.1) and shown by dotted lines. Similar WBAN settings can be found in [131, 136]. A well-defined and simplified channel model given by IEEE 802.15 task group 6 [137] is adopted in our simulation. The path loss between any two sensors deployed above body surface is given by:

$$PL(d)[dB] = a \times log_{10}(d) + b + N \tag{6.1}$$

where a and b are coefficients of linear fitting, d is the direct distance between nodes n_i and n_j, N is a random variable of zero-mean normal distribution with standard deviation

σ_N. We choose one of the suggested values by IEEE 802.15 task group 6 [137] under the frequency band 2.4GHz outdoors ($a = 29.3, b = -16.8, \sigma_N = 6.89$). Given the direct distance between n_i and n_j, the path loss can be calculated. Furthermore, we consider a noise model where the received signal power is given by:

$$P_r(d)[dBm] = P_s - PL(d) - N_0 \tag{6.2}$$

where P_s represents the transmission power, P_r the received signal power, and N_0 the noise power.

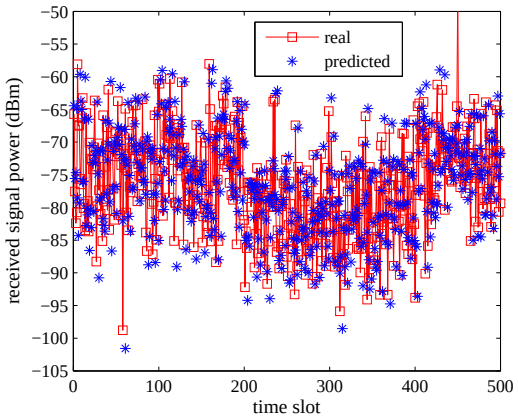
On one hand, the transmission power of body sensors must be kept less than an upper bound (13.98 dBm [137]) in order not to produce any harm to tissues. On the other hand, it must be strong enough to ensure the successful transmission, i.e., to maintain P_r at a certain level so that the receiver is able to filter data from noise. Under these circumstances, we define the minimum requirement of successful delivery with a power margin, and consider that a packet can be decoded correctly if and only if the ratio of received signal power to noise power is larger than the power margin. In our simulation, the power margin is 10 dB and the receiver sensitivity -90 dBm [138].

We repeatedly alternate the body posture between sitting and standing, each of which lasts a fixed period of time (i.e., 50 or 200 simulated time slots). The postural mobility has direct impact on link quality. For example, from Fig. 6.7 we can see that the quality of the link from ankle-mounted sensor n_3 to data sink n_0 (received signal power at n_0) in sitting status is higher than that in standing status.

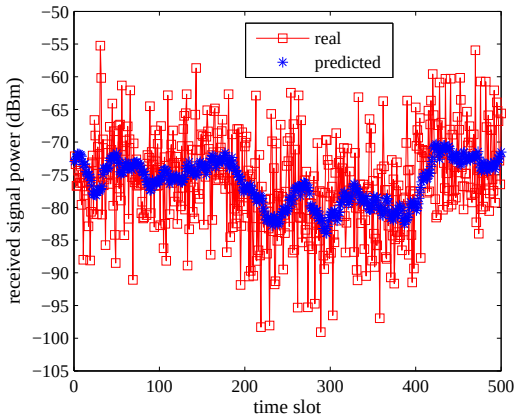
6.5.2 Simulation Results

Prediction Accuracy

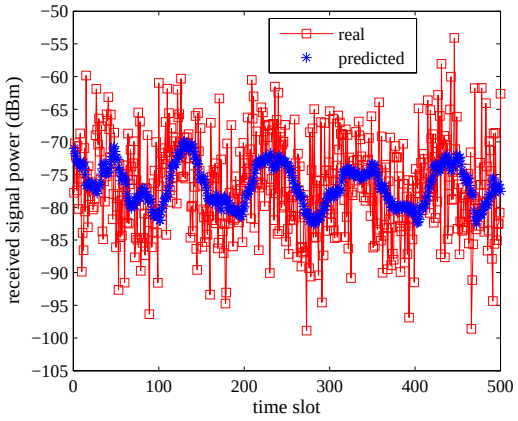
We set the AR model order $p = 20$, posture period = 200 time slots, and employ a *sliding-window technique* for smoothing the noisy link quality measurements (i.e., received signal power). Specifically, we slide a window of certain size w (in time slot) along the time series, compute the average of the measurements within the window, and input the results into the AR model for prediction. Figures 6.8(a) and 6.8(b) show the predicted values and the true values between nodes n_3 and n_0, respectively with $w = 1$ and $w = 20$. We observe that when $w = 1$ the predicted link quality varies significantly along with the real values. The big variation is due to random channel noise. It hides the regularity of link quality brought by periodic postural mobility and renders the prediction results useless. In the case of $w = 20$, the regularity can be easily observed. Thus, we choose $w = 20$ in the rest



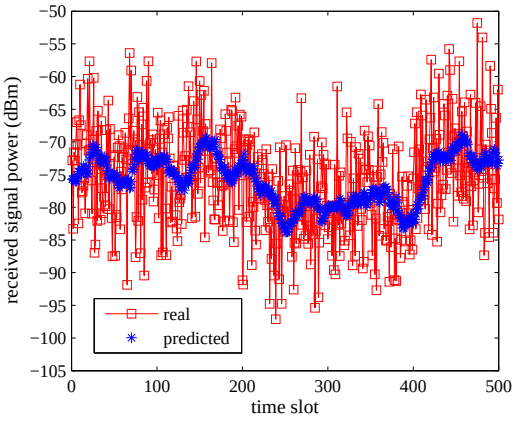
(a) Window size = 1



(b) Window size = 20



(c) Posture period = 50

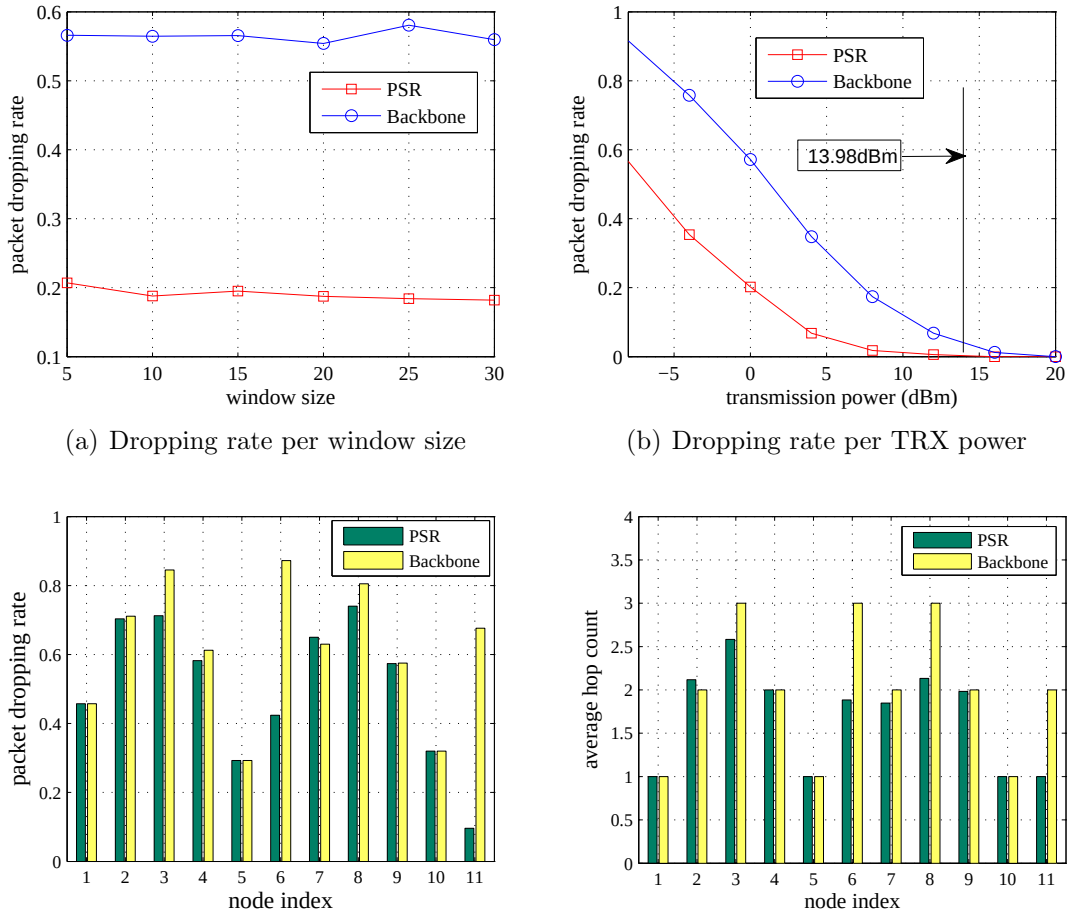


(d) Posture period = 200

Figure 6.8: Prediction accuracy

of our simulation. Figures 6.8(c) and 6.8(d) show the influence of posture period on link quality prediction with $p = 20$ and $w = 20$. It can be seen that the trends of predicted values well matches that of the real values for the link from n_3 to n_0 whether posture period is set to 50 time slots or 200 time slots. The above results indicate that link quality can be predicted, and the prediction can be exploited to enable better link selection to improve routing reliability.

Reliability Performance



(a) Dropping rate per window size

(b) Dropping rate per TRX power

(c) Dropping rate per node

(d) Hop count per node

Figure 6.9: Reliability performance

Figure 6.9(a) shows that n_3 is able to find a better link by PSR than by Backbone. We observe that the packet dropping rate for the single hop from n_3 toward n_0 is reduced from 0.6 to 0.2. This per-hop reliability gain helps nodes improve end-to-end routing reliability. We also find out that the gain slightly changes over different window sizes. The reason is that the channel condition is extremely unstable, and the random channel noise and vibrating path loss diminish the difference of the results. From Fig. 6.9(b), it is observed that as transmission power increases, per hope packet dropping rate in both PSR and Backbone decreases, and PSR slowly loses its advantage over Backbone. This is because high transmission power increases link quality in general and diminishes the reliability difference due to algorithm design.

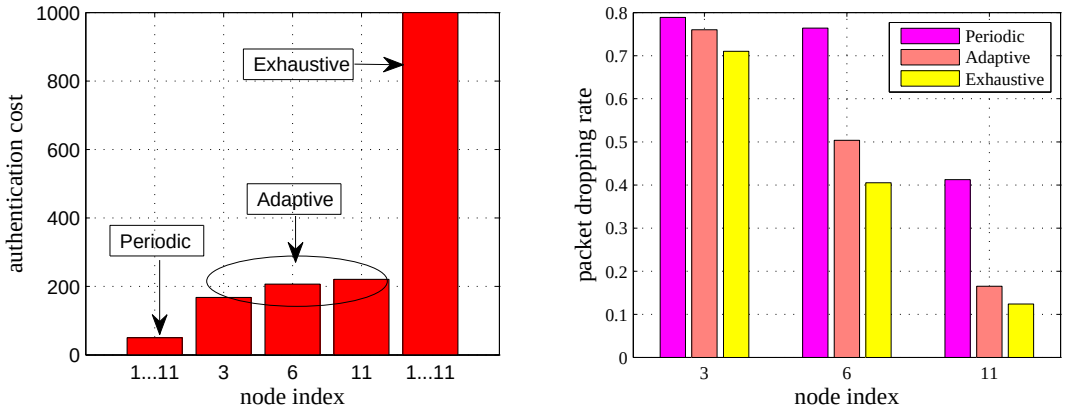
Figures 6.9(c) and 6.9(d) show end-to-end packet dropping rate and average hop count between different sensors and the data sink n_0. It can be observed that PSR outperforms Backbone in both aspects. The reason is that nodes when adopting PSR are able to find a better relay path by referring to link quality prediction results. If two nodes become each other's neighbor due to the body movement, the node with smaller hop count may be selected as a relay for the node with larger hop count (subject to link quality check) in PSR. Such opportunistic routing enables nodes to save more energy by reducing the number of relaying. For instance, according to Fig. 6.7, n_3 may directly transmit a data packet to n_5 for sitting status, rather than going through n_4, and the hop count to n_0 is reduced to 2 from 3 (in Backbone).

Security Performance

Data authentication is realized by simple equality check. Hence, we focus on source authentication cost. We examine three source authentication policies in the context of PSR: exhaustive authentication, periodic authentication, and adaptive authentication. The exhaustive authentication policy requires each node to check every source authentication request in any time slot; periodic authentication policy requires that each node periodically checks source authentication requests at regular intervals (set to 20 time slots in our simulation); adaptive authentication policy inherits the periodic authentication policy, and it additionally requires each node to adaptively disable or enable source authentication (see Section 6.3.4). We define authentication cost as the number of false source authentication requests that a node responds to. In our simulation, an attacker sends every node 1000 false source authentication requests, one per time slot. Figure 6.10 shows authentication cost and end-to-end packet dropping rate of three nodes n_3, n_6, n_{11} during 1000 time slots with the three authentication policies being applied.

Among the three policies, we observe that the exhaustive one achieves the lowest packet

dropping rate. This is because nodes do not miss any neighbor and are always able to find the best link (i.e., with highest received signal power at the other side) as next hop. But this policy has the highest authentication cost due to its exhaustive nature. The periodic policy leads to the opposite performance: highest packet dropping rate and lowest authentication cost. It is because nodes are often unable to discover and use quality links as source authentication is blindly closed at fixed intervals. The performance of adaptive policy as expected is in between. It achieves low packet dropping rate (comparable to the exhaustive policy's) at small authentication cost (comparable to the periodic policy's) due to the intelligent source authentication enabling/disabling. In particular, the resultant authentication cost is less than 300, meaning that over 70% false requests are directly filtered.



(a) Authentication cost

(b) Packet dropping rate

Figure 6.10: Security performance

6.6 Related Work

Research has been carried out for efficient data communications in accordance with the multi-hop architecture of WBANs. For example, Latre et al. [136] aim to improve energy efficiency and communication reliability by activity scheduling. In their solution, a static routing tree is built in advance, and time is slotted. Time slots are assigned to sensors according to the routing tree, which then transmit their data only during their assigned time slots. The assignment is carefully done in a hierarchical and distributed manner to reduce

idle listening and minimize signal interference. Quwaider et al. [139] propose a dynamic power assignment, that is, to determine the necessary transmission power for each wireless link. In their solution, a sender transmits every packet together with the information about the transmission power used. A receiver node measures the received signal strength and decides whether the transmission power is too large or too small, and it informs the sender to adjust the transmission power accordingly, improving communication reliability.

A few researchers focus on efficient routing algorithms, which are the foundation of data communication. They exploit the delay tolerant network and postural information [132, 140, 141]. In [140], the authors aim to minimize end-to-end delay by avoid using nodes that have a high storage/buffering delay due to topological disconnections. They develop a probabilistic distance-vector packet based routing algorithm. This algorithm uses a stochastic link cost formulation to capture multi-scale topological localities in human postural movements. It assumes that, if a link is connected in current time slot, the probability that the link will remain connected in the next time slot increases at a fixed rate. This assumption may not hold however in reality. In [141], a few variants of DTN routing are presented in the WBAN context. They implicitly assume that a link has constant quality (by ignoring link quality different in routing), which as we previously discussed is not reasonable due to node mobility and RF energy absorption, and they require each node to have possibly unrealistic restricted mobility, intermittently coming within up to 2-hop distance from the sink.

6.7 Summary

In this chapter, we proposed a prediction-based secure and reliable routing framework (PSR) for WBANs. This framework requires each sensor node to locally maintain a prediction model and obtain the neighborhood conditions in the immediate future. With the prediction results, the nodes can choose the incidental links of the best quality for packet relay to improve routing reliability and adaptively enable/disable source authentication function to resist data injection attacks. Through both analysis and simulation, we demonstrated that PSR indeed enables secure and reliable routing.

Chapter 7

Conclusions and Future Work

In this chapter, we summarize our contributions in this thesis, propose our future research work, and give our final remarks.

7.1 Conclusions

The major contributions of this thesis can be summarized as follows:

- First, we have studied the profile matching application from a novel perspective, i.e., user anonymity. We have proposed a novel family of privacy-preserving profile matching (PPM) protocols including eCPM, iCPM, and iPPM [57]. We have shown that the eCPM achieves conditional anonymity while iCPM and iPPM achieves full anonymity. For the eCPM, we have further developed the anonymity-enhancing technique which enables users to be self-aware of the anonymity risk level and take appropriate actions to maintain the k-anonymity level where k is a parameter defined by each individual user.
- Second, by taking the human social behavior, we have studied the data forwarding strategy in the opportunistic MSN. We have presented a morality-driven privacy-preserving data forwarding (PDF) protocol [29], while considering multiple factors in the forwarding utility including forwarding capability, forwarding costs, and morality factor. Based on the game theoretic analysis, users always maximize their own utility and decide to forward their packets with certain probability. We have shown that

the cooperation and privacy preservation, two conflicting goals, can be achieved in the PDF among a group of users with social morality.

- Third, we have proposed a distributed trustworthy service evaluation (TSE) system where the local service providers maintain the TSE by themselves. We have studied the potential malicious attacks conducted by both the service providers and the users. Note that, it is very challenging to restrict the malicious behavior from the service providers and the users in an untrusted distributed environment. We have introduced the possible review attacks and the Sybil attacks [58], and devised effective defensive mechanisms to resist these attacks.

- Fourth, we have studied the routing problem in WBANs by proposing a distributed prediction-based secure and reliable routing framework (PSR) [9]. In the PSR, using past link quality measurements, each node predicts the quality of every incidental link, and thus any change in the neighbor set as well, for the immediate future. When there are multiple possible next hops for packet forwarding, the PSR selects the one with the highest predicted link quality among them. Specially-tailored lightweight source and data authentication methods are employed by nodes to secure data communication. We have demonstrated that the PSR significantly increases routing reliability and effectively resists data injection attacks through in-depth security analysis and extensive simulation study.

7.2 Future Work

Our research has already made significant progress in the security and privacy preservation of mobile social networks. However, since mobile social network is a promising platform in pervasive environments, there still exist several research directions to be explored to complement this thesis. Therefore, the following three research topics will be investigated as a continuation of my Ph.D. thesis work.

Gesture-assisted Secure Information Sharing: Previously, we introduced the profile matching application which is very useful for many social activity in real life. With the smartphones, our capabilities in sensing and communication are significantly improved, and our social activities can be carried out in a more secure and efficient way. However, due to the broadcast nature of wireless medium, it is very difficult to negotiate a shared secret and implement secure information sharing if two users have no pre-established knowledge. Gesture-based information sharing is a unique research direction in the MSN. The gesture information is only visible to the close-enough neighbors. The users can make simple

gestures clear enough such that the target user can repeat it. In order to achieve secure information sharing, the gesture can be changed per every session. In the meantime, the accelerometer sensors and gyroscope sensors of smartphones can be used to detect the gesture and help the users to check if two gestures are the same. One interesting research direction is how to limit the physical and visual spaces such that the gestures are visible to only the target user. Besides, it is also interesting to explore more applications using the gesture-assisted secure information sharing.

Social-context based Private Information Leakage: The information to be shared by the users in the MSN is closely related to the social context including the profile of neighboring users and the service of neighboring LSPs. For example, in the shopping mall, people surrounded by the clothing stores expect to share and receive the discount information of clothes; in the conference, participants are willing to discuss research topics and projects with other research scholars. Based on the social context, the disclosed personal information can be used to identify an user's behavior in different levels. In the previous example, if a research scholar discusses research topics in the shopping mall, his behavior will be easily distinguished from nearby customers. Thus, to achieve privacy preservation, the social context should be considered in the MSN communication protocol design. Most existing privacy-preserving profile matching protocols [28,31] aim at minimizing the profile information disclosure but neglect the relations between the disclosed information and the social context. From [57], it is shown that the anonymity variation of an user depends on the profile information of its nearby users. Thus, the effectiveness of profile matching protocols in terms of privacy preservation needs to be further validated in different social contexts. To explore practical social context and propose effective protocols for specific social contexts is an important research direction.

Trustworthy and Malicious Attacks: Distributed systems are vulnerable to sybil attacks where an adversary manipulates bogus identities or abuse pseudonyms to compromise the effectiveness of the systems. Especially for the MSN, the users often adopt multiple pseudonyms for protecting their location privacy [29,57]. Thus, it is very challenging to restrict the sybil attackers who legally have multiple pseudonyms but maliciously use them. In the MSN, sybil attacks can be extended to a mobile version, called mobile sybil attacks (MSAs), which can be launched by mobile users anytime anywhere. The MSAs are hardly to be detected because their behaviors are difficult to be monitored. The previously introduced TSE system is subject to the MSAs [58]. One solution can be pervasive and cooperative monitoring, i.e., requiring normal users to monitor other users' behaviors and submit the monitoring results to a centralized authority. Then, a centralized authority can correlate the results and detect the MSAs by viewing the statistic information. This method is similar to the traditional sybil attack detection [142] in online social networks.

However, in the MSN, this method requires extensive communication overhead and incurs unexpected detection delay. Another solution [58] is to embed a secret into the multiple pseudonyms of one user. When the attacker uses the pseudonyms across the predefined boundary, its real identity can be calculated from these pseudonyms. In both solutions, how to define the boundary between the MSAs and the good behavior is very challenging. Location information can be integrated into the boundary design of the MSAs detection.

7.3 Final Remarks

In this thesis, we have presented a suite of security and privacy-preserving protocols for mobile social networks and applications. In addition, we have also identified couple of future research topics to complement this thesis. To facilitate our research accomplishments and findings to benefit the real world situations, we will carry out experiments to further confirm our research findings.

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