Privacy Protection for Mobile Cloud Data: A Network Coding Approach

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Abstract—Taking into account of both the huge computing power of intruders and the untrustedness of cloud servers, we develop an enhanced secure pseudonym scheme to protect the privacy of mobile cloud data. To face the huge computing power challenge, we develop an unconditionally secure light-weight network coding pseudonym scheme. For the privacy issue of untrusted cloud server, we further design a two-tier network coding to decouple the stored mobile cloud data from the owner’s pseudonyms. Therefore, our proposed network coding based pseudonym scheme can simultaneously defend against attackers from both outside and inside. We implement our proposed two-tier light-weight network coding mechanism in a group location based service (LBS) using untrusted cloud database. Compared to computationally secure Hash-based pseudonym, our proposed scheme is not only unconditionally secure, but also can reduce more than 90% of processing time as well as 10% of energy consumption.

Index Terms—Privacy protection; big data and cloud computing; network coding; location based services.

I. INTRODUCTION

Data collected from the sensors embedded in smartphones offer great commercial potential for mobile cloud services, but also pose new challenges on privacy protection. With the properties of continuous changing and updated over time, mobile data are particularly valuable for big data analytics to understand and predict each individual behaviors. Because mobile data provide highly personal information, the privacy issues of mobile cloud data raise a lot of concerns [1]. However, using current security techniques to protect mobile cloud data privacy will face a number of new challenges in protecting mobile privacy [2]. First, we can no longer rely on a protection mechanism with computational security assuming that sophisticated cipher cannot be broken easily by attackers. This is because the attackers become more powerful in the era of cloud computing. Second, mobile devices with limited computing power cannot conduct complex encryption and decryption algorithms. Third, private mobile cloud data are stored in public cloud servers, which increases the opportunities to be attacked by other cloud tenants.

To defend against malicious attackers with huge computing power in outsourced database (ODB), we propose an unconditionally secure network coding based pseudonym scheme to protect mobile privacy against the following two security threats. First, for the outsider security threat, the ownership information of mobile data is protected to the highest unconditional security level, in which the ciphertext will not be broken even with infinite computation time. Since the inherent distribution nature of network nodes is integrated into network coding, it is impossible to decipher the complete plaintext unless all the nodes are attacked. Secondly, for the insider security threat from the attackers staying in the same ODB, we develop a two-tier network coding technique for decoupling data ownership. As a result, the insider attackers cannot know the relationship of the stored data and their owners at all.

To demonstrate the advantages of our proposed network coding privacy protection scheme, we implement it for a group location based service (LBS) with ODB [3]. A group LBS can help a group of users share their locations. Fig. 1 shows the proposed security system model for group LBS. The privacy issues of providing such a group LBS can be classified into the following three aspects:

- Authenticating users’ data while preventing an untrusted ODB provider from knowing the relation of a user and his/her stored data [4];
- Sharing data with multiple members in the group of interest while maintaining the same protection level as the two user case [5];
- Storing data in a multi-tenant cloud computing environment with the threat of attackers staying in the same ODB [6].

An unconditionally secure framework for mobile cloud applications has been rarely seen in the literature. Our proposed unconditionally secure network coding based pseudonym scheme can overcome the aforementioned three challenges, and has the following two major contributions:

- A data ownership decoupling mechanism is presented, which can achieve unconditional security level and resolve the security concerns for untrusted ODB.
- A light-weight network coding scheme is proposed which can reduce the processing time by 90% compared to the Hash-based pseudonym. A user only needs to encode his/her identity one time when logging in to the trusted certifying server. The remaining operations for pseudonym changing and uncloaking are performed by the trusted certifying server. None of decoding operations are needed in mobile terminals.

The rest of the paper is organized as follows. Section II discusses the related work for location privacy protection. In Section III, we explain the system security model for group LBS using ODB. In Sections IV and V, we present the proposed network coding based pseudonym and analyze its security performance. In Section VI, we discuss the issues
of data ownership, user authentication, and service continuity. Section VII compares the performance of the proposed network coding based pseudonym with Hash-based pseudonym. Finally, concluding remarks are given in Section VIII.

II. RELATED WORKS

In the literature, location privacy is generally protected by either pseudonyms or anonymization.

A. Pseudonym-based Location Privacy Protection

Pseudonym techniques can protect location privacy by disconnecting a user’s location data with his/her genuine identity [7]–[13]. Existing pseudonym schemes can be classified into two types. The first type of pseudonym techniques aim to change the pseudonyms intelligently so that the attacker cannot distinguish the spatial difference from other members. The authors of [7] proposed to frequently change pseudonyms based on the mixed-zone concept, where users’ pseudonyms are mixed together. In [10], disposable interface identifiers were frequently assigned to users. When a node is not allowed to disclose addresses, a silence period (defined as a transition period between changing pseudonyms) was introduced [12]. When users’ pseudonyms in some area are changed after a silence period, a hacker could not find the target user. In [11], the pseudonym mechanism was improved by using a Bayesian approach to resolve the frequency changing issue. In [14], a game-theoretic model for the non-cooperative behavior analysis of mobile nodes in a mixed zone was proposed. A location proof updating system for vehicular networks was designed in [10]. In [15], the authors proposed a dynamic mixed zone of which the size is determined by the vehicle’s predicted location, traffic statistics, and privacy requirement.

Another type of pseudonym techniques focus on designing the unlinkable and irreversible pseudonym based on cryptographic method. The Hash function is widely used to generate a unique and secure pseudonym [13]. However, it has been shown that attackers with computational power provided by cloud computing can break Hash-based cryptography [16]. The brute force method can deduce the original message from a Hash value [17]. Furthermore, existing pseudonym techniques cannot completely protect data ownership if an ODB provider can link a particular pseudonym with its stored data in ODB during an authentication process.

B. Anonymization-based Location Privacy Protection

Anonymization techniques can protect location privacy by generalization and suppression techniques, i.e., with an expression of lower granularity. In [18] the $k$-anonymity concept was introduced so that a user’s location cannot be distinguished from other $k-1$ users’ locations. Instead of reporting the exact location, a user sends a region containing the locations of other $k-1$ people. In [19], the CliqueCloak algorithm was proposed to provide different $k$-anonymous requirements for each user. A privacy-preserving architecture for LBS with different anonymization techniques was suggested in [20]. A node density-based location privacy scheme was proposed to improve anonymity without degrading quality of service (QoS) [21]. The authors of [22] proposed a cluster based anonymization scheme to replace the real node identities with random identities generated by the cluster heads. In [23], a clustering anonymization for vehicular networks was developed to hide the road and traffic information. However, all the above anonymization techniques cannot protect location data shared by a group of users since an individual’s location...
is concealed.

C. Objective of This Paper

The objective of this paper is to improve location privacy protection to unconditional security level and prevent an ODB provider from linking a particular pseudonym with its stored data. To our knowledge, privacy protection for group LBS in the context of ODB has not been fully investigated. We suggest to adopt network coding for pseudonym generation, which has received little attention in the literature so far.

Network coding is a generalized routing method in which messages are computed by intermediate nodes with algebraic encoding. Previous works have shown that network coding can provide robustness [24]–[26] and improve throughput [25], [27] as well as confidentiality [28]. More recently, network coding is employed to improve the security and reliability of distributed storage systems such as recovering lost data in multiple storage nodes [29], preventing eavesdropping over untrusted networks [30], and checking integrity of outsourced data [31].

Although it was proved that network coding possesses the properties of irreversibility [32] and verifiable data integrity [33], a stronger security property of network coding that can achieve unlinkability between coded data has been rarely studied yet. In our previous work [34], the network coding based pseudonym scheme and the corresponding security mechanism for group LBS using ODB was introduced, but the security analysis of the proposed mechanism is not yet investigated.

To this end, we develop a two-tier coding method to mix user identity with watchword/seed and then generate two keys for certification and anonymization. In this paper, on top of the work in [34], we further analyze the security performance of the proposed pseudonym scheme. We will prove that network coding can provide unlinkable pseudonyms to unconditional security level for group LBS by analysis. It will be demonstrated that the proposed two-tier network coding method can preserve the privacy of data ownership even if an untrusted ODB provider has huge computing power.

III. SYSTEM MODEL

A. Location Based Service (LBS) Applications Scenario

As mentioned before, the group LBS is considered as an example to investigate the security performance issues for mobile cloud applications. With users’ interests as well as their locations, LBS system establishes a “group” of users with the same interests to help customers’ meetup activities. We implemented a location-based group scheduling service on the ODB model, called JOIN [35], which can easily arrange a meetup by sharing their current available time and locations for polling, voting, and broadcasting. Fig. 2 illustrates a service scenario of JOIN, in which users A, B and C join the “Let’s drink coffee” group. While user A is approaching to his preferred coffee shop, users B and C are nearby coincidentally. JOIN server will provide the proximity information of its group members users B and C to customer A, and the advertisements for this coffee shop. The locations and activities of customers in this meetup will be stored in the cloud database for future commercial promotions, such as group coupon distribution.

In this group LBS application scenario, it is worthwhile investigating the following security issues. First, customers shall release their identities to the service provider and to other group members. During the sharing process, it is likely that a hacker will eavesdrop the location data and their identities. Moreover, due to the use of ODB, an adversary can possibly pretend to be an authorized user and then modify the customers’ private information. Clearly, a more trustworthy LBS provider needs to protect customers’ identities and location data in a more sophisticated security mechanism.

B. Security Models and Assumptions

Figure 1 shows the proposed security model for a mobile cloud system with ODB, consisting of users devices, a service engine, cloud databases, and a trusted certifying server. The service engine contains three major processors: the login processor, service data processor (e.g., scheduling a meetup), and service result translator (e.g., anonymization). The cloud database stores the service information and location data. Rather than in cloud databases, customers’ data are stored at the certifying servers, consisting of authentication processor and pseudonym processor. Referring to Fig. 1, the general information flows of privacy preserved LBS are described as follows.

1) Step 1: A customer sends his/her identification as well as the device identification to the certifying server. Then the authentication processor within the certifying server verifies customers’ identities.
2) Steps 2 and 3: The login processor is activated to respond the service requests of customers.
3) Steps 4 and 5: The customer sends the location data to the service engine. Then the service processor can access other service-related information from the cloud database, such as the addresses of the nearby coffee shops.
4) Steps 6 and 7: After receiving the privacy level requested by the customer, the result translator sends the pseudonym to the certificate server.
5) Step 8: The pseudonym processor “uncloaks” the pseudonymous result.
6) Step 9: The simplified location records are stored in the cloud database with various privacy levels. A low privacy level could show group members at the scale of street locations, whereas the high privacy level could show your friends only at the scale of a city.

To make the privacy analysis more tractable, the considered JOIN group LBS is implemented in an experimental platform, invoking the following assumptions and conditions:

- A group of users trust each other so as to being willing to share their locations and identities.
- The service provider and the cloud database provider are semi-honest [36]. Hence, these providers shall follow the protocol properly, while allowing them to keep all the records of involved computations and data exchanges.

Noteworthily, under the semi-honest requirement, there still exists a possibility of deriving private data of other parties from the intermediate computation records.

IV. IMSI-BASED GROUP SECURITY (IGS) ALGORITHM

A. Algorithm Design

In this subsection, we present network coding based pseudonym integrated with the international mobile subscriber identity (IMSI). Stored in a subscriber identity module (SIM) card, IMSI is a unique number associated with current mobile phones to identify the subscribers. Current Android-based mobile platform provides the application programming interface (API) to access the IMSI number of mobile phones. Clearly, location data themselves are not quite useful as long as a hacker does not know the ownership of these data. Hence, we propose to encrypt IMSI to conceal a customer’s privacy.

Fig. 3 (a) and (b) illustrate the basic idea of the proposed IMSI-based group security (IGS) algorithm, in which a two-tier coding scheme is developed to generate KeyA for authenticating a legal customer’s identity, and KeyB (pseudonym) for protecting customer’s private data (e.g., location). First, KeyA is generated by mixing customers’ IMSI and watchwords, which are selected by customers as their secrets to protect their IMSI information. Watchwords shall not be revealed to any party. Second, mixing each customer’s KeyA and a uniformly distributed random seed results in KeyB.

Fig. 3. Proposed two-tier coding scheme with encrypted international mobile subscriber identity (IMSI), where KeyA and KeyB are used for authentication and pseudonym generation, respectively.

- **Network coding**: In efficient routing and secure storage schemes [32], network coding technique has been adopted. Vandermonde transform matrix is the key element in network coding.

Vandermonde matrix is used in our proposed two-tier network coding scheme. Denote $A$ as an $n \times n$ Vandermonde matrix, where $[A_{i,j}] = (a_j^n - 1)$ and the coefficients $a_j$ are distinct nonzero elements in a finite field $F_q$, $q = 2^n > n$. Let $b = (b_1, \ldots, b_n)^T$ be the mix of IMSI and watchwords. Next, we compute $c = (c_1, \ldots, c_n)^T = Ab$ and randomly select the segment of $c$ as the key value in the two-tier network coding scheme.

The aforementioned key generation functions can be adopted in our pseudonym generation scheme. Fig. 3 shows the proposed two-tier coding because a pseudonym in our scheme is generated from two sequential processes. In the first tier, IMSI and a watchword are mixed by the key generation function to yield a cipher pseudonym. This can protect the data ownership privacy during an authentication process. In the second tier, the cipher pseudonym of the first tier is mixed with random seeds to result in the second cipher pseudonym. We use the second cipher pseudonym to protect the data privacy when sharing data with others and storing data in an ODB.

Now we detail the proposed IGS algorithm. Initially, a customer sends his/her genuine identity and KeyA to the certifying server. If KeyA is certified, the certifying server generates an initial pseudonym (KeyB) by the input KeyA, and then activates the login processor. Algorithm 1 describes the detail procedures of the proposed pseudonym generation algorithm. Note that the tolerance distance and the silence period reflect the customers’ preferred privacy level and QoS requirements. The former indicate the maximum acceptable location bias of a customer, and the later specifies the period of changing pseudonyms [37]. The pseudonym processor exchanges KeyBs under the condition that the pseudonym timer reaches the silence period and any other group member is within the range of the tolerance distance. Otherwise, a new KeyB will be regenerated. Since the pseudonyms are mixed with nearby members’ pseudonyms, the proposed IGS algorithm will impose ambiguity on a customer’s exact location and thus protect his/her location privacy. Finally, a customer uses the generated KeyB to update the current location.

B. Proposed IMSI-based Group Secure (IGS) Algorithm

In this subsection we detail the IGS algorithm and the service procedures when applying the proposed pseudonym
Algorithm 1 Pseudonym (KeyB) generation algorithm

1: if a customer sends the KeyA which is authorized by the certifying server then
2: activate the login processor
3: generate and send KeyB to the customer
4: start a timer
5: else
6: send a reject information to the customer
7: end if
8: if timer ≥ silence period then
9: if tolerance distance ≥ distance(customer, a randomly selected friend F within the same group) then
10: exchange KeyB of the customer and F and also reset the timer
11: else
12: send a command of KeyB’s changing to the customer and also reset the timer
13: end if
14: end if

generation algorithm in JOIN. Fig. Aa) shows the register process. Each customer should register a unique account. Initially, a customer generates KeyA with his/her watchwords and transmits KeyA to the server with password and genuine identity. Fig. Ab) shows the login process of the JOIN services. A process thread is initiated and retained after the verification of the identification and the password. Since the thread is retained, the certifying server can identify the customer in the communication afterwards. Furthermore, the certifying server generates an initial KeyB from KeyA and a random seed. Then the KeyB is delivered to the customer.

Fig. 5a) shows the activity initiation process of the JOIN services, where the dotted line and the solid line in this figure is used to denote data stored in the memory and on the hard disk, respectively. A customer can initiate a new activity (i.e., invites friends to go somewhere) and receive information of nearby friends by sending KeyB and location to the server. Then the server sends the requests to all other group members. Each certificated member has to send his/her KeyB and locations to the server responding to this request. Next the JOIN server searches the nearby friends from the location record table and provides some group information (e.g., the top 10 restaurants, coffee shops, or bakeries with fresh-baked bread) from the service data in the cloud-based ODB. Then this group information as well as KeyB and the location of the nearby friends are sent to the certifying server. The certifying server decodes KeyB with a genuine identity and generates a new KeyB based on the proposed IGS algorithm. Finally, the customer receives the service result from the certifying server.

Fig. 5b) shows the storage process of the JOIN services. The JOIN server stores each customer’s KeyB and location in the cloud database. Note that storing a less accurate location in the ODB can result in a higher privacy protection. For example, storing New York City is more secure than storing Manhattan in the database. Finally, data in the memory will be cleared after the activity is finished.

V. PRIVACY ANALYSIS

A. Security Problem Formulation

In this subsection, we will prove that the proposed network coding based pseudonym scheme can guarantee the unlinkability of locations and customers to the unconditional security level. Although the irreversibility feature of network coding can prevent a hacker from deducing valuable information [32], a hacker can still link the relation between the pseudonyms of the same customer. Thus, the unlinkability feature is desirable for a pseudonym scheme. First, the hardness assumptions for Hash functions are given. Then we present the information-theoretic security proof for the proposed network coding pseudonym scheme. The security of the group LBS security model is evaluated based on the probability of a hacker being able to break into a security system. The basic idea of our security system is to use a customer’s pseudonym to hide his/her identity. The pseudonyms are generated by encrypting the IMSI of the customer’s device through either network coding or a Hash function.

Consider a scenario where adversary A can eavesdrop all the links on the Internet, and know the detailed information of key generation functions (i.e., Hash function or Vandermode matrix A). The goal of this adversary is to find the correspondence between the customer’s ID and his/her locations. Since a customer’s (ID, KeyA) and (KeyB, location) are stored in two separate storage nodes, adversary A can break the system once the relations of (ID, KeyA) and (KeyB, location) are known. A security problem for this kind of group LBS can be formulated as follows.

IMSI Security Problem Given $k(A_i)$ and $k(B_j)$, determine whether $IMSI_i = IMSI_j$. Here $k(A_i)$ and $k(B_j)$ represent the $i$-th customer’s keyA and the $j$-th customer’s keyB generated from the same key generation function $k()$, respectively. We denote the mixing of IMSI and watchwords as $A_i$ and the mixing of KeyA and random seeds as $B_j$.

Next, we derive the following theorem.

Theorem 1 Adversary A can find the correspondence between ID and location if and only if A can correctly solve IMSI Security Problem.

Proof: Assume that adversary A can find the correspondence between ID and location. Given the location associated with $k(B_j)$, adversary A can know its corresponding ID of the customer. By eavesdropping the link between the device and the certifying server, adversary A can get the customer’s $k(A_j)$. If $k(A_j) = k(A_i)$, the answer for IMSI Security Problem is “YES”; otherwise, the answer is “NO”. By contrast, assume an adversary A can solve IMSI Security Problem. For any given $k(B_j)$ and its corresponding location $l$, adversary A can answer IMSI Security Problem for each KeyA in the database records. If the answer is “YES” for a certain KeyA with ID $d$, then $d$ is located at $l$.

To reduce the possibility of IMSI Security Problem to be solved, the hardness assumption of the Hash function used as the key generation function is given as follows: It is computationally infeasible in determining whether two output
Certificate Server

Certificate Server

ensure the probability of
give the definition that the considered LBS system is
solved is equal to the probability of random guessing. Next, we

Lemma 1 Assume an LBS system generate \{k(A_i), k(B_j)\}. Let \( A[k(A_i), k(B_j)] \) be the guess of adversary \( A \). If

\[
Pr\{A[k(A_i), k(B_j)] = \text{Yes}|\text{IMSI}_i = \text{IMSI}_j\} \leq \frac{1}{2} + \varepsilon_1 \tag{1}
\]

and

\[
Pr\{A[k(A_i), k(B_j)] = \text{No}|\text{IMSI}_i \neq \text{IMSI}_j\} \leq \frac{1}{2} + \varepsilon_2 \tag{2}
\]

where \( \varepsilon_1 \) and \( \varepsilon_2 \) are negligible, then the system is secure.

Definition 1 The system is secure if \( \left| Pr\{\text{an adversary correctly solves IMSI Security Problem}\} - \frac{1}{2} \right| \leq \varepsilon \), where \( \varepsilon \) is negligible. Note that a function \( f : \mathbb{N} \rightarrow \mathbb{R} \) is called negligible if for every polynomial \( p \) there exists a positive integer \( N(p) \) such that \( |f(n)| \leq \frac{1}{p(n)} \) for all \( n \geq N(p) \).

Proof: Let

\[
P_Y \triangleq Pr\{A[k(A_i), k(B_j)] = \text{Yes}|\text{IMSI}_i = \text{IMSI}_j\} \tag{3}
\]

and

\[
P_N \triangleq Pr\{A[k(A_i), k(B_j)] = \text{No}|\text{IMSI}_i \neq \text{IMSI}_j\}. \tag{4}
\]

Without loss of generality, assume an LBS system with only two customers. We have that \( Pr\{\text{an adversary correctly solves IMSI Security Problem}\} \leq \frac{1}{2} P_Y + \frac{1}{2} P_N \leq \frac{1}{2} + \frac{1}{2} \varepsilon_1 + \frac{1}{2} \varepsilon_2 \). Thus, it follows that \( |Pr\{\text{an adversary correctly solves IMSI Security Problem}\} - \frac{1}{2}| \leq \varepsilon \), where \( \varepsilon = \frac{1}{2} (\varepsilon_1 + \varepsilon_2) \) is negligible.

Next, we analyze the independence of the IMSI and the generated pseudonyms.

Theorem 2 The information mutually held between IMSI and KeyA or KeyB of a customer is \( I(k(A_i); IMSI_i) = I(k(B_j); IMSI_j) = 0 \), where the mutual information \( I() \) is defined by \( I(X; Y) = \sum_{y \in Y} \sum_{x \in X} p(x, y) \log \left( \frac{p(x, y)}{p(x)p(y)} \right) \).

Proof: Let \( e^{(h)} \) represent a subset containing arbitrary \( h \) components of vector \( e \). Denote \( e_{i,j} \) as the subvector formed from the \( i \)-th to the \( j \)-th position of vector \( e \). The set of the \( i \)-th and the \( j \)-th rows of matrix \( D \) is represented as \( D_{i,j} \). Assume that the length of IMSI be \( m \) and the length KeyA and KeyB be \( k \). Represent \( b \) as the uncoded data (e.g., the mixing of IMSI and watchwords), where \( b_i \) are uniformly distributed.

Fig. 4. Register and login process of the JOIN services.

Hash values lead to the fact that part of two corresponding
input messages are the same.

B. Analysis of Network Coding based Pseudonym

Now we evaluate our security framework for which network
coding techniques are used to encrypt the customer’s IMSI.
Referring to Theorem 1, the perfect privacy protection is to
ensure the probability of IMSI Security Problem being
solved is equal to the probability of random guessing. Next, we
give the definition that the considered LBS system is secure.

The system is
secure if \( |Pr\{\text{an adversary correctly solves IMSI Security Problem}\} - \frac{1}{2}| \leq \varepsilon \), where \( \varepsilon \) is negligible.
Initiate Activity
Request location of all other group members.

Find out nearby members.

Replace KeyB with ID.
Generate KeyB with IGS algorithm.

For simplicity, the key is selected from arbitrary contiguous k components of $c = (c_1, \cdots, c_n)^T = Ab$. The mutual information $I(c_{p+1:p+k}; b^{(m)})$ for $0 \leq p \leq n - k$ can be calculated as:

$$I(c_{p+1:p+k}; b^{(m)}) = I(b^{(m)}; c_{p+1:p+k}) = H(b^{(m)}) - H(b^{(m)}|c_{p+1:p+k}), \quad (5)$$

where

$$H(b^{(m)}|c_{p+1:p+k}) = \sum_{j=1}^{m} H(\hat{b}_{seq(j)}|c_{p+1:p+k}),$$

$$b_{seq(j-1)} = \hat{b}_{seq(j-1)}, \cdots, b_{seq(1)} = \hat{b}_{seq(1)} \quad (6)$$

In (6), $seq(j)$ is the j-th element of a random integer sequence within the range 1 to n, and $b_i$ represents the given value for the random variable $b_i$. Since the $n \times n$ Vendermonde matrix $A$ is nonsingular \cite{38}, we can apply the Gaussian elimination to obtain the reduced row echelon form of the submatrix $S$, in
\[ S_{i,j} = [A_{i,j}], \quad p+1 \leq i,j \leq p+k. \] Then Adversary Reduced Matrix \( \mathbf{M} \) is obtained as (7), where the other element of \( \mathbf{M} \) are the same as \( \mathbf{A} \). We can also obtain Adversary Reduced vector \( \mathbf{v} \) of which the elements \( v_{p+1} \cdots v_{p+k} \) are represented as

\[
\mathbf{v}_{p+1:p+k} = \begin{bmatrix}
    v_{p+1} \\
    \vdots \\
    v_{p+k}
\end{bmatrix}.
\]

Each element in \( \mathbf{M} \) and \( \mathbf{v} \) results from the basic row operations to reduce \( \mathbf{S} \) to \( \mathbf{I}_p \). Thus, we obtain \( k \) equations to solve \( n \) unknown elements \( b_i \):

\[
v_i = \sum_{j=1}^{p} m_{i,j}^{-1} b_j + b_i + \sum_{j=p+1}^{n} m_{i,j}^{-1} b_j,
\]

where \( p+1 \leq i \leq p+k \). Since we cannot solve any \( b_i \) without \( n-k \) components of \( \mathbf{b} \) for \( 1 \leq j \leq n-k \), it follows that

\[
H(b_{seq(j)}|c_{p+1:p+k}, b_{seq(j-1)} = b_{seq(1)}, \ldots, b_{seq(1)} = b_{seq(1)}) = H(b_{seq(j)}) = H(b) .
\]

For \( n-k \leq j \leq m \), the number of equations is more than the number of unknown elements. Thus, we obtain

\[
H(b_{seq(j)}|c_{p+1:p+k}, b_{seq(j-1)} = b_{seq(1)}, \ldots, b_{seq(1)} = b_{seq(1)}) = 0 .
\]

Substituting (10) and (11) into (6), we have

\[
H(b^{(m)}|c_{p+1:p+k}) = \begin{cases} 
    mH(b) , & m \leq n-k \\
    (n-k)H(b) , & m > n-k .
\end{cases}
\]

Since \( b_i \) are i.i.d random variables, it follows that

\[
H(b^{(m)}) = H(b_{seq(1)}, b_{seq(2)}, \ldots, b_{seq(m)}) = mH(b) .
\]

Finally, substituting (12) and (13) into (5), we can obtain

\[
I(c_{p+1:p+k}; b^{(m)}) = \begin{cases} 
    0 , & m \leq n-k \\
    (m-n+k)H(b) , & m > n-k .
\end{cases}
\]

Note that we select \( k = n/2 \) and \( m \leq n/2 \) in our network coding based pseudonym scheme to ensure \( I(c_{p+1:p+k}; b^{(m)}) = 0 \).

According to Theorem 2, we know that KeyA or KeyB are independent of IMSI. As a result, the probability for an adversary to correctly solve IMSI Security Problem is the same as random guessing. This is implied that

\[
\begin{align*}
\Pr \{ A[k(A_i), k(B_j)] = \text{Yes} | \text{IMSI}_i = \text{IMSI}_j \} &= \Pr \{ A[k(A_i), k(B_j)] = \text{Yes} \} \\
&= \frac{1}{2} \\
&\leq \frac{1}{2} + \varepsilon_1.
\end{align*}
\]

and

\[
\begin{align*}
\Pr \{ A[k(A_i), k(B_j)] = \text{No} | \text{IMSI}_i \neq \text{IMSI}_j \} &= \Pr \{ A[k(A_i), k(B_j)] = \text{No} \} \\
&= \frac{1}{2} \\
&\leq \frac{1}{2} + \varepsilon_2 .
\end{align*}
\]

Based on Lemma 1, we conclude that the proposed network coding scheme can achieve the unconditional security level.

VI. DISCUSSION

In this section, we discuss the security issues in terms of privacy, authentication, and continuity for the proposed group LBS scheme. Then, we compare the security performance of the proposed pseudonym scheme with that of traditional pseudonym schemes.

A. Data Ownership Privacy

As shown in the previous section, network coding can provide unconditional security rather than computational security provided by Hash functions. Note that the unconditional security property of the proposed IMSI pseudonym is contributed from the uncertainty of the customer’s watchword. Therefore, the privacy of location data ownership is fully preserved even if one can eavesdrop IMSI, KeyA, or KeyB. This property ensures that the proposed pseudonym scheme can prevent the ownership information from being accessed by eavesdroppers. For the same reason, our system is collusion-resistant to the insider attack even when a service provider and a cloud database provider collaboratively attempt to decrypt the pseudonyms. Furthermore, it is discussed that the connection between a pseudonym and its ownership information can be derived by analyzing messages (e.g., location and group member information) subsequently [33]. In the proposed IGS algorithm, customers’ keyB is exchanged randomly within the same group after a silence period, thereby increasing the difficulty of de-anonymization. Compared to the approach using a new KeyB, the proposed method can confuse the eavesdropper because the customers in the same group have similar interests and movement patterns. The silence period is a design parameter specified by a random variable within
a certain range [37]. When the durations of two customers’ KeyBs are overlapped, the temporal relation of these two customers cannot be correctly linked from the new KeyB and the old KeyB. In general, a longer silence period results in lower location timeliness (i.e., the elapsed time since the location was acquired) but provides higher privacy protection. Thus, a cloud database cannot store the precise locations because they are strongly associated with customers. For example, if a customer usually stays in one place, we can guess that he/she may own the house. Fortunately, many group LBS do not require precise locations for each customer. At last, we notice that the collision issue (i.e., two or more customers having the same KeyA/KeyB) will not happen in our proposed scheme since the certifying server will check the validity of each key in the login process.

B. Customer Authentication

With the help of the authentication center of cellular mobile service operators, the proposed IMSI pseudonym can prevent illegal access which will be blocked in the login process. In the proposed IMSI pseudonym, a customer generates KeyA based on his/her own IMSI. A customer can update location information only if he/she is an authorized customer. Even if an adversary can steal a customer’s SIM card to get IMSI, information only if he/she is an authorized customer. Even if an adversary can steal a customer’s SIM card to get IMSI, this adversary still cannot log in to the system without the customer’s watchword.

C. Service Continuity

In group LBS, service continuity is important because the system provider can record and analyze the historical location data of a customer. The proposed IMSI-based pseudonym can retain the individual identification of a customer’s pseudonyms because the unique IMSI is used in pseudonym generation. Therefore, a customer can query his/her location record by providing KeyA to the certifying server. In addition, historical location can be used for social data mining services. In contrast, most of conventional random pseudonym approach will eliminate the individual identification of pseudonyms. Therefore, new location data cannot be appended to the same historic records when users change their identifications, reinstall the program, or change devices. In this case, location records become difficult to be traced since the ownership information of a pseudonym is hard to be known. With the uniqueness provided by IMSI, the proposed privacy protection scheme can be operated and retain the service continuity simultaneously.

D. Comparison with Conventional Pseudonym Schemes

Compared to conventional random pseudonym approaches, the proposed network coding based pseudonym has the following advantages. First, as mentioned above, the proposed IMSI pseudonym can further improve data ownership privacy, customer authenticity, and service continuity. Especially, the proposed pseudonym scheme can provide unconditional security rather than the computational security of Hash-based pseudonym. The property of unconditional security offers great robustness against brute force attacks in cloud computing environment. Besides, the designed two-tier coding method can reduce the computational complexity and energy consumption in mobile devices compared to Hash schemes. A customer only needs to encode its identity one time when logging in to the system. No further decoding procedures are required. Moreover, the designed certifying server can authenticate and authorize individual customers. Note that the certifying server handles the key collision and unclcloaks the pseudonym only according to one’s KeyB. Thus, the certifying process can be implemented in a distributed manner to avoid the service bottleneck and the single point of failure in the system [40], [41]. Last but not least, the proposed network coding based pseudonym is compatible with the existing pseudonym approaches and security communication protocols such as IP security (IPSec) and secure socket layer (SSL).

VII. EXPERIMENTAL RESULTS

Since mobile devices should perform key generation when customers log in to the LBS or update their locations, processing delay and power consumption for key generation function are important performance issues. The applications of network coding may be limited because of the computational complexity and energy consumption in mobile devices [42]. To examine the delay performance and the energy consumption of the proposed network coding scheme, we implemented the JOIN services and performed experiments based on HTC Desire with a Qualcomm QSD8250, which is a low-power ARM based 1 GHZ processor. We choose the three most widely used Hash functions (i.e., MD5, SHA-1, and SHA-2), and network coding schemes with different Galois field sizes. Figure 6 shows the processing time versus the length of IMSI for different key generation schemes. One can observe that the processing time of SHA increases sharply when the length of IMSI is around 140 bits. This is because input data are broken down into chunks for processing in SHA and MD5. Chunks of input data will be appended to fit in with the chunk size. Also, the processing time of network coding approach is
not highly affected by Galois field size because the Galois field mathematical operations are always in the range of field size rather than growing exponentially. Finally, it is important to note that the processing time of network coding is shorter than that of Hash functions when the IMSI length is shorter than 120 bits. In the existing communication systems, a standard IMSI is usually 50 bits long or even shorter. Our results show that using network coding to encrypt a standard IMSI can reduce more than 95% of processing time in mobile devices compared to using Hash functions.

Figure 7 shows the system energy consumption versus running time for different key generation schemes. The system energy, including both coding energy and transmission energy, is tested with eight packets coded together, each of one KB length, and a transmission energy per bit of 200 pJ/bit [43]. Paper [43] has identified when a small field size is used, the total system energy consumption is dominated by the extra RF retransmissions. In contrast, as field size becomes large, significantly increased energy is required for performing the coding process with less influence on the expected number of transmitted packets. Thus, it is worthwhile to investigate the optimal field size of the proposed network coding scheme in terms of energy consumption. As shown in Fig. 7, although network coding with field size $2^{10}$ consumes more energy compared to MD5 or SHA, network coding with field size $2^8$ can reduce about 10% of the energy consumption compared to MD5 or SHA. Hence, we can conclude that network coding with field size $2^8$ is a promising function for energy-limited devices. Finally, it is worthwhile mentioning that the proposed scheme can provide unconditional security with any network coding parameters.

VIII. CONCLUSIONS

In this paper, we proposed a lightweight network coding pseudonym scheme to protect the ownership of mobile data in an untrusted cloud database by disconnecting the relation of data and its identity. We develop the IMSI-based group secure (IGS) algorithm for group LBS based on the proposed pseudonym scheme. Our theoretical results show that the proposed scheme can achieve unconditionally secure privacy protection. Our experimental results indicate that the proposed network coding based pseudonym cannot only exhibit better delay performance, but also provide lower energy consumption compared to Hash-based pseudonyms. Our proposed scheme is fully compatible with existing data security techniques. This work is the first step to exploit the potential of network coding in providing secure pseudonym. Besides the LBS, we will further investigate the applicability and limitation of network coding based pseudonym in the applications of machine-to-machine (M2M) communications.

REFERENCES

[1] J. Reilly, S. Dashit, M. Ervasti, J. D. Bray, S. D. Glaser, and A. M. Bayen, “Mobile phones as seismological sensors: Automating data extraction for the iShake system,” IEEE Transactions on Automation Science and Engineering, vol. 10, no. 2, pp. 242–251, 2013.

[2] S. Yu, “Big privacy: Challenges and opportunities of privacy study in the age of big data,” IEEE access, vol. 4, pp. 2751–2763, 2016.

[3] L. J. Chen, C. R. Hong, D. Deng, H. C. Lee, and H. H. Hsieh, “SDDO: a secure database outsourcing solution for location-based systems,” International Workshop on Privacy in Geographic Information Collection and Analysis, p. 4, 2014.

[4] S. M. Khan and K. W. Hamlen, “AnonymousCloud: A data ownership privacy provider framework in cloud computing,” IEEE 11th International Conference on Trust, Security and Privacy in Computing and Communications, pp. 170–176, 2012.

[5] W. Lou and K. Ren, “Security, privacy, and accountability in wireless access networks,” IEEE Wireless Communications, vol. 16, August 2009.

[6] Y. Zhu, D. Ma, D. Huang, and C. Hu, “Enabling secure location-based services in mobile cloud computing,” Proceedings of the Second ACM SIGCOMM Workshop on Mobile Cloud Computing, 2013.

[7] A. Beresford and F. Stajano, “Location privacy in pervasive computing,” IEEE Pervasive Computing, pp. 46–55, Jan-Mar 2003.

[8] D. Singelé and B. Preenel, “Location privacy in wireless personal area networks,” Proceedings of the 5th ACM Workshop on Wireless security, 2006.

[9] J. M. del Álamo, A. M. Fernández, R. Trapero, J. C. Yelmo, and M. A. Monjas, “A privacy-considerate framework for identity management in mobile services,” Mobile Networks and Applications, vol. 16, no. 4, pp. 446–459, 2011.

[10] Z. Zhu and G. Cao, “Toward privacy preserving and collusion resistance in a location proof updating system,” IEEE Transactions on Mobile Computing, vol. 12, no. 1, pp. 51–64, 2013.

[11] X. Liu, K. Liu, L. Guo, X. Li, and Y. Fang, “A game-theoretic approach for achieving k-anonymity in location based services,” IEEE Conference on Computer Communications, pp. 2985–2993, 2013.

[12] R. Lu, X. Li, T. H. Luan, X. Liang, and X. Shen, “Pseudonym changing at social spots: An effective strategy for location privacy in VANETs,” IEEE Transactions on Vehicular Technology, vol. 61, no. 1, pp. 86–96, 2012.

[13] S. Mathews and B. Jinila, “An effective strategy for pseudonym generation & changing scheme with privacy preservation for vanet,” International Conference on Electronics and Communication Systems, 2014.

[14] F. Julien, M. M. Hossein, H. Jean, and P. David, “Non-cooperative location privacy,” IEEE Transactions on Dependable and Secure Computing, vol. 10, no. 2, pp. 84–98, 2013.

[15] B. Ying, D. Makrakis, and H. Moutiah, “Dynamic mix-zone for location privacy in vehicular networks,” IEEE Communications Letters, vol. 17, no. 8, pp. 1524 – 1527, 2013.

[16] C. Teat and S. Pehlsverger, “The security of cryptographic hashes,” Proceedings of the 49th ACM Annual Southeast Regional Conference, 2011.

[17] H. Kumar, S. Kumar, R. Joseph, D. Kumar, S. K. S. Singh, A. Kumar, and P. Kumar, “Rainbow table to crack password using md5 hashing algorithm,” IEEE Conference on Information and Communication Technologies, 2013.

[18] M. Gruteser and D. Grunwald, “Anonymous usage of location-based services through spatial and temporal cloaking,” The First International Conference on Mobile Systems, Applications, and Services, 2003.
[19] B. Gedik and L. Liu, “Location privacy in mobile systems: A person- 
alyzed anonymization model,” International Conference on Distributed 
Computing Systems, 2005.

[20] C. T. Chow and M. F. Mokbel, “Privacy in location-based services: A 
system architecture perspective,” The SIGSPATIAL Special: Letters on 
Privacy in Location-based Services, 2009.

[21] K. Miura and F. Sato, “A hybrid method of user privacy protection 
for location-based services,” International Conference on Complex, 
Intelligent, and Software Intensive Systems, 2013.

[22] A. Gurjar and A. B. Patil, “Cluster based anonymization for source 
location privacy in wireless sensor network,” International Conference 
on Communication Systems and Network Technologies, 2013.

[23] B. Ying and D. Makrakis, “Protecting location privacy with clustering 
anonymization in vehicular networks,” IEEE Conference on Computer 
Communications Workshops, 2014.

[24] R. Koetter and M. Médard, “An algebraic approach to network coding,” 
IEEE/ACM Transactions on Networking, vol. 11, no. 5, pp. 782–795, 
2003.

[25] W. Qiao, J. Li, and J. Ren, “An efficient error-detection and error- 
correction (EDEC) scheme for network coding,” IEEE Global Telecommu-

[26] N. Cai and R. W. Yeung, “Network coding and error correction,” 
Proceedings of the IEEE Information Theory Workshop, pp. 1–5, 2011.

[27] D. Zeng, S. Guo, Y. Xiang, and H. Jin, “On the throughput of two-way 
relay networks using network coding,” IEEE Transactions on Parallel 
and Distributed Systems, vol. 25, no. 1, pp. 191–199, 2014.

[28] J. P. Vilela, L. Lima, and J. Barros, “Lightweight security for network 
coding,” IEEE International Conference on Communications, pp. 1750– 
1754, 2008.

[29] H. C. Chen, Y. Hu, P. P. Lee, and Y. Tang, “NCCloud: a network-
coding-based storage system in a cloud-of-clouds,” IEEE Transactions on 
Computers, vol. 63, no. 1, pp. 31–44, 2014.

[30] Y.-J. Chen, L.-C. Wang, and C.-H. Liao, “Eavesdropping prevention for 
network coding encrypted cloud storage systems,” IEEE Transactions on 
Parallel and Distributed Systems, vol. 27, no. 8, pp. 2261–2273, 2016.

[31] H. C. Chen and P. P. Lee, “Enabling data integrity protection in 
regenerating-coding-based cloud storage: Theory and implementa-

[32] P. F. Oliveira, L. Lima, T. T. Vinhoza, J. Barros, and M. Medard, “Coding for trusted storage in untrusted networks,” IEEE Transactions on 
Information Forensics and Security, vol. 7, no. 6, pp. 1890–1899, 
2012.

[33] F. Chen, T. Xiang, Y. Yang, and S. S. Chow, “Secure cloud storage 
meets with secure network coding,” IEEE Transactions on Computers, 
vol. 65, no. 6, pp. 1936–1948, 2016.

[34] Y. J. Chen and L. C. Wang, “A security framework of group location-
based mobile applications in cloud computing,” IEEE Parallel Processing 
Workshops, 2011.

[35] Y. T. Lee, L. C. Wang, and R. H. Gau, “Implementation issues of 
location-based group scheduling for cloud applications,” IEEE VTS Asia 
Pacific Wireless Communications Symposium Conference, May 2010.

[36] Q. Chai and G. Gong, “Verifiable symmetric searchable encryption for 
semi-honest-but-curious cloud servers,” IEEE International Conference 
on Communications, pp. 917–922, 2012.

[37] L. Huang, K. Matsuura, H. Yamane, and K. Sezaki, “Enhancing wireless 
location privacy using silent period,” IEEE Wireless Communications and 
Networking Conference, 2005.

[38] A. Klíner, “The Vandermonde matrix,” The American Mathematical 
Monthly, 1967.

[39] A. Narayanan and V. Shmatikov, “De-anonymizing social networks,” 
IEEE Symposium on Security and Privacy, 2009.

[40] Q. Zhang, J. Zheng, Y. Tan, R. Wang, and Y. Li, “Cross-domain 
authentication alliance protocol based on isomorphic groups,” Journal of 
Computers, vol. 6, no. 4, pp. 650–656, 2011.

[41] J. Li and F. Bai, “A distributed cross-realm identification scheme based 
on hyperchaos system,” Advances in Computer Science, Intelligent 
System and Environment, pp. 147–152, 2011.

[42] C. T. Chow, L. Wang, K.-W. Lee, and M. Gerla, “Understanding processing 
overheads of network coding-based content distribution in VANETs,” 
IEEE Transactions on Parallel and Distributed Systems, vol. 24, no. 11, 
pp. 2304–2318, 2013.

[43] G. Angelopoulos, M. Médard, and A. P. Chandrasakran, “Energy-aware 
hardware implementation of network coding,” Springer Networking 
Workshops, 2011.

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