Efficient Anonymous Key Exchange Protocol for Roaming in Wireless Networks

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Abstract

Group signature schemes existentially provide anonymity, non-repudiation and can make a mobile device untraceable. But using group signature only in designing anonymous key exchange system is time wasting and consumes much of other computing resources hence the use of it must be minimal especially when deployed on resources-constrained mobile devices. In .this paper, we propose the combined use of group signature because of its inherent security properties which are very important when a mobile user roams in the insecure wireless network and message authentication code to reduce the huge computational burden occasioned by group signature's expensive public key operations resulting in unbearable authentication latency. In this paper, we built two authenticators, a signature based authenticator and a message authentication code based authenticator. These models are based on the Canetti-Krawczyk model. We implemented the design using Java 8 on Android Studio 2.2 and tested it on Genymotion based emulator on Oracle VM VirtualBox. The experiment result showed a significant reduction in the authentication time when message authentication code based authenticator was executed compared to authentication time result in the group signature based authenticator. We further compared our model with a similar model and find that ours was superior in efficiency measured from authentication latency when a user roams from his home domain to a visited network and other networks subsequently while maintaining same security characteristics.

Keywords: *Wireless network, Roaming, Authentication, security, Anonymity, untraceability, Authenticationlatency, Groupsignature, message authentication code, mobile device, Anonymous key exchange, Visited network*

1. INTRODUCTION

Nowadays we have witnessed the expansive deployment of wireless networks locally and internationally. This, expectedly, is enabled by availability and affordability of mobile devices including PDAs, smart phones, etc. This proliferation enhances the mobile users' mobility as these technologies allow people to get connected seamlessly, have access to, and enjoy normal network services as they move about from their local domain to a foreign domain without being limited by geographical coverage of their home network. A wireless network that provides its subscribers with the ability to access services while outside its coverage is said to provide roaming services. Before access is granted to roaming users by foreign networks, these users must be authenticated. Authentication involves ensuring that network services are not obtained fraudulently hence, it is very crucial that the identities of mobile users engaged in roaming must be authenticated to prevent illegal use of resources, etc. However, the authentication credentials of these mobile users must be protected from third parties to ensure privacy of users. Anonymous roaming is a key requirement when people roam among visited networks. Allowing third parties, such as eavesdroppers, access to users' roaming data can have very serious consequences to the detriment of the user. Firstly, the real identity of the mobile user must not be known by anyone else except the mobile user and the home network. This is referred to as identity anonymity. Secondly, the location of the mobile user should also be kept secret from other network users while abroad. We refer to this as location anonymity. A privacy policy specification can require the home network to gain knowledge of the real identity of a mobile user only when it is extremely necessary such as when the foreign network bills the home network for services enjoyed by the mobile user or when the mobile user exhibits malicious behavior or breaks one the rules a warrant of revocation can be issued by a constituted authority to reveal such user's real identity.

To realize the scenario above an anonymous authentication protocol design is a good way to achieve it. We must always take cognizance of the limited computational resources of mobile terminal to keep the protocol not too complex. In a roaming scenario, there are typically three entities involved: the home network, the roaming mobile user and the visited foreign network. It is natural for the home network that must have a roaming agreement with the visited network. Where this is applicable, the visited network must authenticate home network's subscribers before granting them access to its roaming services they roam to visited network. Most existing authentication protocols such as those of [6], [7], [8], and [9] require a mobile user, the visited network, and the home network to participate in the roaming service. These protocols adopt three-party authentication technique. The disadvantages of this technique include: first, many interactive message flows are needed (not less than 4 flows). Here it takes a long time for the home server to communicate with the visited server because they are far away from each other; second, the home server must always be online and available making it vulnerable to authentication problem; third, according to [10], since the visited server must verify messages by communicating with the home server, there may be a Denial-of-Service (DoS) attack on the protocol because the home server will be verifying a lot of messages sent to it from visited servers. The structure for a three-party authentication is shown in figure 1.

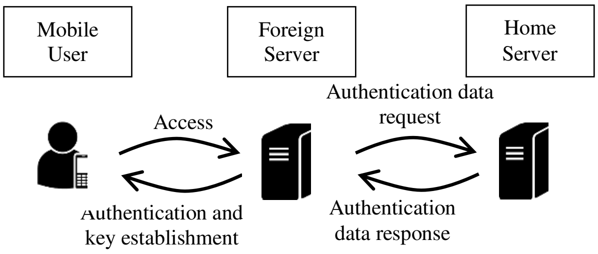

Mobile User
Foreign Server
Home Server
Access
Authentication data request
Authentication and key establishment
Authentication data response

Figure 1: Three-Party Authentication Architecture

To improve upon the lapses of most three-party authentication protocols, recently anonymous authentication schemes involving only the roaming mobile user and the visited network have received significant research attention and have made some progress. These protocols which do not need the real-time participation of the home network in the authentication process are referred to as two-party authentication protocols shown in figure 2. Examples of two-party protocols include those of [11] and [12].

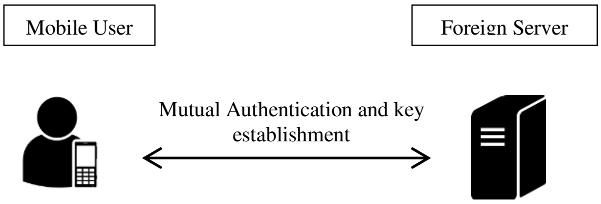


Figure 2: Two-Party Authentication Architecture

Although authenticating a mobile user is pertinent, the privacy of the user is paramount. Roaming authentication protocols exposes the users' privacy in terms of their identities and location information at the authentication phase. The disclosure of a user's identity may allow unauthorized entities to track the user's movement history and current location and therefore create users' behavior profiles. Any illegal access to information relating to the user's location without his attention can be a serious violation of his privacy. Identity and location anonymity are important properties for roaming services and these anonymity characteristics are the focus of this paper.

2. RELATED WORKS

In [1] an anonymousauthentication protocol based on group signature for mobile roaming networks was carried out.The protocol involves only a mobile user and theuser's visited server, without the real time involvement of the user'shome server until the user's identity (ID) needs to be revealed.The protocol gives a method that to reduce the computational burden the mobile terminals, minimizes expensive pairing operations. It was shown thatthe protocol greatly reduces the average authenticationlatency while security and anonymity are still preserved. The limitation of this protocol is that foreign servers are given information to identify revoked users and this information can enable the foreign servers to link other protocol runs involving the revoked user. Hence the protocol does ensure unlinkability.

In [2] the authors proposed a privacy-preserving universal authentication protocol, called *Priauth*, which provides strong user anonymity against both eavesdroppers and foreign servers, session key establishment, and achieves efficiency. Most importantly, Priauth provides a way to trace users' signatures in individual period, an approach that adequately tackles the problem of user revocation and ensures unlinkability while supporting strong user untraceability. But the protocol utilized expensice and resources-hungry bilinear pairing-based group signature both when the user connects to the first foreign network and in subsequent connections to other foreign networks. This has great negative impact on the overall authentication process.

A short group signature scheme that supports Verifier-Local Revocation (VLR) is constructed in [3]. In this model, revocation messages are only sent to signature verifiers and to both signers and verifiers. This is appealing for systems providing attestation capabilities. Their signatures are as short as standard RSA signatures with comparable security. The security of their group signature scheme is based on the Strong Diffie-Hellman assumption and the Decision Linear assumption in bilinear groups. They gave a precisemodel for VLR group signatures. The weakness of their protocol lies in the fact that protocol runs involving the same user could be linked. Therefore the scheme does not satisfy the backward unlinkability. Again, since the protocol does not consider differentiation in application of the group signature during different stages of the authentication, the computational load involved is bound to be high.

In [4] the authors identified verifier-local revocation as an approach of membership revocation in group signatures. In the approach, only verifiers are involved in the revocation mechanism, while signers have no involvement. They proposed VLR group signature schemes with the backward unlinkability from bilinear maps and asserted that their protocol is suitable for mobile environments since signers have no load. Here, we do nor seem to agree totally with this assert since group signature schemes are known to be naturally computationally demanding in terms of computing resources. We believe that anonymity, untraceability, revocation, etc. could still be achieved by using a scheme which is computationally less demanding.

The authors in [5] proposed a novel protocol to achieve privacy-preserving universal authentication protocol for wireless communications. This is to secure the communication as the data are sensitive or to ensure that the user is billed for services rendered in their scheme, revoking multiple users is to associate a key with every nonempty subset of users in the group such that if one or more users are revoked, the VA uses the key associated with the subset of the remaining users to encrypt the new key and transmits the new group key to them. The advantage of this approach is that the communication overhead is only one message for revoking any number of users. However, the number of keys stored by the VA and the users is exponential in the size of the group. Also, this approach suffers from all the users in the subgroup being automatically revoked. In such case, their protocol runs can be linkable. This approach has two cots overheads;Storage is computed in terms of keys that each user (respectively, VA) maintains and revocation cost is computed in terms of the encryptions performed, and the number of messages transmitted, by the VA.

In view of related literatures, it is obvious that the focus of most of the literatures is either choosing primitives to ensure privacy while trading off computational expense on the communicating parties or being resource efficient while trading off privacy concerns. Hence, this paper proposes a new model that pays attention to both privacy of the mobile user and computational efficiency through reduced latency.

3. MODELLING AND SIMULATION

3.1 Methodology

We divide the authentication process into two; (1) when the mobile user first roams to foreign network (2) when the mobile user subsequently roams to a different foreign network. We propose to use these different approaches because group signature is quite an expensive cryptographic scheme therefore minimal usage is advised. Our protocol deploys group signature scheme message authentication code in the two authentication processes respectively. The reason for this combination is that group signature existentially provides anonymity and untraceability and message authentication code is less expensive in terms of computational complexity. In the group signature scheme, when U roams to a visited network V, U can sign messages on behalf of the group without showing its ID. By verifying the group signature, V is sure that U is one of the valid users of H. The home server does not need to be always online and few message flows are needed for authentication [12].

In consideration of the resources restrictiveness of mobile devices, the foreign server is made to sign messages destined for a mobile user using the Elliptic Curve Digital Signature Algorithm (ECDSA) scheme since ECDSA signature verification takes less time compared to its group signature counterpart. Details of our protocol model are as follows.

Our protocol is based on the system architecture is shown in figure 3 and is consists of two phases: an initialization and authentication phases. The authentication phase is divided into two parts as earlier stated: authentication process when U connects to V_1 and authentication process when U connects to V_2.

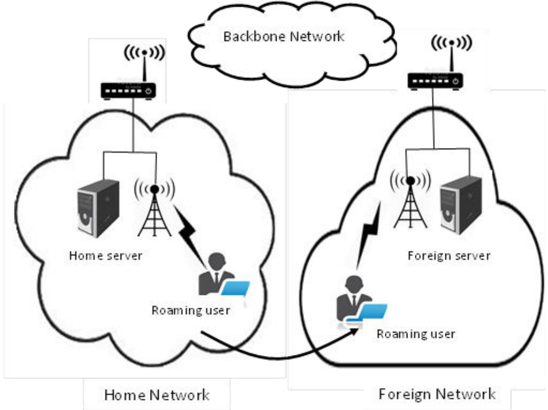


Figure 3: Protocol System Architecture Model

To achieve revocation and unlinkability, the verifier local revocation with backward unlinkability (VLR-GS BU) group signature variant is used when U connects to the first visited server, V_1 and mutual authentication code (MAC) when U roams to the second visited server, V_2

3.2 Protocol Initialization Phase

H (also known as the group manager) computes initialization parameters. The parameters include

(i) H selects a random number $\gamma \in \mathbb{Z}$ and computes a group manager private key (gmpk) computed as:

$$gmsk = \gamma \quad (1)$$

(ii) The group manager public key (gmpk) is given as,

$$gmpk = (g_1, g_2, h_1, h_2, \ldots h_T, w) \quad (2)$$

where given Fq a finite field with an elliptic curve E, G_1 a multiplicative cyclic group of prime order p and G_2 a multiplicative group of exponent p, with some power of p as its order, g_1 is a generator of G_1 and g_2 is an order-p element of G_2. The elements g_1 and $g_2$will be selected at random as part of system setup. h_1, h_2,

… h_T represent randomly selected $h_j \in G$ for each interval j and w is given as $w = g_2{}^{\gamma}$.
(iii) H uses the above computed parameters to generate a vector of N user's secret keys *usk* and a vector of N x T revocation tokens (*urt*) for each registered user with current time intervals to ensure unlinkability as follows:

$$usk = (usk[1], usk[2], \ldots, usk[N]) \quad (3)$$

$$urt = (urt[1][1], \ldots, urt[1][T], \ldots, urt[N][T]) \quad (4)$$

(iv) The user secret key for *N* users is given as:

$$usk[i] = (A_i, x_i) \quad (5)$$

Where $Ai = g_1{}^{1/(\gamma+x_i)}$ for all i $\in [1, N]$ and $x_i \in \mathbb{Z}$ is selected randomly.
(v) Next, randomly selected $h_j \in [1, T]$ is used to compute the revocation token at time interval j of $user_i$with secret key (A_i, x_i) as:

$$B_{ij} = h_j^{x_i} \quad \text{for all i } \in [1, N] \text{ and } j \in \mathbb{N} \quad (6)$$

(vi) H computes an alias for each registered user intending to roam using secret splitting mechanism from:

$$alias_U = (w||ID_H) \oplus ID_U \oplus ID_H \quad (7)$$

Where ID_H is the Home Server identity, ID_U is the identity of the user, U and $\oplus$ is an Exclusive-Or operator.

3.3 Authentication Phase

(1) Authentication Process when U connects to V_1:
A pairing-based verifier-local revocation group signature with backward unlinkability and the conventional digital signature scheme, ECDSA are used in this process. The process is shown in figure 4 and illustrated as follows:

(i) U selects a random number, N_U and computes $N_U G$ (we assume $G_1 = G_2 = G$, from bilinear map) and sends $(ID_H, N_U G)$ to V_1.
(ii) V_1 selects a random number N_{V_1}, computes a ECDSA signature, σ_{V_1} with its secret key, sk_{V_1} as follows:

$$\sigma_{V_1} = \text{ECDSA.sig}(sk_{V_1}, N_{V_1}G, NUG) \quad (8)$$

and sends $(ID_{V_1}, N_{V_1}G, \sigma_{V_1})$ to U. $ID_{V_1}$is the identity of the first network visited by U. After that, V_1 computes a session key used between V_1 and U as follows

$$k_{V_1 U} = N_{V_1}(N_U G) \quad (9)$$

(iii) U verifies V_1's signature, σ_{V_1} with V_1's public key, pk_{V_1} by running ECDSA verification algorithm, ECDSA.ver$(pk_{V_1}, N_{V_1}G, NUG, \sigma_{V_1})$ and accept or reject connection based on the verification result as follows:

$$\sigma_{V_1} = \begin{cases} 1, & \sigma validacceptconnection \\ 0, & \sigma validrejectconnection \end{cases}$$

If the signature σ_{V_1} equals to 1, U computes a session key to between U and V_1 as follows:

$$k_{UV_1} = N_U(N_{V_1}G) \quad (10)$$

It then computes a temporary alias by encrypting $alias_U$ given to it by its home network using its session key k_{UV_1}. Then it computes a group signature, $\sigma_u$with usk[i] as:

$$\sigma_u = \text{G.Sig}(gmpk, usk[i], j, alias, N_{V_1}G) \quad (11)$$

and sends (alias, σ_u) to V_1. Otherwise, if the signature $\sigma_{V_1} = 0$, connection rejected.
(iv) V_1 verifies the signature from U with home server's public key, *gmpk* by running verification algorithm, G.Ver(gmpk, usk[i], j, alias, N_{V_1}G, σ_u).

$$\sigma_U = \begin{cases} 1, & \sigma valid, \text{allow } connection \\ 0, & otherwise \text{ disallow} \end{cases}$$

V_1 allows connection if $\sigma_U = 1$ and disallow otherwise.

(2) Authentication Process when U connects to V_2: Message Authentication Code (MAC) reduces roaming authentication time when U connects to V_2. This is shown in figure 5 and illustrated as follows: (i) V_1 passes (alias, ID_H, k_{V_1U}) to V_2(ii) U selects a new random numberN'_U, encrypts the message (alias, ID_{V_1}, $N'_U G$) using its session key, k_{UV_1}, and send $E_{k_{UV_1}}$(alias, ID_{V_1}, $N'_U G$) to V_2. (iii) V_2 takes out k_{V_1U}, from message in (i) above and use it to decrypt alias to get $alias_U$. Then it selects a random number N_{V_2}, computes a session key k_{V_2U} and a new alias by decrypting the alias received from V_1 from:

$$k_{V_2U} = N_{V_2}(N'_U G) \text{ and alias}' = E_{k_{V_2U}}(alias_u)$$

then, it computes a message authentication code (MAC) value σ_{V_2} using σ_{V_2} = $\text{MAC}_{K_{V_2U}}$ ($N'_U G$, N_{V_2}G) and sends (ID_{V_2}, N_{V_2}G, σ_{V_2}) to U
(iv) U computes a session key between U and V_2 as

$$k_{UV_2} = N'_U(N_{V_2}G)$$

It then verifies the MAC valueσ_{V_2} by computing

$$\sigma'_U = \text{MAC}_{K_{UV_2}}(N'_U G, N_{V_2}G)$$

and compare it with σ_{V_2} received from V_2. If σ_{V_2} = MAC value σ'_U, then σ_{V_2} is valid and U updates its ID and computes a new MAC value as:

$$\text{alias}'' = E_{k_{UV_2}}(alias_u)$$

$$\sigma''_U = \text{MAC}_{K_{UV_2}}(\text{alias}'', N'_U G, N_{V_2}G)$$

and sends (alias" , σ''_U) to V_2. Otherwise U rejects the connection.

(v) V_2 verifies the MAC value $\sigma''_U$by computing

$$\sigma_{V'_2} = \mathrm{MAC}_{K_{V_2U}}(\text{alias", N'UG, } N_{V_2}\text{G})$$

then it compares it with MAC value σ''_U received from U. If $\sigma_{V'_2} = \sigma''_U$, V_2takes alias" as U's temporary identity and k_{UV_2} as new session key. Otherwise V_2 rejects the connection. If k_{UV_2}= K_{V_2U} and alias' = alias" secure re-authentication.

4. IMPLEMENTATION AND RESULTS

The Protocol is implemented using Java 8 on Android Studio 2.2, and tested in a Genymotion supported VirtualBox to provide the needed virtualization support.

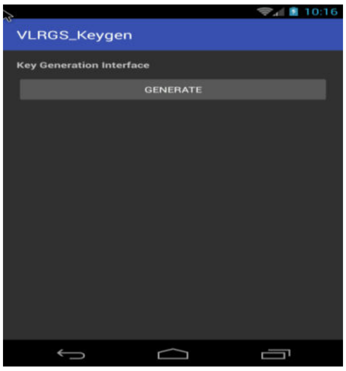
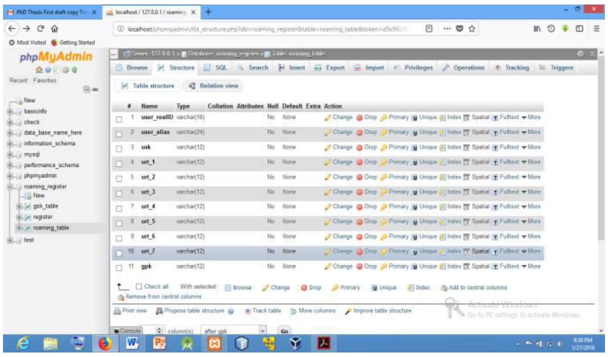
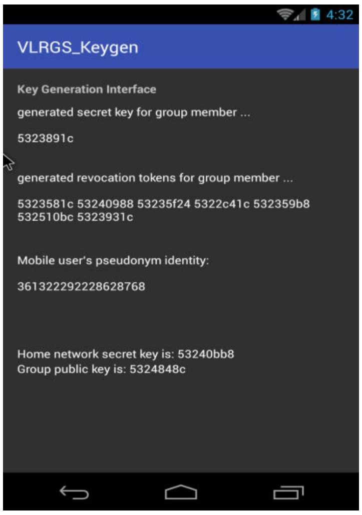


Figure 4: The Key Generation Initial Interface



#	Name	Type	Collation	Attributes	Null	Default	Extra	Action
1	user_realID	varchar(16)			No	None		Change Drop Primary Unique Index Spatial Fulltext More
2	user_alias	varchar(24)			No	None		Change Drop Primary Unique Index Spatial Fulltext More
3	usk	varchar(12)			No	None		Change Drop Primary Unique Index Spatial Fulltext More
4	urt_1	varchar(12)			No	None		Change Drop Primary Unique Index Spatial Fulltext More
5	urt_2	varchar(12)			No	None		Change Drop Primary Unique Index Spatial Fulltext More
6	urt_3	varchar(12)			No	None		Change Drop Primary Unique Index Spatial Fulltext More
7	urt_4	varchar(12)			No	None		Change Drop Primary Unique Index Spatial Fulltext More
8	urt_5	varchar(12)			No	None		Change Drop Primary Unique Index Spatial Fulltext More
9	urt_6	varchar(12)			No	None		Change Drop Primary Unique Index Spatial Fulltext More
10	urt_7	varchar(12)			No	None		Change Drop Primary Unique Index Spatial Fulltext More
11	gpk	varchar(12)			No	None		Change Drop Primary Unique Index Spatial Fulltext More

Figure 5: roaming_table Design Structure

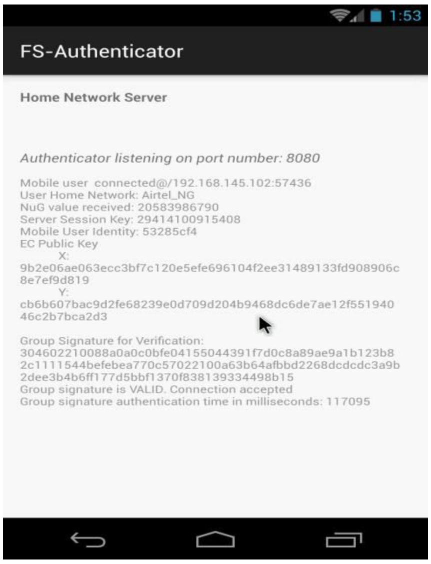


```
Key Generation Interface

generated secret key for group member ...

5323891c


generated revocation tokens for group member ...

5323581c 53240988 53235f24 5322c41c 532359b8
532510bc 5323931c


Mobile user's pseudonym identity:

361322292228628768


Home network secret key is: 53240bb8
Group public key is: 5324848c
```

Figure 6: The Key Generation Result Interface

Figure 4 shows the key generation interface, where the home server generates the group public key *gpk,* a vector of N user secret keys *usk,* a vector of NxT user revocation tokens *urt,* anda group master secret key *gmsk*. These keys are store in MySQL database named *roaming_table* (see figure 5 below).

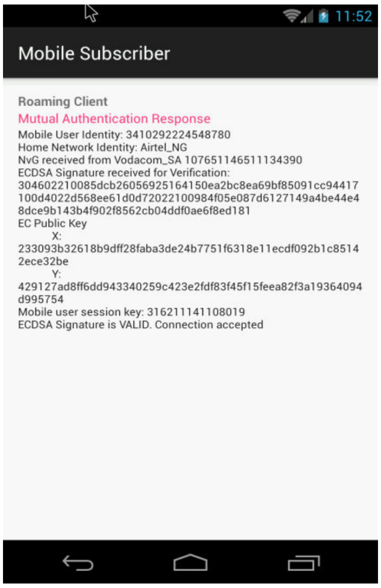
Figure 6 shows the output of the implemented key generation algorithm including a secret key for a roaming user, revocation tokens for the interval, in this case one week (7 days).



```
Home Network Server


Authenticator listening on port number: 8080

Mobile user  connected@/192.168.145.102:57436
User Home Network: Airtel_NG
NuG value received: 20583986790
Server Session Key: 29414100915408
Mobile User Identity: 53285cf4
EC Public Key
        X:
9b2e06ae063ecc3bf7c120e5efe696104f2ee31489133fd908906c
8e7ef9d819
        Y:
cb6b607bac9d2fe68239e0d709d204b9468dc6de7ae12f551940
46c2b7bca2d3

Group Signature for Verification:
304602210088a0a0c0bfe04155044391f7d0c8a89ae9a1b123b8
2c1111544befebea770c57022100a63b64afbbd2268dcdcdc3a9b
2dee3b4b6ff177d5bbf1370f8381393344498b15
Group signature is VALID. Connection accepted
Group signature authentication time in milliseconds: 117095
```

Figure 7: Group signature verified by V_1.

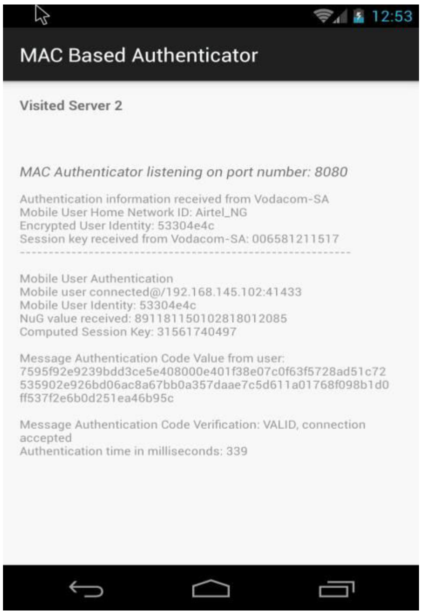
This shows group signature received from mobile subscriber for verification. The result of implementation of the verification algorithm is shown in figure 7 as the received group signature is verified by the FS-Authenticator. The total signature-based authentication is also shown to be 117095 millseconds.



```
Roaming Client
Mutual Authentication Response
Mobile User Identity: 3410292224548780
Home Network Identity: Airtel_NG
NvG received from Vodacom_SA 107651146511134390
ECDSA Signature received for Verification:
304602210085dcb26056925164150ea2bc8ea69bf85091cc94417
100d4022d568ee61d0d72022100984f05e087d6127149a4be44e4
8dce9b143b4f902f8562cb04ddf0ae6f8ed181
EC Public Key
        X:
233093b32618b9dff28faba3de24b7751f6318e11ecdf092b1c8514
2ece32be
        Y:
429127ad8ff6dd943340259c423e2fdf83f45f15feea82f3a19364094
d995754
Mobile user session key: 316211141108019
ECDSA Signature is VALID. Connection accepted
```

Figure 8: ECDSA signature verification

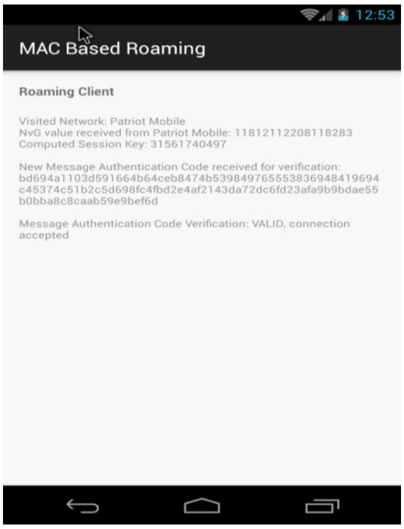
The implemented ECDSA signature is shown in figure 8 as the mobile user received the signature from FS-Authenticator for verification 8.
When mobile user roams to V_2, V_1 sends mobile user's authentication information to V_2. Figure 9 and 10 show key exchanges between V_1 and V_2.



```
Visited Server 2

MAC Authenticator listening on port number: 8080

Authentication information received from Vodacom-SA
Mobile User Home Network ID: Airtel_NG
Encrypted User Identity: 53304e4c
Session key received from Vodacom-SA: 006581211517
-------------------------------------------------------------

Mobile User Authentication
Mobile user connected@/192.168.145.102:41433
Mobile User Identity: 53304e4c
NuG value received: 89118115010281801 2085
Computed Session Key: 31561740497

Message Authentication Code Value from user:
7595f92e9239bdd3ce5e408000e401f38e07c0f63f5728ad51c72
535902e926bd06ac8a67bb0a357daae7c5d611a01768f098b1d0
ff537f2e6b0d251ea46b95c

Message Authentication Code Verification: VALID, connection
accepted
Authentication time in milliseconds: 339
```

Figure 9: MAC-Based Authentication – V_2.

It can be seen from figure 9 that the total MAC based authentication time is 339 milliseconds.
The results of authentication using the Signature based authenticator and the MAC Based authenticator confirms that group signature based authentication is very expensive and resource consuming than the MAC based authentication resulting in authentication times as shown in figure 9 and 10. This justifies the deployment of MAC based authentication in subsequent authentication after the user roams from the first foreign network.



```
Roaming Client

Visited Network: Patriot Mobile
NvG value received from Patriot Mobile: 11812112208118283
Computed Session Key: 31561740497

New Message Authentication Code received for verification:
bd694a1103d591664b64ceb8474b5398497655538369484196 94
c45374c51b2c5d698fc4fbd2e4af2143da72dc6fd23afa9b9bdae55
b0bba8c8caab59e9bef6d

Message Authentication Code Verification: VALID, connection
accepted
```

Figure 10: MAC-Based Authentication – Mobile User.

5. ANALYSIS

5.1 Security Analysis

The design of our protocol is based on the CK-Model [13]. Based on this, we design we can design our key-exchange protocol in an idealized model, and then translate it using general tools to obtain security in the realistic model. It includes three parts: Authenticated-links Adversarial model (AM); Unauthenticated-links adversarial model (UM); Authenticators. AM is considered as an idealized model where the communication links are perfectly authenticated; UM is the realistic setting of adversary-controlled links; Authenticators are the so-called general algorithm tools that translate a protocol which is Session-key secure (SK-secure) in AM into a protocol which is SK-secure in UM. Since the protocol design in this paper follows from the CK model, our protocol guarantees security.

5.2 Anonymity and Unlinkability

User anonymity is achieved due to the existential anonymity of a special group signature algorithm which employs verifier local revocation. With this algorithm, V is not able to obtain the identity of the real signer since it does not have U_i's revocation token $u[i][j]$, only U_i's home server H has. User untraceability is also achieved by the anonymity of the deployed scheme. When U_i exists in the revocation list, RL of H during a particular interval j, V can obtain $u[i][j]$ and uses it to make sure that U_i is revoked for interval j. V cannot link U_i's protocol run during any interval j_1 to $u[i][j]$, because the revocation token of each user changes for every interval j where $j_1 \neq j$. Based on this, our authentication and key exchange system can achieve anonymity and unlinkability of U_i's protocol runs during past and future periods.
Besides, nobody including V_1 knows U's new temporary ID, so none of the entities taking part in the communication protocol can identify and trace U. Even if V_1 gets $N_{V_2}G$ and N_UG, it still cannot compute $K_{V_2}U = N_{V_2}(N_uG)$ due to DDH assumption, and thus cannot get alias which is encrypted using $K_{V_2}U$. From the above analysis, our protocol can ensure secure and anonymous key exchange between the communicating parties.

6. EVALUATION AND COMPARISON

The difference between our protocol and that of [12] is that when U roams subsequently to other foreign networks, UPK operations are constant (still 29.515 ECSM + 12.95Pairing) but only 11.5ECSM are needed in our protocol. The authors in [1] did a similar work and obtained a better result than the result in this work but in their protocol when a user is revoked, the users previous cannot protocol runs are linkable. This means that their protocol does not provide backward unlinkability which our protocol provides.

The protocol developed in this paper is compared with the protocol in [12] in terms of user public key (UPK) operations and UPK computation latency. When U first connects to a network, 8.75 Elliptic curve scalar multiplication (ECSM) plus 12.95Pairing operations are needed in both protocols. When U roams to another network, UPK operations are still 8.75ECSM plus 3Pairing in [12], but only 2ECSM operations are needed in our protocol.

Let X_{UV_1} be UPK operations when U connects to V1, and (X_{UV_2}, X_{UV_3} , · · · , X_{UV_n}) be UPK operations when U roams to networks (V_2, V_3, · · · , V_n), then we calculate the average UPK operations as follows:

$$X_{Average} = \frac{X_{UV_1} + X_{UV_2} + X_{UV_3} + \cdots + X_{UV_n}}{n} \qquad (12)$$

wheren is the number of networks the user has roamed. Going by equation (12), $X_{Average}$ in [12] is 29.515 ECSM + 12.95Pairing. In the case of the protocol developed in this paper,

$$X_{Average} = \frac{29.515\text{ECSM} + 12.95\text{Pairing} + 2\text{ECSM}(n-1)}{n}$$

$$= 11.5\text{ECSM} + \frac{29.515\text{ ECSM} + 12.95\text{Pairing}}{n} \qquad (13)$$

In equation (13) above 29.515 ECSM + 12.95Pairing represents the user public key operations involved in authentication process when the user roams to the first visited network using group signature scheme in [14]. The time of authentication obtained in our case is 117095 milliseconds (0.12 seconds approx.).

Let L_{UV_1} be computation latency for UPK operations when U connects to V1, and (L_{UV_2}, L_{UV_3} , · · · , L_{UV_n}) be that when U roams to networks (V_2, V_3, · · · , V_n), then the average latency is computed as follows:

$$L_{Average} = \frac{L_{UV_1} + L_{UV_2} + L_{UV_3} + \ldots + L_{UV_n}}{n} \qquad (14)$$

Based on the authentication delay of 117095 milliseconds obtained in this work (see figure 7), 1ECSM and 1Pairing need 2300 milliseconds and 3800 milliseconds respectively in a terminal with a 2.20GHz processor, so $L_{Average}$ in [12] would be permanently 117095 milliseconds, but in our protocol it is:

$$L_{Average} = \frac{117095 + (n-1) \text{ x } 26450}{n}$$

$$= \frac{117095 + (26450n - 26450)}{n} = \frac{90645 + 26450\,n}{n}$$

$$= 26450 + \frac{90645}{n} \qquad (15)$$

In this evaluation it can be seen from equation (15) that the bigger *n* is the smaller the computation latency. This is not the case for a scheme employing only the expensive group signature example [16].

Figure 11 is the average latency comparison between the protocol developed in [12] and our protocol according to the user's roaming frequency. From the figure we can see that, the more frequently the user roams among different networks, the less time it will take in authentication.

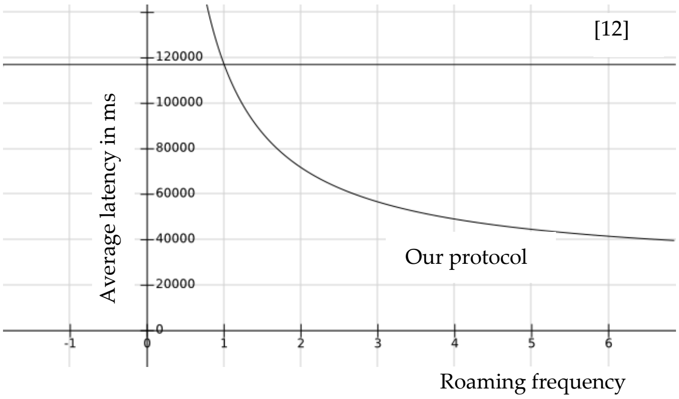


Figure 11: Average latency comparisons

7. CONCLUSION

According to the results obtained in this work, generating a group signature imposes a significant burden on the computing terminal and needs 117,095 milliseconds for authentication. On first connection to a foreign network, it may be bearable for U to wait this long. When U roams to another network such as V_2, re-authentication process has to restart, and U has to wait another 117,095 milliseconds. It will become unbearable for U to be interrupted regularly when U roams among foreign networks frequently. Because group signature weighs so much on computing resources minimal usage of it is needed. It can be adequate to make use of a group signature when U connects to V_1, but it is not necessary to do that again when U roams to V_2. This is the reason why this work employs message authentication code which greatly reduces roaming authentication time to 339 milliseconds.

User anonymity is easy to be revoked by its home server; untraceability is achieved because when a user is revoked in a particular time interval, say j, he cannot be linked to any of his previous protocol runs; the foreign servers do not have to communicate with the home server to authenticate the user, so it needs few message flows. The analysis shows that the protocol is practical for roaming in wireless networks in which users are roaming frequently.

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