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# Summary

Wireless Mesh Network (WMN) technology ispromising multi-hop, ubiquitous and high speed networking technology for metropolitan broadband wireless access. Being a service providing system, payment is an important component of WMN structures. In our project, namely *SSPayWMN*, we will design and implement a Secure and Seamless Payment scheme for Wireless Mesh Networks. Security of the system developed is not only confidentiality and integrity of the transmitted messages but also anonymity of the users getting broadband access service from the WMN. Moreover, fairness of the payment scheme and enforced honesty of the participants are also important design issues. Seamless handover among the gateways and the operators in the above secure and fair setting will also be provided in SSPayWMN. The implementation and the performance evaluation of SSPayWMN will be performed in a network simulator environment.

In this document, we provide the design of the cryptographicprotocols to be used to achieve our security goals under the light of the system and user requirements previously described in Deliverable 1.

# Introduction

Wireless Mesh Networks [1] is a multi-hop wireless networking technology to provide broadband ubiquitous access in metropolitan area. WMN provides flexibility for topology design and has self-organized nodes. These nodes could form routing tables and provide high-speed connection end to end. WMNs are easy to set up and they have manageable overheads.

In the WMN structure that we assume in SSPayWMN project there are mobile clients and operators, who will be charging the service they give. We assume there is more than one operator and users should be able to get service from these operators. In case of a roaming situation, service should not be interrupted and users should continue getting service without noticing operator change has occurred. Related studies for broadband access usually fully trust the operators, but in real life operators may unintentionally overcharge their users and these cause disputes between the customers and the operators. Even in the cases where the operator is right, it is very difficult to convince the customer since the operators generally do not have justifiable proofs that cannot be denied by the customers.

In SSPayWMN project, our aim is to design a secure payment scheme which is fair to both the operator and users. Using cryptographic tools and techniques, all system parties will make sure that they talk to the correct entity and providing/getting service in an undeniable way. We will design and implement a secure prepaid payment scheme and we will prove our system’s effectiveness by implementing our system on a network simulator. By doing so, we aim to get near real life performance results for critical use cases.

We will design our system considering our main requirements; which are wide coverage, roaming, seamless connection, seamless roaming, anonymity, mutual authentication, two-way honesty, preventing double spending, and unlinkability.

The symbols used in this report are given in Table 2.1.

Table 2.1: The List of the Symbols

|  |  |
| --- | --- |
|  | XOR operation |
|  | Concatenation |
|  | Encryption of using the key |
|  | Decryption of using the key |
|  | Taking hash of times |
|  | Taking HMAC of using the key |
|  | th element of the hash chain (usage order) |
|  | Public key of TTP |
|  | Private key of TTP |
|  | th Access Point or its identity |
|  | th Operator or its identity |
|  | Public key of |
|  | Private key of |
|  | Serial Number |
|  | Nonce created by entity |
|  | Previous Alias |
|  | New Alias |
|  | Public key certificate of |
|  | Initialization Vector |
|  | Timestamp |
|  | Connection Request |
|  | Disconnection Request |
|  | Roaming Request |
|  | Change Alias Request |
|  | Mobility Request |
|  | Response (used in various protocol as positive acknowledgment) |
|  | Disconnection Acknowledgement |
|  | Roaming Acknowledgement |
|  | Mobility Response |

# Cryptographic Notes

In our protocols, we use relevant cryptographic primitives. For public key encryption and signature purposes, we use 2048 bit RSA [1]. For symmetric encryption and decryption, we use AES-128 [2]. SHA-256 [3, 4] algorithm is employed as hash function and to form hash chains. For Challenge-Response protocols we use HMAC [3, 4] algorithm.

# Connection Card Structure

*Connection Card* is the main deed that clients buy from the TTP and use to get Internet service. We use a prepaid system, in which connection cards include credits as tokens. Hash tokens are generated using hash chains as discussed below. Connection cards also have unique *Serial Numbers* (), which are to be used for alias computation.

Tokens for getting Internet service are basically links in a hash chain. For each set of tokens, the TTP picks on a random and takes hashes of it many times. The number of hash operations is actually the number of token in a set. For example, if the client wants a hundred hash tokens, then the hash of is taken hundred times. More formally a hash chain with 100 tokens is constructed in the following way.

…

is the first token to use. Then we use the token in the increasing order of token index. In this way, we exploit one-way property of hash algorithms such that an attacker cannot learn the next token even if she knows the previous ones.

Connection Cards are refillable with hash tokens, which are to be sold by the TTP. Operators compete with each other to provide high-quality service for broadband access in the WMN since the users are assumed to have free roaming.

Serial Number is a 128-bit value. With this setting, the system is able to support up to users. Hash tokens are to be generated using SHA-256 hash algorithm; hence they are 256-bit long.

Considering current technology, smart cards are suitable tools to be connection cards. A simple Connection Card with 4 KB memory could store a and approximately 1000 hash tokens.

# Alias Computation

Aliases are temporary identifiers for clients. They change frequently using a secure protocol. Untraceability is achieved by changing aliases by the previously stated way however it is only durable to some extent.

The serial number () of the Connection Card, which is bought from an operator, will be used as a base for client’s aliases. An alias will be computed by performing the following operations:

1. Client will pick a random 128-bit unsigned number and call it her .
2. Perform XOR operation with and her nonce; take the hash of the output.
3. Client will use this alias whenever her identity is required.

Aliases are 128-bit values; even if it is a very small possibility to have the same alias with another client at a given point of time, there is still a nonzero probability. To address this problem, TTP checks the proposed alias to be a unique one. This check is done in *Change Alias* protocol.

The nonce values used in computation of the aliases are to be sent in encrypted messages to the TTP in the related protocol. Therefore only the client and the TTP can relate the aliases originated from a particular .

# Anonymized Hash Chains

Clients change their aliases periodically to make their actions unlikable to their aliases. However, an adversary could trace a client’s actions by tracing the link between the hash tokens of the client.

To provide full untraceability in the system, clients form up anonymized subhash chains. The client and the TTP guesses the amount of the hash tokens that will be used in the next session. The Change Alias Interval () and Hash Token Renewal Interval () determine the Length of Anonymized Subhash Chains () as following:

The generation of the anonymized subhash chains is depicted in Figure 6.1.



Figure 6.1. Generation of Anonymized Subhash Chains

Before any authentication or changing alias phase the client sends the first hash token of the remaining hash chain (In Figure 6.1 the first hash token is H0). TTP knows the value of the client. TTP and the client are able to form the anonymized subhash chain simultaneously. When the client sends the first hash token of the remaining hash chain to the TTP, TTP counts backwards from the received hash token times. Computes the corresponding anonymized hash token and takes the hash of the output times. These operations form up an anonymized subhash chain and the anonymized hash tokens are spent in reverse order.

In a case of a disconnection or connection drop before spending all the hash tokens in the anonymized subhash chain, client stores the index of the last used hash token index. For the next connection request the client sends the first hash token in the remaining hash chain to the TTP. For the new session, both the client and the TTP generate a new anonymized subhash chain.

In a mobility situation, clients transfer the next anonymized hash token to the new access point. The clients start to get service from the new access point when the transfer is finished.

An adversary could not relate two different anonymized subhash chains since using the hash output of XOR of a hash token and a random nonce value generates the hash chains. Every time a new anonymized subhash chain is generated a different nonce value is used. The hash operation on the seed of the anonymized subhash chain prevents any relation between different anonymized subhash chains. A demonstration of this scheme is as follows:

On the previous example it is infeasible to find the input by using or . Therefore, an adversary could not discover any hash token in the original hash chain by exploiting anonymized subhash chain because of the irreversibility property of hash algorithms. Moreover, and could not be related in feasible time. Therefore, usage of anonymized subhash chains provides complete unlinkability between different sessions.

# Protocols of the System

In this section, we will explain the protocols of the system. There are 10 protocols in the system. End-to-end Two-way protocols consist of Initial Authorization and *Reuse of a Connection Card*, *Disconnection* and *Change Alias* protocols. Initial Authorization and *Reuse of a Connection Card* protocols are executed each time a client connects to the system. These protocols are not necessary for ongoing connections. *Change Alias* protocol exists to provide untraceability to some extent. Clients’ actions could not be related to previous sessions when they execute *Change Alias* protocol. *Disconnection* protocol is necessary for operators to collect their money from the TTP. *Disconnection* protocol marks the end of the provided service. End-to-end Two-way protocols send packets from clients to the TTP and return the packets back to clients. *Update Packets* protocol is an End-to-end One-way protocol, which sends packets from clients to the TTP. *Update Packets* protocol ensures the stability of the system and prevents any inconvenience in a case of connection interruption. Other protocols i.e. *Seamless Mobility*, *Seamless Roaming*, *Packet Transfer* and *Access Point Authentication* are independent protocols and do not belong to any group. *Seamless Mobility* and *Seamless Roaming* protocols are executed in mobility situations of the clients. *Distribution of Access Point Public Keys* protocol is performed for distributing the signed public keys of the access points. This protocol is not implemented in the simulations and it is assumed to occur before the system deployment.

## Initial Authorization and Reuse of a Connection Card

Initial Authorization is the beginning for system usage. Whenever a client purchases new hash tokens from the TTP, she will need to authorize herself to TTP. Initial Authorization Protocol, shown in Figure 7.1, achieves mutual authentication and authorization of the user.

The clients may disconnect before using up all the credits in a connection card. *Reuse of a Connection Card* (*Reuse-CC*) protocol allows the clients to connect using the remaining credits in a card. *Reuse-CC* protocol does not differ extensively from *Initial Authorization* protocol. The main difference is instead of sending first hash token; the client sends whichever token is the next one. Alias will change before the protocol starts. Both protocols compute new aliases before sending the Connection Requests (). The crucial point here is that TTP should be able to update last hash value entry of the client in the database and associate it with the new alias.

The access point is a member of a mesh backbone and a particular access point is to be selected according to its transmission power. Since it is assumed that all access points have the same attributes, the serving access point is the closest access point to the client.

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Figure 7.1. Initial Authorization and Reuse-CC

Mobile clients introduce themselves to the operator using *Initial Authorization* protocol. in *Initial Authorization* protocol, in *Reuse of a Connection Card* protocol. TTP already knows mobile user’s serial number () and the first element, , of her hash chain. The mobile user does not want to reveal her to any adversary because that will be used all the time and it is sensitive information from security and privacy points of view. To achieve anonymity, the mobile client computes an alias and uses this value instead of . The mobile client will change her alias periodically as she continues to get service (*Change Alias* protocol will be explained later).

*Initial Authorization* and *Reuse-CC* steps are described below.

1. Client computes an alias using a nonce that she generated.
2. (The is assumed to have credits)
3. Client sends this to .
4. Client starts to generate an anonymized subhash chain as the network processes client’s .
5. receives the connection request and relays the request through mesh backbone.
6. Gateway receives the and relays it to the operator.
7. Operator relays to TTP.
8. TTP receives the connection request () and decrypts it using its private key.
9. TTP checks alias' uniqueness within its database of users, it would make the client start over the protocol if alias is not unique.
10. It computes .
11. TTP checks and association. Store and
12. TTP computes
13. TTP generates anonymized subhash chain by taking the hash of times. The output of the last hash operation gives the first token of the anonymized subhash chain, which is .
14. TTP computes
15. TTP sends to the Operator.
16. Operator receives and verifies the signature using public key of TTP.
17. Operator sends to the gateway.
18. The Operator gets and and stores these values.
19. GW receives and verifies the signature using public key of TTP.
20. GW uses the shared secret key with and calculates
21. GW sends to the .
22. GW verifies the signature of TTP.
23. GW stores and .
24. receives and decrypts it using the shared secret key with GW.
    1. verifies the signature using public key of TTP.
    2. It calculates and and stores these values.

The wired links are secured however the medium between GW and APs are insecure; therefore, the packets that are sent through this medium are encrypted with shared secret keys between GWs and APs.

## Access Point Authentication

After authentication processes of the client with the TTP, a second authentication step begins. Client and access point will mutually authenticate each other for safe communication; this protocol ensures the feature -Mutual Authentication- of SSPayWMN.

Figure 7.2, describes the protocol briefly.

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Figure 7.2. Access Point Authentication

1. sends a challenge request to the client, which started connection.
2. When client receives this challenge request:
   1. Client drops the packet if it is not the that she sent connection request.
   2. Client drops the packet if there was not any .

If (a) and (b) are 3 invalid then the client sends a 128-bit challenge to the .

1. takes the HMAC of this challenge, and uses relevant anonymized subhash token as the key of HMAC.

   2. sends to the client.
2. Client also takes the HMAC of the challenge and uses the stored anonymized subhash token as the key. Then it compares the result with the one that access point sent.
   1. If it is authenticated, client starts to use access point to get Internet service.

## Packet Transfer

After mutual authentication of client and , the client starts to send data packets as shown in Figure 7.3. These packets represent the Internet usage of the client. Client could send as many packets as she wants in the period of time, which is bought by a hash token. In this protocol the usage of hash tokens and data packets are explained.

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Figure 7.3. Packet Transfer

1. Client starts the session with the first anonymized hash token (in this case current has value is ) of the remaining hash chain.
2. receives , and updates client’s service starting time.
   1. Checks if
   2. If true sends acknowledgement () to client and updates currently used hash value as .
3. Client sends first 512-byte data packet .
4. If the client gets served for over the threshold value (5 minute interval is used in simulations) then the AP asks for the next hash token.

The steps between (1) and (4) are repeated as long as client gets Internet service.

## Changing Alias

Anonymity property is achieved by using aliases, but complicated part is achieving untraceability. The aliases should change on a basis that an adversary, who knows a certain client’s alias, could not be able to trace client’s activity on her home network, and also could not trace her movements among the operators or access points. Clients generate anonymized subhash chains to break the correlation between the hash tokens that they receive service with. Clients do not fully trust to the operator and it’s access points and assume that the access points could store the hash tokens and correlate the hash tokens of different sessions.

To be able to change alias in a safe way, client needs to communicate with TTP but interrupting TTP very often would slow down the entire operation due to extra delays. Therefore periodic changes of aliases are mandatory and these changes are achieved by making access points to ask all of the active clients for new aliases after a certain period of time. Attackers or access points themselves would know that aliases are changed but would not know the mapping between old aliases and the new ones. Such a protocol is also used in Mix Networks.

Simultaneous alias changes aim to prevent attacks that would aim to analyze network traffic of access points and examine connection requests. Enforcing alias change by the access points, a more generalized control over the clients is achieved. Attackers could not understand which client wanted to change her alias, because all the clients getting service from a particular access point have requested to change their aliases at that particular time.

The client should request changing alias, because client and the TTP should be the only parties who know association between an alias and a client’s SN.

is a local timer that runs on every Access Point. All of the timers are set roughly to the same time manually. System designer decides on the time value on which the access point will count down from (50 minutes of time period is used in simulations). The timer period is updateable by the TTP. TTP knows every access points’ public key, it could send new interval by encrypting the new value with the public keys of the access points. However, this process is not covered in simulations.

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Figure 7.4. Changing Alias

Changing Alias Protocol is shown in Figure 7.4 and described below.

1. Client continues to get service, in other words uses the *Packet Transfer* protocol.

When the countdown finishes, Access Points broadcast "Change Alias" command to all of their clients. The interval value is a system parameter; 50 minutes of interval value is used in the simulations.

1. Client receives "Change Alias" command.
2. Client computes a new alias by picking up a new random nonce and computes .
3. Client forms a Change Alias Request ()
4. The client sends the to .
5. Client generates a new anonymized subhash chain as the TTP processes the connection request of the client.
6. receives and relays it to the GW via mesh backbone.
7. Gateway forwards to operator.
8. Operator forwards to TTP.
9. TTP receives Change Alias Request () and decrypts it using its private key.
10. TTP checks for new alias' uniqueness and starts over the protocol if not unique.
11. TTP computes .
12. TTP computes
13. TTP generates anonymized subhash chain by taking the hash of , times. The output of the last hash operation gives the first token of the anonymized subhash chain, which is .
14. It checks SN and association and stores and .
15. It computes .
16. TTP sends to operator.
17. Operator receives .
18. Operator sends to the GW.
19. The operator computes and and stores these values.
20. GW receives .
21. The GW encrypts the and calculates
22. GW sends to the .
23. The GW calculates and , and stores these values.
24. receives and decrypts it as follows:
25. The verifies the signature using public key of TTP.

The reveals and and stores these values.

## Update Packets

In standard flow of the system, after authentication, access points handle the accounting. Because of the fact that access points keep the last alias and token of the client they are able to validate next token by performing hash operation to the token they kept and compare it with new coming hash token. However it is essential to send periodic updates to the TTP to provide stability in the system in the case of client drops.

Access points keep track of ongoing communications, after some time passed without update from a user it send disconnection request by itself. When access points broadcast change alias commands they delete all the record related to previous connections therefore they do not send unnecessary disconnection packets to TTP.

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Figure 7.5. Update Packets

Protocol design of Update Packets protocol is shown in Figure 7.5 and the details of the protocol are explained below.

1. After client sends the first anonymized subhash token, the access point starts to count the time passed. After units of time (value of is a system parameter, 1 minutes of an time interval is used in simulations), access point encrypts the Alias and lastly used hash token using the public key of the TTP and sends this cipher text to the GW.
2. The GW receives the update packet and forwards it to TTP through related operator.
3. TTP receives the update packet and decrypts the packet using its private key. TTP updates the last token used by the client.

In a case of client drops from the network, access point concatenates the Alias, hash value and a time stamp and encrypts them with the public key of TTP. Sends it to TTP as a disconnection request from the client.

## Disconnection

To be able to run Reuse-CC, the client has to run a proper disconnection protocol. The Update Packets protocol brings stability to the system in case of a connection interruption, but the main assumption is that most of the users will be disconnecting from the operator using the *Disconnection* protocol that we explain in this section and in Figure 7.6.

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Figure 7.6. Disconnection

Disconnection protocol is described below.

1. Client forms a disconnection request

* Client sends the packet to the .

1. relays to the mesh backbone, to make it reach to the GW.
2. GW receives and forwards the to the Operator.
3. Operator receives and forwards the to the TTP.
4. TTP receives the .

* TTP calculates SN and checks the relevancy between SN and .
* TTP computes the Alias, similar with the previous end-to-end two-way protocols.
* TTP computes
* TTP sends the to the Operator.

1. Operator receives .

* Operator relays to GW.
* Operator verifies the signature and marks client as disconnected.

1. GW receives .

* It relays to the mesh backbone.
* GW verifies the signature and marks client as disconnected.

eventually gets the , verifies the signature on it and disconnects the particular client, which corresponds to the it received. Ideally access points are assumed to delete all information about the past connections for the sake of freeing memory space. However if operators decide to trace user’s actions then they could do so for a limited time until the client changes it’s .

## Distributing Access Point Public Keys

Achieving seamless mobility in home operator and also to support seamless roaming, a public key distribution mechanism is integrated in SSPayWMN system.

In Figure 7.7, a generic model for public key distribution is shown. This protocol has two parts; one is certificate generation for access point public keys, the other one is distribution of the public keys. The part between operator and the TTP is offline. This part of the protocol runs during set-up, before the deployment of the access points in the field.

If an operator wants to add a new access points to the metropolitan area then it should perform the same protocol but his time only for the new access points.

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Figure 7.7. Distributing Access Point Public Keys

Distributing Access Point Public Keys algorithm is described below.

1. Operator generates public/private key pairs for the access points in its mesh backbone and embeds these keys to them before the deployment.

* Operator forms an access point list (); which consists of access points and their corresponding public keys.
* Operator sends this list to the TTP through a secure channel or in offline manner.

1. TTP receives the and starts to generate certificates for every access point and public key pair.

* Certificates are formed as:
* TTP stores these certificates for distribution.
* Other protocols are employed (such as *Initial Authorization* or *Reuse-CC* protocols) of SSPayWMN for certificate distribution. Suppose an AP does not possess its certificate. In such a case whenever this access point gets a connection request it will concatenate a certificate request to the packet. When the TTP receives such a request, it concatenates corresponding certificate to the connection response. Then, TTP sends the connection response and together to the operator.

1. Operator receives the connection response and the certificate and relays these packets to the access point through gateway and mesh backbone.

Access point receives and stores its certificate and broadcasts it to the nearby access points.

## Seamless Roaming (Payment Related)

*Seamless Roaming* is run whenever the client changes the serving access point with a new one, and start to get service in a different operator’s network.

Public Key Cryptography enables us to handle seamless roaming without performing the authentication process from scratch. As it is shown in Figure 7.8, client gets a signed roaming ticket from its old access point and uses this signed ticket to maintain to get Internet service from a new access point. In parallel the old access point sends a disconnection request to it’s operator for the client.

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Figure 7.8. Seamless Roaming

*Seamless Roaming* protocol is described below. In this protocol, the client would like to switch from its old operator () to a new one (). In this setting, is the last access point that the client gets services from . , is the access point that the client would like to continue to get services in network.

1. Client sends a () to .
2. receives and forms a Roaming Acknowledgement ().

* sends to the client.
* consists of the roaming ticket that the client uses to get services from the .

1. starts the disconnection protocol for the client after sending the .

* This disconnection protocol runs in parallel with the roaming protocol. Thus it does not put an extra delay in roaming. Old operator () stores disconnection acknowledgement () to support its claim to get funds for the services that it provided until roaming occurs. TTP stores the information that this disconnection is due to a roaming to in order not to get confused when disconnects without a connection request reached to it.
* In this scheme, ’s signed ticket serves as a formal document, which represents the beginning of the session with .

1. Client receives and forwards it to the new operator ().

decrypts using its private key. The rest of this step is the same with (4) of *Seamless Mobility* protocol.

## Seamless Mobility in Home Operator (Payment Related)

*Seamless Mobility* is run whenever the client performs a handover between two access points of her home operator.

Every access point has its public/private key pair and ability to broadcast it’s public key, handoff in home operator could be handled in a seamless way. As it is shown in Figure 7.9, client gets a signed handover ticket from its old access point and uses this signed ticket to maintain to get the Internet service from a new access point.

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Figure 7.9. Seamless Mobility in Home Operator

Seamless Mobility protocol is described below. In this setting, is the last access point that the client gets service. , is the access point that the client would like to continue to get service.

1. Client sends a Mobility Request () to .
2. receives and forms a Request Acknowledgement ().

* sends to the client.
* consists of the mobility ticket that the client uses to get services from the . It is signed by and encrypted for .

1. Client receives and forwards it to the new access point ().
2. decrypts using its private key.

* reveals the signed ticket of the . sends this signed data to it’s affiliated operator to use it for collecting funds from TTP.
* verifies the signature over this signed ticket using ’s public key. Then, it checks in order to decide whether the ticket has expired or not.
* Then, starts a challenge-response protocol with the client.

The rest of this protocol is the same as *Access Point Authentication* protocol.

# Payment to the Operators (Settlement)

In our system, operators claim their money from the TTP, as they show their service logs. A log proves a service that has been provided between a connection request and a disconnection request.

Operators store CRs of the clients; we described CRsin Initial Authorization and Reuse of a Connection Card protocols. When a client makes a disconnection request, operator stores the disconnection request as well. After receiving the DR, operator forms its log as follows.

Where TS stands for timestamp. We make operators to add timestamps to make TTP’s job easier.

Let’s look at what is going to happen when TTP receives these two logs from an operator.

1. TTP will sort the logs according to their TS value; this sorting process would ease the operation.
2. TTP first processes CR. CR is a request; which is encrypted with the public key of TTP. CR consists of Alias, nonce and the first hash token to be used to get service.

Consider

TTP decrypts it using its private key, and gets SN by the XOR operation:

Note that SN’s first token used is Hf.

1. TTP decrypts the Signed Connection Response using its public key, and gets the alias and the hash token. TTP compares the values with the ones in connection request. If they match,then it is a valid log.
2. The abovementioned log is only a service starter; operator needs to show service ending log to claim its money from the TTP.

Service ending log naturally has a larger TS value; that is why that log comes later in the sorted list of logs.

TTP takes the ending log and decrypts DR using its private key.

TTP gets Alias, nonce and hash token from the decrypted DR. TTP makes theXOR operation: and gets the SN. Note that SN used is the hash token came with the DR to end the service.

1. TTP takes the Signed Disconnection Response and decrypts it using its public key. TTP gets the alias and the hash token from it, and compares the values with the ones came with the DR. If the values match, TTP considers the log as a valid service ending log.
2. After validating the logs, TTP performs the hash operation over service ending hash token until it reaches the service starter hash token. TTP counts these hash operations. This count is mapped to funds for the provided service.

We need to consider misuse of logs by the operators. Consider the situation of a client:

* Gets service from his home operator between H0 and H10
* Gets service from a foreign operator between H11 and H20
* Gets service from his home operator between H21 and H30

In this type of situation home operator has two CRs and DRs.Whereas foreign operator has a CR and DR. Let’s look at the look at the logs of home operator:

We see that home operator served between H0 and H10 also served between H21 and H30. Home operator would want to take money for serving between H11 and H20. It could pretend that it has served the client between H11 and H20 by not sending Log2 and Log3. Because Log2 indicates that client is disconnected from the operator at H10 and Log3 indicates that Client started to get service from the operator at H21. By sending only Log1 and Log4 home operator tells TTP that it served the client between H0 and H30. Operator would want money for serving 30 hash tokens.

In that kind of situations there should be a foreign operator which has served between H11 and H20. Foreign operator would have two logs as follows.

Foreign operator proves that it has served between H11 and H20 by showing the signed RP and DA.

TTP would see that it has already paid home operator for service to that particular client between H11 and H20. This means that home operator tricked TTP to pay more.

In our system TTP is the one who has the authority, it pays operators their money. If it finds an operator misbehaving it could give a penalty to the operator and do not pay for future services, or there could be several other kinds of penalties, since TTP has the proof it could bring the subject to the court as well.

# Conclusion

In this section, we discuss which of the requirements are met.

The requirements for a secure and seamless pre-payment scheme were discussed. In this section the success of the proposed system on meeting the requirements and simulation results are discussed.

#### Wide Coverage

The main strong side of WMNs is economical wide network coverage. This objective was important since the proposed system intends to serve high amount of users within a large metropolitan area. To test SSPayWMN’s success on providing network service within a wide area, we have used ns-3. In our simulations all of the mesh routers cover an circular area of 100 meters of radius. In our simulations 1 km2 area is covered. The size of the area could be widened with more access points.

#### Seamless Mobility and Roaming

Seamless Mobility and Roaming property of the system describes the ability of the users to handover between access point without experiencing a noticeable delay. To provide seamless mobility and roaming, we have implemented *Seamless Mobility* and *Seamless Roaming* protocols. These protocols transfer the current hash token of the client to another access point. The client does not stop getting service from the old access point until these protocols are finished. Whenever these protocols finish their process, client starts to get service from the new access point. Usage of these protocols prevents clients to wait for another authentication and disconnection processes.

#### Anonymity

This property of the system is required to keep the clients anonymous; therefore, this property prevents any adversary to compromise a client’s real identity or any other sensitive information. To provide anonymity, SSPayWMN employs aliases. Only TTP and the client herself could relate the aliases to client’s identity. We have computed the aliases using a hash function over an output of XOR operation on SN and a random Nonce. In this way SN remains a secret because of the irreversibility property of the hash functions. For law-enforcement reasons, users must give their identities to Trusted Third Party (TTP) for getting connection cards. Therefore, as far as TTPkeeps clients’ identities secret, users can remain anonymous.

#### Untraceability

As mentioned earlier, our system employs aliases to provide anonymity. However, in case of an adversary compromises the client’s alias, the adversary could trace all the actions of that client. Untraceability is achieved in two steps: the first one is untraceability of client aliases; the second one is the untraceability of client’s hash tokens. The first part of is achieved by forcing the clients to change their aliases periodically. Our way of alias generation prevents any relation between sessions of the clients. The second part of untraceability is achieved by usage of anonymized subhash chains. These hash chains have limited amount of hash tokens that are enough for a client until the next change alias round. Every time a client changes her alias she becomes unlinkable with previous sessions. SSPayWMN supports untraceability to some extent, which is a significant contribution for prepayment systems on WMNs.

#### Mutual Authentication

This property is required to provide security of the client and prevent an adversary to mimic an access point. Furthermore, this property is necessary to prevent an adversary to mimic a valid client. Mutual Authentication has two steps: the first one is the client’s authentication and the second one is the network’s authentication. The network authenticates clients in *Initial Authorization* and *Reuse-CC* protocols. Clients send their SN and corresponding hash tokens to get authenticated. In the system, the client and the TTP are the only parties who know these values. Therefore, when client provides these values, she authenticates herself. On the other hand, in *Access Point Authentication* protocol access point also proves that it knows the current hash token of the client. Since, hash functions are irreversible, no one but the owner of the hash chain could not know the current hash token by looking at the previous ones. *Access Point Authentication* protocol provides the second part of the mutual authentication property.

#### Two-way honesty

This property means that in SSPayWMN, it not possible for clients to con operators; whereas, it is not possible for operators to overcharge clients. In SSPayWMN, we addressed this objective by using hash tokens as e-currency. Because of the irreversibility property of hash algorithms it not feasible to find the next hash token by using the previous hash tokens. In case of a denial of a provided service by the client, operators could show the logs of the provided network service with the corresponding hash token. Therefore, it is not possible for a client to deny provided network service. On the other hand, operators could not overcharge their clients because an operator could not know the next hash token in the hash chain by exploiting the previous hash tokens.

#### Performance

The performance of SSPayWMN has been evaluated with simulations using ns-3. Two groups of simulations are performed: unit tests and real-life scenario simulations. Unit tests ensured the stable performance of the protocols in stand-alone run; whereas, real-life scenario simulations ensured the stable system performance in real-life situations. We have conducted real-life scenario simulations for different clients counts: 100, 300 and 500. We have compared the protocol performances considering the change in clients count. The difference between the average delay values of different real-life simulations showed that with increasing number of clients SSPayWMN protocols show higher network delays. However, the increase is linear; therefore, SSPayWMN ensures stable performance in different sized networks.

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