secure and seamless payment for wıreless mesh networks

by  
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SECURE AND SEAMLESS PAYMENT FOR WIRELESS MESH NETWORKS

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DATE OF APPROVAL ........................................

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Abstract

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 works for broadband access usually trust operators fully, 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. Our requirements are to be studied under two categories. One of them is network requirements and the other one is cryptographic requirements. They are briefly explained in following sections.

KABLOSUZ ÖRGÜ AĞLARI İÇİN GÜVENLİ VE KESİNTİSİZ ÖN ÖDEMELİ MİKROÖDEME

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Anahtar Kelimeler: Ön Ödemeli Sistemler, Güvenlik, Mikro Ödeme, Kablosuz Örgü Ağlar

Özet

Kablosuz Örgü Ağları (KÖA) çok sekmeli, erişimin her yerden sağlanabildiği, yüksek hızlı ve gelişmekte olan bir ağ teknolojisidir. Kablosuz Örgü Ağları ağ yapısında esneklik sağlar ve kendiliğinden kurulabilen dinamik bir yapısı vardır. Bu ağlardaki elemanlar rota tabloları oluşturabilirler ve yüksek hızda iletişim sağlayabilirler. Kablosuz Örgü Ağları kurulması kolay sistemlerdir ve ekstra yükleri azdır.

Bizim KÖA sistemimizde mobil halde kullanıcılar ve verdikleri hizmete göre ücret talep eden operatörler var. Varsayımımıza göre birden fazla operatör olacak ve kullanıcılar istedikleri operatörlerden hizmet almakta özgür olacaklar. Operatör değişikliği olduğu durumlarda servis kesintisiz şekilde devam edecek ve kullanıcı operatör değiştirdiğinin bile farkına varmayacak. Bu alanda yapılan diğer çalışmalar genel olarak operatörlere sonsuz güven ilkesine dayanarak tasarlanmıştır. SSPayWMN projesinde biz operatörlere mutlak güven ilkesini benimsemedik ve sistemimizi bu doğrultuda kurduk. Bunun nedeni operatörlerin istem dışı ücret almalarını engellemek. SSPayWMN sisteminde bir kullanıcı parasını ödemediği hiç bir hizmeti alamaz aynı zamanda kimse kullanıcının almadığı hizmetin parasını da alamaz. Bu proje operatör için de kullanıcı için de isteklerin kriptografik yollarla ispatlanmasına olanak tanıyor.

SSPayWMN projesinde amacımız hem operatörler hem de kullanıcılar için adil bir sistem kurmatı. Kriptografik araçlar ve algoritmalar kullanarak bütün ağ elemanları kullandıkları servisi ve ödedikleri ücerti ispatlayabilme şansına sahipler. Kurduğumuz sistemin güvenli ve hızlı olduğunu bu dökümanda anlatıyoruz ve efektif çalıştığını görebilmek için network simulasyonı sonuçlarını da paylaşıyoruz. Bu sayede gerçek hayattaki uygulamaya çok yakın sonuçlar elde etmiş oluyoruz.

Sistemimizi ana gerekliliklere göre kurduk. Bu gereklilikler iki dalda incelenebilir. Bu alanlar ağ gereklilikleri ve kriptografik gereklilikler. Bu dallar dökümanın ilerleyen sayfalarında açıklanacaklar.

*To my dear family*

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# INTRODUCTION

Wireless Mesh Networking (WMN) is multi-hop wireless networking technology to provide broadband ubiquitous access in metropolitan area. WMN provides flexible service like ad hoc networks, and supports this flexibility with the centralized structure of Wi-Fi. With the assistance of wireless mesh routers, WMNs are easily established. Moreover, WMNs provide high connection speeds with manageable overhead.

In this project, a secure prepaid payment scheme for broadband Internet access will be designed and developed in a simulation environment. This scheme will be particularly for Wireless Mesh Networks with multiple operators. The users in this system will be able to switch among several operators without needing to re-authenticate themselves.

## Contribution of the Thesis

Authentication, confidentiality, non-repudiation, fraud protection will be provided in our system. The users will not be able to deny using credits for the services actually obtained; the operator will not be able to charge more than the usage amount. Moreover, inter-operator settlement will be performed in a secure way such that each operator will have cryptographic proofs of use for the services that they provide to other operators' customers. In order to provide privacy of individuals, our scheme will provide untraceability such that no unauthorized entity will be able to track down a particular user.

Since the clients are mobile, they may hand over among different mesh routers (i.e. access points) of the same operators. They may also roam among different operators, not only due to coverage reasons, but also for having a better quality service. Our system aims to have seamless mobility and seamless roaming for payment purposes such that when the client gets service through a new AP or switch to another operator, authentication and authorization are not performed from scratch.

From security point of view, we aim to have mutual authentication between client and the network in our protocols. Anonymity of the clients and untraceability across different usage periods (a.k.a. unlinkability) are privacy related goals of the protocols.

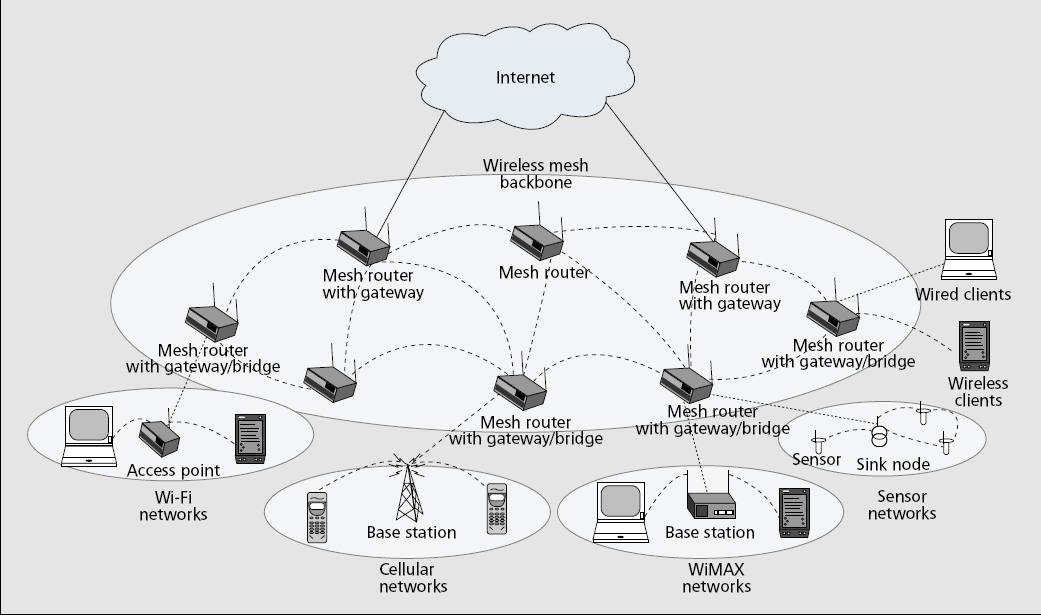
From payment point of view, our main aim is to have a fair system in which all the claimed transactions bear cryptographic proofs. In this way, the clients cannot repudiate using a service and the operators cannot claim for services that they do not provide. The latter is especially important during inter-operator settlement; it is also important to resolve client disputes.

## Organization of the Thesis

The organization of the thesis is as follows…

# Background on wireless mesh networks

Wireless Mesh Network (WMN) is multi-hop wireless networking type, designed as an alternative to traditional centralized wireless networking achieved by access points. WMNs offer flexibility and easy deployment since nodes in the network form neighborhood dynamically. Wireless mesh routers enables WMN to provide broadband access and connectivity within the network. WMNs achieve high connection speeds with reasonable delays. See Figure 1 for a sample WMN infrastructure.



Wireless Mesh Networks are a special kind of ad hoc networks. The main idea is the same, which is to provide connectivity from every node of the network without using a central node. Mesh routers do not need any access point to talk with each other they only need to be close enough. Neighborhood relationships and routing tables are formed dynamically at the setup phase of the network and even if the topology changes during the run mesh routers could adapt to new structure and form neighborhood information once again.

## 2.1 Components of WMN

There are three kinds of WMNs; they differ according to functionality of their nodes. We will briefly explain these three kinds as following.

**Infrastructural Backbone**: Figure shows the infrastructural backbone, where dash and solid lines represent wireless and wired connectivity respectively. This kind of WMN consists of mesh routers, forming up a mesh backbone to enable clients to connect to them. Internet service is provided by special mesh elements called gateways. Gateways are located within mesh backbone but they do not interfere to routing protocols or relay any packets. They are always source or the destination of the packets.

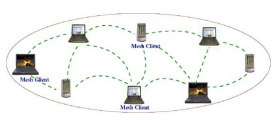
Infrastructural backbone enables clients to connect to mesh network using conventional wireless or wired technology. Mesh routers in the bakbone has bridging capabilities so it is possible to connect to these routers using Wi-Fi, WiMAX or wired networks.

This WMN type is the most commonly used one and we will be using this type in our proposed scheme as well.

Infrastructural mesh networking is useful for community and neighborhood networks. Mesh routers could be placed at the top of the buildings and provide broadband access to any client passes by or stays at these buildings.

**Client WMNs:** This kind of WMN enables peer-to-peer connection between client nodes. It is more likely an adhoc network. In this architecture clients form up the network, handling all the relaying and routing. They also provide end user applications to the customers, so there is no need for mesh routers in this structure.

A client sends a packet through a route and that packet is hopped by any intermediate node to reach to destination. The Figure shows the client WMN architecture.



**Hybrid WMNs:** As its name states this kind of architecture is a mix of the first two architectures. The Figure shows the general structure. In this networking style, a client WMN could connect to a infrastructural mesh backbone via wireless or wired communication. The infrastructural part provides broadband access to any kind of network, whereas client WMN provides adhoc communication to local clients.

## 2.2 Characteristics

The characteristics are explained as follows:

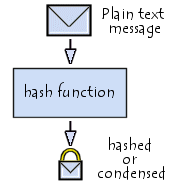
* **Multi-hop Wireless Network:** The main goal to deploy wireless mesh networks is to extend the coverage of any given network. It is available to extend the connectivity without establishing new base stations or sacrificing the channel capacity.
* **Support for Adhoc Networking:** Adhoc networking provides self-forming, self-healing and self-organization. It is fairly easy to deploy such a network.
* **Mobility:** Mesh routers do not have mobility usually, whereas clients could be mobile or stationary depending on the scenario.
* **Bridging:** Mesh networks provide service for other types of networks, it is possible to connect a Wi-Fi network to the backbone or it is even possible to connect with backbone using an Ethernet cable.

# Background on Cryptographic functions

We will give brief information for cryptographic functions. In 3.1 we will explain hash functions. In 3.2 we will describe hash chain which we have used as tokens for prepaid internet service. 3.3 will give details of message authentication code, which is also known as HMAC. 3.4 about symmetric encryption and 3.5 will give detailed information about public key cryptography.

## 3.1 Hash Functions

Hash functions are irreversible mathematical functions that generate an alphanumerical value given an input block.

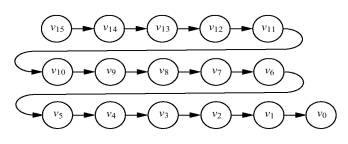


<http://en.kioskea.net/contents/crypto/signature.php3>

* Hash functions may take various sized inputs but their output length is fixed.
* Hash functions are completed in a fairly small amount of time, which makes them very eligible for security systems.
* It is fairly easy to generate a hash output but it is infeasible to find the input by only knowing the output. That feature is called irreversibleness of hash functions.
* Different inputs may generate the same output but it is infeasible to find an alternative input by only knowing a sample input. That feature is called strong collision resistance.

## 3.2 Hash Chains

Hash chains are formed by applying a hash algorithm to an initial value and using the output as an input for following hash functions. Length of the hash chain is determined by the number of times the hash algorithm is run.



<http://www.stanford.edu/class/cs259/WWW04/projects/project01/01%20-%20writeup.html>

Since hash functions are irreversible, it is easy to go forward in the chain but it is not computationally feasible to go backwards. Which means a person could find any value on the chain if he knows the initial value but this situation is not possible for a person who knows the last value on the chain.

Hash chains are formed using a hash algorithm to a result of hash algorithm several times. Each output becomes a member of the hash chain and in systems that use hash chains they chain members are used in reverse order, meaning that the last output is the first one to be used.

Hash chain with 3 elements is denoted as:

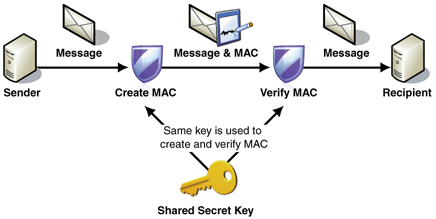
More generally, hash chain with *n* elements is denoted as:

n

One-wayness of the hash chains makes these values to be used as prepaid service tokens since it is not feasible to find the next token by knowing the previous one but it is easy to confirm next token by looking at the previous one.

Hash chains are easy and fast to compute that’s why they are widely used in cryptographic systems. Especially in SSPayWMN, we have a delicacy for delay. We cannot afford big delays for computations so hash chains are the perfect tools for us to use in our system.

## 3.3 HMAC



<http://msdn.microsoft.com/en-us/library/ff648434.aspx>

Message Authentication Codes (MACs) are used for authentication purposes. A shared secret key is used for MAC functions and this secret key authenticates two entities to each other.

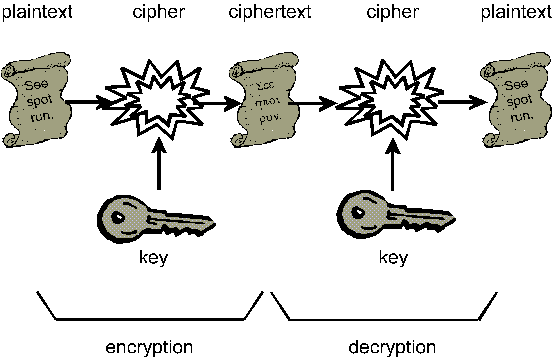
As it is explained in <http://tools.ietf.org/html/rfc2104>.

*HMAC* (*K*,*m*) = *H* ((*K* ⊕ *opad*) ∥ *H* ((*K* ⊕ *ipad*) ∥ *m*))

Where

* *H* is a cryptographic hash function,
* *K* is a secret key padded to the right with extra zeros to the input block size of the hash function, or the hash of the original key if it's longer than that block size,
* *m* is the message to be authenticated,
* ∥ denotes concatenation,
* ⊕ denotes exclusive or (XOR),
* *opad* is the outer padding (0x5c5c5c…5c5c, one-block-long hexadecimal constant),
* and *ipad* is the inner padding (0x363636…3636, one-block-long hexadecimal constant).

## 3.4 Symmetric Cryptography



<http://www.unicom.com/pw/pubnetinfosec/>

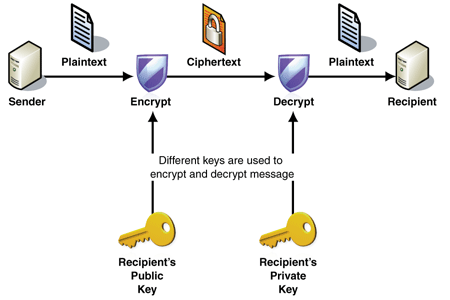
Symmetric cryptography is one of the most important ways to achieve security in science of cryptography. It requires two parties that are agreed on a single secret key. Key size depends on the algorithm but it is preferred that it should be at least 128 bits long.

In this context a party uses its secret key to encrypt a plain text message and sends it to the other party. Considering the environment the link between the two parties is assumed to be insecure. Since the message is encrypted an eavesdropper could not decrypt the message and cannot understand what it is about even if he was successful to acquire the message.

When the second party receives the message he will use the same secret key on the received cipher text. Only then the message will be able to be read.

Symmetric cryptography is the oldest way of cryptography and there are a lot of algorithms to achieve symmetric cryptography. Most recent and secure ones are AES, 3DES, Blowfish …etc.

## 3.5 Public Key Cryptography



<http://msdn.microsoft.com/en-us/library/ff647097.aspx>

Public Key Cryptography (PKC) is the mostly used cryptographic tool in this project. It is vitally important for this project to achieve authentication and confidentiality.

In PKC there are two types of keys. First of them is public key the other one is private key. These two keys are computationally related. Public key is accessible by everybody in the system whereas the private key is only known to its owner.

There are two ways to use PKC. The first one is using public key for encryption and private key for decryption. This scheme provides confidentiality.

* Sender uses recipient’s public key over a plaintext for encryption. The output is a cipher text.
* Sender sends the cipher text to the recipient.
* Recipient receives the cipher text and uses his private key to decrypt the message. The output is plain text.

An eavesdropper, who has managed to acquire the cipher text, could not understand the content of the cipher because he does not know the private key of the recipient.

The other way to use PKC is using private key for digital signature. In this scenario:

* Sender uses his own private key to sign a plain text.
* Sender sends the signed message to recipient.
* Recipient uses sender’s public key to verify the signature on the message and if the operation is successful than it means the message came from the signer indeed. Because no one in the system is able to generate that signature but only the signature owner.

RSA is the most common PKC algorithm. The key length depends on the algorithm and RSA could use different key length as well. The algorithms are called RSA-1024, RSA-2048. In SSPayWMN we used RSA-2048 for PKC.

# Requirements for a secure and seamless mıcropayment scheme ın wıreless mesh networks

For a payment scheme designed for Wireless Mesh Networks requires following attributes:

* **Wide Coverage:** Users should be getting service within a large area.
* **Roaming:** Users should connect and maintain their connection and continue to get service even while they are moving. Designed connection method should apply to different operators.
* **Seamless Connection:** Users should be able to switch between access points as they move without noticing it.
* **Seamless Roaming:** Users should be able to switch between operators as they move without noticing it.
* **Anonymity:** It should not be feasible to track down a user’s network actions from their payments (unless law enforcement requires doing so).
* **Mutual Authentication:** For preventing malicious use of network, both user and network should be mutually authenticated. Moreover, man-in-the-middle and replay attacks must be prevented.
* **Two-way honesty:** clients cannot deny that they did not take service. Operators cannot claim that they provide service more than they actually provided. These are to be guaranteed using strong cryptographic protocols.
* **Preventing Double Spending:** A payment token should not be able to be used to get more services that its value. In particular, the payment token should not be used twice or more.
* **Unlinkability:** It must not be possible to relate connection sessions of the users with other connection sessions. In this way, higher level of privacy could be provided.

## 4.1 Requirements of the Network

In SSPayWMN project, our design of Wireless Mesh Networks will not only consists of mesh backbone but also Wi-Fi clients and wired servers. Mesh backbone will basically relay the packages from clients to server to make the users able to get service.

Servers of the operators are wired and will be communicated via regular 802.3 Ethernet protocol in its local area. Mesh backbone will communicate within itself using 802.11s protocol. Clients will use 802.11a/b/g Wi-Fi protocols to connect to the access points/mesh routers.

Mesh backbone will use Hybrid Wireless Mesh Protocol (HWMP) [16] routing for finding the shortest path to the gateways.

The system will be implemented in a simulation environment using a simulation tool such as OMNeT++ [2], ns-3 [3], etc. We will measure the delay metrics using some application scenarios in this simulation environment.

## 4.2 General Overview of the Proposed Scheme

Since WMNs are service providing system, they should have support for user identification, authentication as well as authorization and accounting. In our SSPayWMN project, our main goal is to design and develop a secure payment infrastructure for WMNs that also considers users' privacy and fairness. The basics of the system model, roles, entities and requirements have been identified in Deliverable 1. As mentioned there, our system model assumes mobile clients and operators, who will be charging the service they give. The operator's mesh backbone is made of several mesh routers which are actually Access Points (APs) with IEEE 802.11s support. This backbone is connected to operator's server via a gateway. There is also a TTP (Trusted Third Party) which may be reachable through operator. These system components are listed, together their icons used in the protocol figures, in Table 1.

|  |  |
| --- | --- |
| D:\My Documents\albert\tt proje\phone.png | Mobile user (client) |
| D:\My Documents\albert\tt proje\accessPoint.png | Access Point (AP) with mesh routing capability. From now on in this document, it is called as AP, but please note that it also has routing capability. |
| D:\My Documents\albert\tt proje\cloudWithoutDots.png | Mesh backbone of the operator |
| D:\My Documents\albert\tt proje\gateway.png | Gateway (GW) that connects the mesh backbone to outer world and also to the operator's server |
| D:\My Documents\albert\tt proje\operator.png | Operator's server (OP). Keeps necessary logs and user info. |
| D:\My Documents\albert\tt proje\trustedThirdParty.png | Trusted Third Party (TTP). Payment related logs are mostly to be generated by the TTP. |

Since the clients are mobile, they may hand over among different mesh routers (i.e. access points) of the same operators. They may also roam among different operators, not only due to coverage reasons, but also for having a better quality service. Our system aims to have seamless mobility and seamless roaming for payment purposes such that when the client gets service through a new AP or switch to another operator, authentication and authorization are not performed from scratch.

From security point of view, we aim to have mutual authentication between client and the network in our protocols. Anonymity of the clients and untraceability across different usage periods (a.k.a. unlinkability) are privacy related goals of the protocols.

From payment point of view, our main aim is to have a fair system in which all the claimed transactions bear cryptographic proofs. In this way, the clients cannot repudiate using a service and the operators cannot claim for services that they do not provide. The latter is especially important during inter-operator settlement; it is also important to resolve client disputes.

The protocols detailed in this deliverable are designed by considering the abovementioned requirements. The symbols used in this document are given in Table 2.

|  |  |
| --- | --- |
|  | 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 |

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.

## 4.3 Connection Card Structure

*Connection Card* is the main deed that clients buy from operators 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 operator picks on a random IV (Initialization Vector) and take 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 IV is taken hundred times. More formally a hash chain with, say, 100 tokens are 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 he knows the previous ones.

The operators inform the TTP (Trusted Third Party) about the associations between and corresponding so that TTP validates them as needed in the protocols.

Connection Cards are refillable with hash tokens, which are to be sold by the operators. We assume a free market strategy in the marketing of the hash tokens. The prices or campaigns related for the marketing of hash tokens are to be decided by the operators. In other words, operators would compete with each other to sell hash tokens. They also 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 16 digit alphanumeric and case sensitive value. In this setting, we are able to support up to users.Hash tokens are to be generated using SHA-256 hash algorithm; so they are 32 bytes long.

We foresee that smart cards can be used as connection cards. A simple Connection Card with 4 KB memory could store a and more than 100 hash tokens.

## 4.4 Alias Computation

In SSPayWMN project, we use aliases as temporary identifiers for clients. Aliases change frequently using a secure protocol that we design. By changing the aliases frequently, we provide anonymity in our system to some extent. We use a mechanism in which the aliases could be computed by the clients and also by the TTP (Trusted third party).

Serial number () of the connection card is used as the base for client’s aliases. The computation process of an alias is given below:

1. Client picks a random 128-bit unsigned number and calls it his nonce, .
2. Perform XOR operation with and this nonce, the resulting value is the alias:
3. Client uses this alias whenever his identity is required.

Aliases are to be updated periodically. The related protocols will be explained later in this document, but in this section we explain how a new alias is computed using the old previous one. Basically, the client picks a new nonce and XORs this nonce with its current alias to compute the next one. More formally, in order to change previous alias, , to a new alias, , the client performs the following steps.

1. Client picks a random 128-bit unsigned number as a nonce value, .
2. Perform XOR operation with and this nonce, the resulting value is the new alias:

The nonce values used in changing the aliases are to be sent in encrypted messages to the TTP in the related protocols. Thus only the client and the TTP can relate the aliases originated from a particular .

One may argue that this kind of alias computation would have a risk of causing same alias for several users. 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. We address this problem by making TTP to check proposed alias to be a unique alias at that point of time. This check is embedded in related protocols as will be described later.

# Protocols of secure and seamless mıcropayment scheme

## 5.1 Initial Authorization

Initial Authorization is the beginning of everything. Whenever a client buys some new hash tokens from an operator, he will need to authorize himself to TTP. Initial Authorization Protocol, shown in Figure 1, achieves mutual authentication and authorization of the user.

In Figure 1, connection between client and serving access point () is either Wi-Fi (802.11b/g) or cellular. 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 we assume all access points have same attributes, the serving access point will most likely be the closest access point to the mobile client.



Connection between serving access point and relaying access point is wireless, and uses 802.11s protocol [5].This mesh backbone is like a cloud from the mobile user’s perspective. It is a black box; which receives packets from mobile user and delivers them to the gateway in a multi-hop manner. Mesh backbone uses HWMP (Hybrid Wireless Mesh Protocol) protocol [6], which is a hybrid routing protocol. Once the mesh nodes deliver a packet through a route, they remember this route when they try to send a packet again, which will decrease packet delivery time.

Connection medium between mesh backbone and gateway () is wireless. Gateways and operators communicate through wireless medium also. The connection between an operator and TTP is either wireless using WiMAX 802.16 protocol or wired using 802.3 protocol.

Our mobile client introduces himself to the operator using *Initial Authorization* protocol. Trusted Third Party (TTP) already knows mobile user’s serial number () and first element of his hash chain (). Mobile user does not want to reveal his to any adversary because that will be used all the time; it is as valuable as mobile client’s identity. To achieve anonymity, mobile client computes an alias and use this value instead of . Mobile client will change his alias periodically as he continues to get service (related protocols will be explained later).

Initial Authorization steps are described below.

1. Client computes an alias using a nonce that he generated.

Client forms a connection request and encrypts this connection request using TTP’s public key, with RSA-2048.

(Assume that connection card has 100 credits)

Client sends this to .

1. receives the connection request and relays the request through mesh backbone.
2. Gateway receives the and relays it to the operator.
3. Operator relays to TTP.
4. TTP receives connection request () and decrypts it using its private key.

TTP checks alias' uniqueness within its database of users, it would make the client start over the protocol if alias is not unique.

It computes

TTP checks and association. Store and

TTP computes

TTP sends to operator.

1. Operator receives and verifies the signature using public key of TTP.

It gets and and stores these values. The value of is the client's alias until he changes it.

Operator sends to the gateway.

1. receives and verifies the signature using public key of TTP.

It stores and .

relays to through mesh backbone.

1. receives and verifies the signature using public key of TTP.

It gets and and stores these values.

sends to the client.

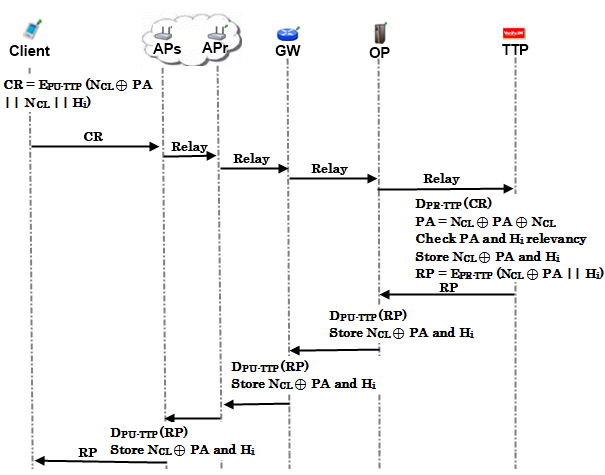
1. Client gets and understands that he is authorized to get service.

In this protocol, we assume that the packet has been sent in encrypted manner in hop-by-hop basis during its route. For the sake of simplicity, we have not shown this encryption and corresponding decryptions in the figure.

## 5.2 Reuse of a Connection Card

The users may disconnect before using up all the credits in a connection card. Reuse of a connection card protocol allows a user to connect using the remaining credits in a card. This protocol does not differ much from initial authorization protocol. The main difference here is instead of sending first hash token; client sends whichever token is the next one. Alias will change before the protocol starts. In our example case that we use below while explaining the protocol, client will send *i*th hash token and try to authenticate himself again. Another difference is that the client changes its alias during the connection. 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.

Figure 2 demonstrates how the protocol actually works end-to-end.



Reuse of connection card protocol is described below.

1. Client computes a new using a nonce that he generated.

*,* where stands for *Previous Alias* of the client

Client forms a connection request and encrypts this connection request using TTP’s public key, with RSA-2048.

Client sends this to .

1. receives this connection request and relays it to the through the mesh backbone.
2. Gateway relays to the operator.
3. Operator relays to TTP.
4. TTP receives connection request () and decrypt it using its private key.

TTP checks alias' uniqueness, start over the protocol if necessary.

It computes

It checks and association and stores (i.e. the new alias) and .

It computes

It sends to operator.

1. Operator receives and verifies the signature using public key of TTP.

It gets and , stores these values.

Operator sends to the gateway.

1. receives and verifies the signature using public key of TTP.

It gets and and store these values.

sends to the .

1. receives and verifies the signature using public key of TTP.

It gets and and store these values.

sends to the client.

1. Client gets and understands that he is authenticated to get service.

In this protocol, we assume that the packet has been sent in encrypted manner in hop-by-hop basis during its route. For the sake of simplicity, we have not shown this encryption and corresponding decryptions in the figure.

## 5.3 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.

Figure 3 describes the protocol briefly.



APS authentication is described below.

1. sends a challenge request to the client which started connection.
2. When client receives this challenge request, it sends a 128 bit challenge to
   1. Client drops the packet if it is not the that he sent connection request.
   2. Client drops the packet if there was not any authentication request.
3. hashes this challenge, and uses relevant hash value (here , but it could be any if the authentication protocol runs after the reuse of a connection card protocol) as the key of :

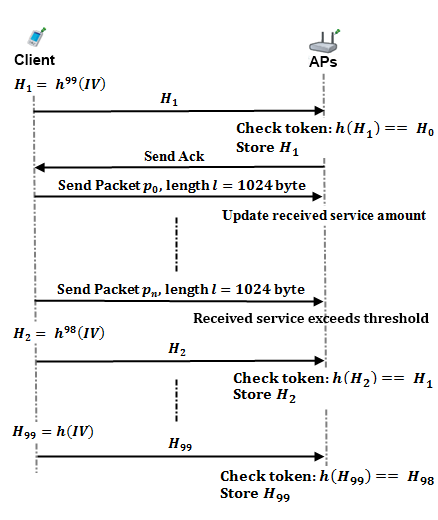
sends response to the client.

1. Client also HMACs the challenge and uses the stored hashvalue () as the key. Then it compares the result with the one that access point sent.

If it is authenticated, client starts to use access point to get Internet service.

## 5.4 Packet Transfer

After mutual authentication of client and client starts to send packets as shown in Figure 4.



1. Before sending data packet, client sends next token first. (It causes client to spend one token for each connection session.)
2. gets from the database. Remember stored client’s alias and hash token in *Initial Authorization* and *Reuse of a Connection Card* protocols.

Then:

* 1. Checks if
  2. If true sends acknowledgement () toClient and updates currently used hash value as .

1. Client sends first 1024 byte data packet .
2. serves the client without wanting any other hash token for a predefined value. This value depends on the operator.
   1. Every time client sends data packets access point will update the amount of service the user got.
   2. Whenever service amount value passes the predefined threshold client will send the next hash token.

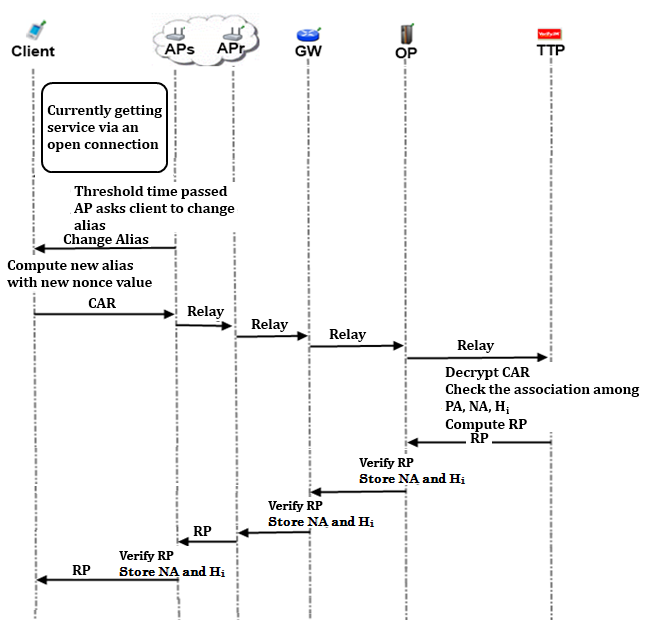
## 5.5 Changing Alias

We achieve anonymity property by using aliases, but tricky part here is achieving unlinkability. We have to change aliases on a basis that an adversary, who knows a certain client’s alias, could not be able to trace client’s activity on his home network, and also could not trace his movements among the operators or access points.

To be able to change alias in a safe way, we have to communicate with TTP but we do not want to bother TTP very often because that would slow down the entire operation due to extra delays caused. That’s why we make use of periodic timer value to make sure that access points would ask 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 [7].

In this way, we prevent any type of attack that would aim to analyze network traffic of access points and examine connection requests. By passing the task of enforcing alias changing to the access points, we gain a more generalized control over the clients. No attacker would understand which client wanted to change his alias, because all the clients getting service from a particular access point have requested to change their aliases at that particular time.

We need to keep actual change alias operation on the client, because client and the TTP should be the only ones who know association between an alias and a client’s .



Changing Alias Protocol is shown in Figure 5 and described below.

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

When the Alias Change Timer value expires, Access Point broadcasts "Change Alias" command to all of its clients. This times value is a system parameter; typical value is a couple of hours.

1. Client receives "Change Alias" command.

Client computes a new alias by picking up a new random nonce and computing , where is the new alias and is the previous alias .

Client forms a Change Alias Request ()

It sends this to .

1. receives and relays it to the via mesh backbone.
2. Gateway forwards to operator.
3. Operator relays to TTP.
4. TTP receives Change Alias Request () and decrypts it using its private key.

TTP checks for new alias' () uniqueness and starts over the protocol if not unique.

TTP computes

It checks and association and stores and .

It computes (

TTP sends to operator.

1. Operator receives and verifies the signature using public key of TTP.

It gets and , and stores these values.

Operator sends to the gateway.

1. receives and verifies the signature using public key of TTP.

It gets and , and stores these values.

sends to the .

1. receives and verifies the signature using public key of TTP.

It gets and , and stores these values.

sends to the client.

1. Client gets the .

Client decrypts it using TTP’s public key and update his last used hash value and new alias.

In this protocol, we assume that the packet has been sent in encrypted manner in hop-by-hop basis during its route. For the sake of simplicity, we have not shown this encryption and corresponding decryptions in the figure.

## 5.6 Update Packets

In our usual flow, after authentication, access points do the accounting. Because of the fact that they 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. But it is essential to send periodic updates to the operator. This is essential because we want to provide a seamless mobile communication, even when user steps out from one access point’s region to another’s. In this kind of situation, clients should authenticate themselves by showing themselves to gateway only. By doing that, we bypass operator and we can decrease authentication time significantly.

In order to use abovementioned protocol, gateways should be aware of client’s lastly used token and connection status. From security point of view, it would be ideal to update gateway entry at every time when a new token is used by the client. However, this would be very inefficient and would increase network traffic. That’s why we define threshold time values for access points and gateways. After passing this threshold time values, access points send update packets to gateways, and gateways send update packets to operator. This mechanism is depicted in Figure 6 and explained below.

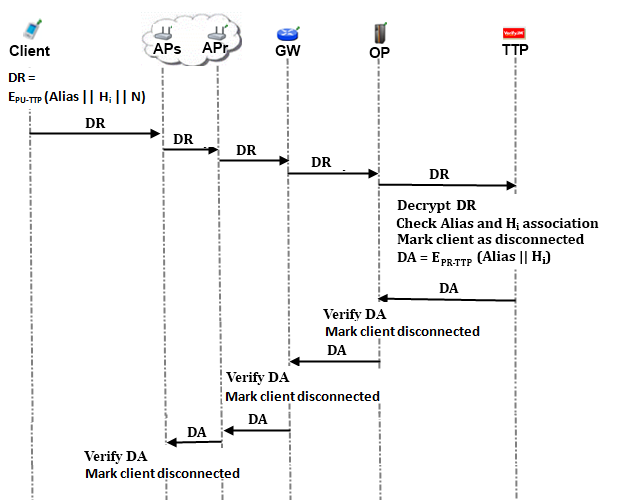


1. After client sends the first token he uses, at the current session, access point starts to count the time passed. After units of time (value of is a system parameter), access point sends lastly used hash token to the relaying access points.
2. Relaying access points forward the token to the gateway.
3. Gateway receives the token and updates the client entry. Gateway updates the last used value for the token.
4. Gateway starts to count the time passed from the lastly arrived token. After units of time (value of is a system parameter), gateway sends lastly used token to the operator.
5. Operator receives the token from gateway and updates the client entry by changing the last used value attributes with the newly received token.

## 5.7 Disconnection

To be able to run Reuse Connection Card Protocol, we have to establish proper disconnection. Our Update Packets protocol brings stability to the system in case of a connection interruption, but we assume 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.

These protocols are designed for the sake of operators, to make them aware of how many users they are serving at a point of time. That information will bring them the opportunity to organize their servers accordingly, deciding on their marketing strategies using traffic density, etc.



Disconnection protocol is shown in Figure 7 and described below.

1. Client forms a disconnection request

Client sends it to the access point.

1. Access Point receives and prepares itself to disconnect that particular client.

AP relays to the mesh backbone, to make it reach to the .

1. receives and forwards the to the Operator.
2. Operator receives and forwards the to the TTP.
3. TTP receives the and . It checks the association between the and this hash token; if the association holds, then it computes a disconnection acknowledgement ().

TTP sends to Operator.

1. Operator receives , verifies the signature on it and marks client as disconnected.

Operator relays to .

1. receives , verifies the signature on it and marks client as disconnected.

It relays to the mesh backbone.

1. Serving Access Point eventually gets the , verifies the signature on it and disconnects the particular client which corresponds to the it received.

In this protocol, we assume that the packet has been sent in encrypted manner in hop-by-hop basis during its route. For the sake of simplicity, we have not shown this encryption and corresponding decryptions in the figure.

## 5.8 Distributing Access Point Public Keys

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

In Figure 8, 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.



Distributing 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.

We make use of other protocols (such as *Initial Authorization* or *Reuse of a Connection Card* 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 operator.

1. Operator receives the connection response and the certificate and relays these packets to the access point through gateway and mesh backbone.
2. Access point gets its certificate and broadcasts it to the nearby access points. It also stores this certificate.

## 5.9 Seamless Roaming (Payment Related)

When the clients need to get service from an access point of a new operator, they roam between old operator and new one. In this kind of situations, we do not bother TTP and save time and computational power.

Because of the fact that every access point has its public/private key pairs and ability to broadcast public keys, we can handle roaming in a seamless way without running the authorization process from scratch. As it is shown in Figure 9, 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 operator.



Roaming protocol is shown in Figure 9 and 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 got services from . , is the access point that the client would like to continue to get services in network.

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

sends to the client.

includes the roaming ticket that the client uses to get services from . It is signed by and encrypted for , thanks to public key distribution mechanism that we employ.

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

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 ().
2. decrypts using its private key.

It gets the signed ticket of the . stores this signed data 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.

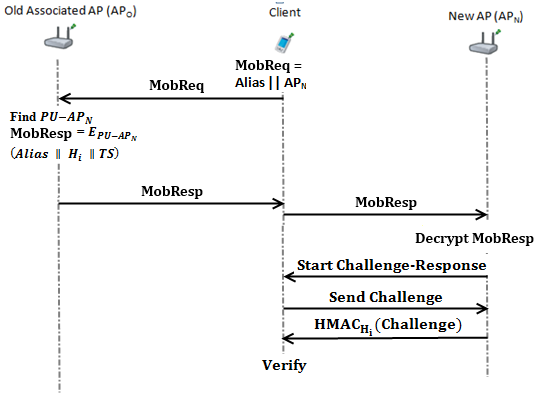
1. Client sends a 128-bit challenge to .
2. computes

sends this HMAC value to the client.

1. Client receives this HMAC. Moreover, it computes the same HMAC using . If the computed one and the received one are the same, then it authenticates .

## 5.10 Seamless Mobility in Home Operator (Payment Related)

When a client moves out of the coverage area of its associated AP or if another AP provides a better service, the client may want to hand off to another AP. For the payment purposes, we develop a seamless mobility protocol in order to avoid a full authorization process during such a handoff. This protocol is shown in Figure 10. The user sends only the ID of the new access point. This protocol uses the service of “Distributing Access Point Public Keys” protocol. With the ID of the new access point, the old access point pops up the public key, and use this public key to encrypt the credentials of the user. In this way, the necessary user and payment information to continue the service at the new AP is sent to it in an encrypted way.



In Figure 10, client moves to the new AP’s () coverage area from old AP (). Seamless mobility is described as follows:

1. Client forms a mobility request () and sends it to .
2. concatenates Alias, , timestamp , and encrypts it with the public key of . It relays this mobility response () to via client.
3. decrypts using the private key of itself and checks whether it is expired or not.
4. If it is not expired, stores and *.* Then sends a challenge request to the client.
5. When client receives this challenge request, it sends a 125-bit challenge to .
6. computes

sends this HMAC value to the client.

Client receives this HMAC. Moreover, it computes the same HMAC using . If the computed one and the received one are the same, then it authenticates.

# Unit test results

Unit tests cover protocol behaviours under low pressure. In these tests there is only one user, and this user performs the same protocol every minute. These tests are done to ensure that modules of the system are fit for use.

As discussed earlier some protocols show similarity considering packet sizes, cryptographic operations and packet routes. Since there would be no difference between unit tests of protocols that are in the same group, there is one result chart for a particular group of protocols.

## 6.1 Unit Test Result for End-to-End Two-Way Protocols

Unit tests for end-to-end two-way protocols consist of a user, running the same protocol every minute. Charts present the average delay of packet delivery over time. In this simulation the user sends the packet to a serving access point and the packet hops 2 times in the mesh backbone until it reaches the gateway. Gateway forwards the packet to operator and operator transmits the packet to TTP. TTP processes this packet and sends it back to the client through the same route.

Figure 8 gives the result for unit test of end-to-end two-way protocols.



Figure 8. End-to-End Two-Way protocols Unit Test Result

As shown in Figure 8, there is a delay that shows variation around 0.04 second. This unstable behaviour is caused by different initial packet delays. System needs some packets to set up paths between mesh nodes. The performance stabilizes in time. Average delay shows a peak by the end however the difference between highest and lowest values of the results is inconsiderable.

## 6.2 Unit Test Result for Access Point Authentication

*Access Point Authentication* protocol consists of a challenge-response protocol. It contains two HMAC operations.

Unit test for this protocol contains a user, trying to run access point authentication protocol with a serving access point every minute. The resulting chart, presented on Figure 9, shows the average delay of the protocol versus time.



Figure 9. Access Point Authentication protocol Unit Test Result

As shown in Figure 9, average delay of access point authentication converges to 0.05 second in the steady state. The initial delay values are higher than the later ones, because nodes need some time to establish and see who is around. At the time of initial deployment, wireless nodes send and receive beacons and perform operations using them.

## 6.3 Unit Test Result for Seamless Mobility and Roaming

*Seamless Mobility* and *Seamless Roaming* protocols have the same behaviour since client sends and receives same length of packets. Thus, they are grouped together for unit tests.

Unit test for *Seamless Mobility* and *Seamless Roaming* protocols consists of a client changes serving access point every minute. Client is located in between two access points and these access points are both eligible for service. Since these protocols must be seamless to the user it is important to get reasonable delays for these protocols.

Figure 10 presents the unit test result for *Seamless Mobility* and Roaming protocols.



Figure 10. Seamless Mobility and Roaming protocols Unit Test Result

In unit test for these protocols, a 0.15 second of network delay for access point change is observed. Similar to other protocols, there is a transitive period at the beginning of the simulations, however it reaches steady state in time and gains balance.

## 6.4 Unit Test Result for Packet Transfer

*Packet Transfer* is the mostly used protocol in the system. It is crucial to have small amount of network delay for this protocol because of it’s often use. Unit test scenario of *Packet Transfer* protocol is that a client sends a 512-byte packet every minute.

Figure 11 shows the unit test result for Packet Transfer protocol.



Figure 11. Packet Transfer protocol Unit Test Result

Unit test gave a higher average delay value at the early parts of the simulation but expectedly it reaches a balance through time. As seen on Figure 11, at steady state, packets are received in a very short amount of time, which is around 0.0002 second.

## 6.5 Unit Test Result for Update Packets

*Update Packets* protocol takes place between AP and TTP. In this simulation access point updates the user info stored at operator. Figure 12 shows the average delay of *Update Packets* protocol over time.



Figure 12. Update Packets protocol Unit Test Result

In the simulation scenario, APs update operator once in every second. Our simulation showed that there is a 0.02second maximum network delay for updating operator for the client usage.

# User Modeling And Mobility

The proposed system intends to serve a variety of users (a.k.a. network clients). Network clients differ in their network usage frequency with respect to time of day, their mobility patterns and frequency of usage.

Certain kinds of actions are defined, such as authorization (initial or reuse of a connection card), disconnection, packet transfer (network usage), payment related roaming and payment related AP handover. All of these actions are triggered as a result of a random event. Connection and network usage related actions are triggered according to a two-state Markov Chain model [8]. Roaming and handoff related actions are triggered by user mobility.

## 7.1 User Actions

In real-life scenario simulations, network usage related actions are modelled using two-state Markov Chain as shown in Figure 13. There are two states that a user could be in: *Connected* and *Not Connected*. State transitions or staying in the same state triggers some actions as described below.



Figure 13. State Diagram of Clients

The initial state is *Not Connected*. In this state, the user switches to *Connected* state with the probability value of . This state transition triggers *Initial Authorization* (if the CC is used for the first time) or *Reuse of a Connection Card* protocol (if the connection has been used before). In this way, the user starts consuming the network and getting the service. While in *Not Connected* state, the user stays in the same state with probability value of .

While in *Connected* state, the user remains connected (i.e. stay in the same state) with the probability of . Staying connected triggers *Packet Transfer* protocol. In other words, the user continues to get service via the currently connected AP. In *Connected* state, transition to *Not Connected* state occurs with probability of. This transition disconnects the user via *Disconnection* protocol.

In this 2-state Markov chain model, the average connection duration, , is calculated as the expected value of staying in *Connected* state, as given below.

(1)

Where, denotes .

The expected value of staying in *Not Connected* state is the average idle time for a user between two connections. This value, , is calculated as follows.

(2)

Where, denotes .

## 7.2 Client Types

Three different user types are outlined with different networking and mobility requirements. Considering whether they are working, studying or domestic provides the differentiation among user types.

The network usage within one day has been modelled in three time slots: (i) night (00:00 – 07:59), (ii) daytime (08:00 – 15:59), and (iii) evening (16:00 – 23:59).

User types are described as follows:

* **Students:** This kind of clients uses network services mostly in the evening when they return back from school. Their possibility to use network services during morning and night is relatively small comparing to mid-day time. Thus, the probabilities for being active are higher for evening. Students are assumed to be mobile at the beginning and end of the *daytime* slot since they go to their school. Until the end of the *night* slot, students would more likely to get service in their homes in an immobile way.
* **Employees:** This kind of clients has routine lives. They are immobile and not so active during nights. However, during the daytime, they are very active and use network services at their work places. Moreover, they are mobile as they commute to/from work from/to home at the beginning and end of the working times.
* **Domestics:** This type of users does not work outside and spend their time at home. Usually the domestics get Internet service in an immobile way. These users are highly active at all times.

The parameters of and are determined based on the abovementioned discussion about the client type characteristics and the time slots. These values are given below. The triplet specify the probability values for night, daytime and evening, respectively.

These values also determine the average connection duration and idle time by using Eq. 1 and 2. For example, a domestic client remains idle during daytime for minutes between connections. Once connected, average connection time for this category is minutes.

## 7.3 User Mobility and Timing

Real-time scenario covers Internet usage of 300 users in a 1-km2 metropolitan area. The simulations time begins at 00:00 a.m. and lasts for 24 hours. Simulation time is divided into 3 parts considering night, daytime and evening. Every part of the day has different statistical values for client behaviours.

Simulations are run for 1440 seconds, however every second in the simulation stands for 1 minute in real life.

In real-life scenario simulations clients are able to move from one location to another. The time and direction of their movement is selected at random but probabilities are affected by user roles. For example, when school is over, a student is most likely to move towards her target destination (e.g. her home).

Clients are assigned a random target access point. Every one of 100 access points has 3 initial clients. The client moves from its current access point to the target access point on the grid. An example movement pattern is shown in Figure 14. As a client moves from access point A to the access points B, if she needs to connect to the Internet, she forms up a new connection with the access point, which is closest to client’s current location.



Figure 14. User Mobility

In real-life scenario simulations, there are two operators and they have same amount of access points. In current simulations, each operator has 50 access points. The client executes handover or roaming if there is an active connection during movement between access points. In such a case, depending on the new access point’s affiliated operator, user’s movement triggers either *Seamless Mobility* or *Roaming* protocols. If new access point’s affiliated operator is same as the one that client currently uses, and then it means the client would perform *Seamless Mobility* protocol for handover. Otherwise, the client would run *Seamless Roaming* protocol.

Clients are assigned uniformly distributed random speeds between 2 km/h to 6 km/h. The clients are assumed to move without a motor vehicle.

# Results for Real-Life Scenario Simulation

Results for unit test simulations are described before; however the most significant results are real-life scenario simulation results. Despite the randomness of the system, users’ actions are highly related to their group and current simulation time.

Charts for the results display the average delay for a particular protocol.

## 8.1 Overview

Final simulations provided the results in Table 2. Charts on Figure 15 and Figure 16 are drawn exploiting the results in Table 2. Considering the results it could be calculated that over 100 minutes of Internet service, workers have only waited for 1 minute for system delays. In average, over 1000 minutes of Internet service needs a delay of 13 to 16 minutes of waiting.

TABLE II  
Simulation Results for Client Types

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Total Internet Usage Time | Total Internet Usage Delay | Average Internet Usage Time for a Client | Average Internet Usage Delay for a Client |
| Student | 95899,26 Minutes | 1698,95 Minutes | 958,99 Minutes | 16,98 Minutes |
| Worker | 101681,64  Minutes | 1316,35 Minutes | 1016,81  Minutes | 13,16 Minutes |
| Non-Worker | 105335,08 Minutes | 1456,12 Minutes | 1053,35 Minutes | 14,56 Minutes |



Figure 15. Total Amount of Internet Usage Times for Client Types vs. Total Delays



Figure 16. Average Usage Times for Client Types vs. Average Delays

As described before the clients are grouped into 3 groups. The client roles and probabilistic values affect their behaviour in the system, which results difference between overall values of the simulations.

Figure 15 and Figure 16 shows the overall results for real-life scenario simulation. Figure 15 shows comparison of minutes clients used as idle or active. Figure 16 shows the average value for the clients of the same group.

## 8.2 Real-Life Scenario Simulation Result for Initial Authorization



Figure 17. Result for Initial Authorization Protocol

*Initial Authorization* protocol is used at the beginning of the service for each user. As it is seen on the chart every one of the 300 users are authenticated at the end of 40th minute.

Simulation starts around the 10th minute in the morning. At the beginning there is a huge amount of users, trying to authenticate. Figure 17 indicates that, this process varies between 0.6 and 2.5 seconds. After 10 minutes it attains a balance and *Initial Authorization* protocol meets a delay of 1 second, which means when users open up their mobile device they would have Internet service after 1 second.

## 8.3 Real-Life Scenario Simulation Result for Reuse of a Connection Card Protocol



Figure 18. Result for Reuse of a Connection Card

*Reuse of a Connection Card* protocol is used after disconnecting from the system. As it is seen it is a highly used protocol in the system. It starts around the 50th minute and used for the entire time of the simulation.

As seen on Figure 18, at the beginning of the protocol the delay changes between 0.1 and 0.6 second. After some time protocol achieves a balance and a 0.4 second of network delay is observed.

## 8.4 Real-Life Scenario Simulation Result for Changing Alias



Figure 19. Result for Changing Alias Protocol

Every active client uses *Changing Alias* protocol in the system in every 50 minutes. The protocol is first used at 50th minute and it is used entire time of the simulation.

As one can see on Figure 19, at the beginning of the protocol the delay for the protocol varies between 0.1 and 0.4 seconds. After some time the average delay for the protocol converges to 0.4 seconds.

## 8.5 Real-Life Scenario Simulation Result for Disconnection



Figure 20. Result for Disconnection Protocol

*Disconnection* protocol first appears around 30th minute and it is used through the entire time of the simulation. Figure 20 shows that, at the beginning of the system Disconnection protocol average delay vary between 0.1 and 0.5 second but through time the average delay meets 0.4 second.

## 8.6 Real-Life Scenario Simulation Result for Update Packets



Figure 21. Result for Update Packets Protocol

*Update Packets* protocol is an end-to-end one-way protocol. It is expected to get lower delay values for this one. Only access points use *Update Packets* protocol and they send packets to TTP. The packets are sent every 10 minutes.

As it is seen on Figure 21, at the early stages of the protocol, the average delay value varies between 0.6 and 1.4 second but then after some time the protocol stabilized around 0.4 second.

## 8.7 Real-Life Scenario Simulation Result for Seamless Mobility in Home Operator Protocol



Figure 22. Result for Seamless Mobility in Home Operator Protocol

*Seamless Mobility* protocol is used when a handover happens between access points. If these access points are belonging to the same operator then it means the client is using *Seamless Mobility* protocol.

By looking at Figure 22, it could be said that*, Seamless Mobility* protocol has an initial average delay that shows difference between 0.2 and 1.2 seconds. A user loses around 0.1 second to make a handover to the new access point.

## 8.8 Real-Life Scenario Simulation Result for Roaming Protocol



Figure 23. Result for Roaming Protocol

*Roaming* protocol is used when a handover happens between access points. If these access points are belongings of different operators then it means the client is using *Roaming* protocol.

*Roaming* protocol has an average delay that varies between 0.05 and 0.2 seconds. There are 2 operators so a client has a %50 chances to make a *Seamless Mobility* or *Roaming* protocols. After some time protocol reaches a balance around 0.2 second of delay.

As one can see on Figure 23, the results for *Roaming* protocol shows a boost until the middle of the simulation time but it decreases and achieves a balance

## 8.9 Real-Life Scenario Simulation Result for Packet Transfer



Figure 24. Result for Packet Transfer Protocol

*Packet Transfer* protocol is the mostly used protocol in the system.

Figure 24 states that, at the beginning of the protocol the average delay value varies between 0.005 and 0.025 but then the protocol achieves a balance around 0.02 second.

# Conclusion

In unit tests, standalone performances of the protocols under trivial usage scenarios are analysed. Unit tests set an example for how the system will behave in empty hours. In this way, the first proof-of-concept implementation of the system is provided and showed that the designed protocols reach steady state.

Uniform probability distribution model enables us to simulate real time scenarios in simulation environment, and gets results closer to real time situations.

There exist different user types, as there are different types of clients in real life. There is also randomness in the system, so there could be different outcomes for the same simulations. The simulations implemented to cover even the most unexpected situations.

Results are significant since the actual usage of the system is a combination of these protocols. Unit tests and real-life scenario simulation results show that the proposed system is a considerable and an effective pre-payment system.